A Cost-Benefit Approach to Evaluating Engine Health Monitoring Systems

Grant Gordon[1], Chris Hickenbottom[2], and Dinkar Mylaraswamy[3]

[1,2] *Honeywell International Inc., 111 S. 34th St., P.O. Box 52181, Phoenix, AZ 85072-2181, U.S.A.*
Grant.Gordon@Honeywell.com
Chris.Hickenbottom@Honeywell.com

[3] *Honeywell International Inc., 1985 Douglas Drive N, Golden Valley, MN 55422, U.S.A.*
Dinkar.Mylaraswamy@Honeywell.com

ABSTRACT

Condition-based maintenance (CBM) enables fleet-level decisions that increase readiness, increase time between overhaul (TBO) and reduce inspections. Since engines account for a significant portion in overall maintenance cost drivers, detection of incipient faults is an important element of the overall CBM equation. The last few years have seen significant progress in design, development and deployment of engine health monitoring. In order for such potential health monitoring solutions to be operationally viable, they must integrate with existing engine designs and maintenance processes. That is, technical factors must be balanced against economic and operational benefits.

A Cost-Benefit Analysis (CBA) is used to provide a comparison of alternative solutions that decision-makers can use to identify the most cost-effective approach to CBM. In this paper we describe our approach to developing the underlying value capture expressions for monetizing cost and benefits. We illustrate the approach to evaluate two options for mechanical components health monitoring techniques for a gas turbine engine. We conclude the paper with how CBA summary results can be presented to a decision maker.

1. INTRODUCTION

The last few years have seen significant progress in design, development and deployment of engine health monitoring solutions (Jaw 2005, Mylaraswamy et al. 2009). This progress is exemplified both with respect to novel sensor development (Uluyol 2010), accurate algorithms and increased coverage of engine components being monitored (Parthasarathy 2011). In order for such potential health monitoring solutions to be operationally viable, they must integrate with existing engine designs and maintenance processes. The technical factors must be balanced against economic and operational benefits. In this paper a Cost-Benefit Analysis (CBA) analysis approach is used to show how competing solutions can be compared to identify the most effective engine health monitoring design for a new development engine.

2. THE APPROACH

At the heart of any CBA is a cost model, with an underlying cash flow structure comprised of elements that work towards (benefits) or against (costs) the business objectives. Commonly there are two approaches to developing a cost model: resources based and activity based (Schmidt, 2009). For a new engine development program, considering condition based maintenance (CBM) capabilities, a resources-based approach is appropriate. Similar to a component improvement program where a new engine component must buy its way onto the platform, a CBM system is intended to bring benefits but is also expected to have its own useful life, operating and maintenance costs that must be compared relative to its benefits. Our analysis proceeds by comparing two different scenarios in a cash flow model, an 'as-is' engine design e.g. no CBM and the 'to-be' configuration e.g. a CBM system with a suite of capabilities.

In our analysis the cost elements follow a structure similar to that provided in the Report of the OSD CBM+ Action Group 2010 Summer Study (Secretary of Defense, 2010). At the top level the cost elements include research and development, infrastructure investment, operation and sustainment of the technology and final disposal. We explicitly track and monetize a cost for the additional weight incur for the engine integrated elements of the technology solution. In addition we have made extensive use of a Cost

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Effectiveness Analysis (CEA) Spreadsheet (US Army 2007) to define and evaluate costs. CEA is a standardize tool developed by the Joint Propulsion Coordinating Committee (JPCC) for evaluating the cost effectiveness of an engineering change to aircraft engines.

The cost is broken down into four categories:

1. Non-recurring Development Cost.
   a. A one-time cost to mature the technology from its current technology readiness level (TRL) to TRL-7.
   b. A one-time cost to develop the necessary CBM infrastructure ground support equipment, CBM servers, engine tests, and common software development.
2. Unit cost for deployment.
   a. A PHM technology may require special sensors, signal processing units and cables. The unit cost for a PHM technology includes the cost to deploy the sensor (if applicable) and any specialized software on the engine.
   b. In addition there will be a cost for installing the any commonly used processing hardware and common software to support the Engine PHM functions on the aircraft.
3. Sustainment cost. The sustainment cost is estimated:
   a. One block change per year that includes a major software modification.
   b. Software configuration changes to update lookup-table, threshold and algorithm settings. We estimate each change will consume 2 man-hours. In the first year of deployment we estimate 48 changes, 24 in the second year and 12 in subsequent years.
4. Added weight was accounted for as a decrease in specific fuel consumption.

More challenging than characterizing the system costs over time is the difficulty of effectively characterizing the CBM system benefits. In this case the true value of any new technology should be measured against a set of metrics that map back to operational and mission effectiveness. As a starting point we used the Army's top level CBM objectives (US Army 2012):

1. Decrease Maintenance Burden on the Soldier.
2. Increase Platform Availability and Readiness
3. Enhance Safety
4. Reduce Operations & Support (O&S) Costs

These objectives cover traditionally financial and non-financial goals. Despite the fact that these non-financial benefits are indeed very important – the Army states that "the most compelling and supportable benefits described in Cost Benefit Analysis (CBA) are those associated with aviator safety and aviation combat power" (Secretary of Defense, 2010) – there is often a reluctance to assign monetary values to non-financial benefits. But clearly the cash flow statement is blind to nonfinancial business outcomes so defining an acceptable value is necessary.

In this paper we focus on monetizing one such objective – namely operational availability caused by downtime and inefficient operations. In order to define the underlying expressions, key system boundaries and assumptions, which can be interpreted as our *cost model parameters,* need to be defined. These are listed in Table 1.

Model Parameters	
Number of engines and aircrafts	Unit-level maintenance man-hour rate
Year of introduction of production engines	Depot maintenance man-hour rate
Engine introduction rate	Average cost of fuel
Average yearly flying hours (FH)	Density of fuel (kerosene)
Average mission length (flight hours)	Analysis period in years

Table 1. Parameters in the cost-benefit analysis

In addition, our analysis considers the rate at which users replace existing maintenance paradigms with new technologies. This adoption rate is expressed through a constant, α, as shown in Table 2.

Year	**Adopter Category**	**Cumulative Acceptance Fraction, α**
1	Innovators (2.5% of population)	0.025
3	Early Adopters (13.5% of population)	0.16
4	Early Majority (34% of population)	0.5
5	Late Majority (34% of population)	0.84
10	Laggards (16% of population)	1.0

Table 2. Adoption rate of maintenance policies due to introduction of CBM technologies

3. QUANTIFYING THE CBM BENEFITS

The objectives of decreasing the Maintenance Burden on the Soldier and reducing Operations & Support (O&S) Costs are financial benefits that are relatively easy to account for in a cash flow model. For example we model the benefit of decreased maintenance burden by considering two sources of activities: (a) scheduled preventative maintenance activities, and (b) troubleshooting activities arising from inconclusive diagnostic indications. Given a frequency of occurrence and cost per occurrence these sources can be evaluated. However increases in aviator safety and aviation combat power (increase platform availability and readiness) are responsible for the majority of a CBM system value. These are not direct financial benefits and are more challenging to model. But given their significance and complexity, this is where we will focus our attention in the paper.

For readiness and availability we monetize the benefits by first establishing how the CBM capabilities can influence Ao. From the definition of operational availability we have (U.S. Army, 1996),

$$Ao = OR = \frac{(OT+ST)}{(OT+ST) + (TCM+TPM+TALDT)} \qquad (1)$$

here Ao is operational availability, OR is operational readiness, OT is operating time, ST is standby time, TCM is total corrective maintenance downtime, TPM is total preventative maintenance downtime and TALDT is total administrative and logistics delay time. By definition, if a CBM capability can reduce TCM, TPM or TALDT, then operational availability can be improved.

To assign a value to the fractional increases in Ao we note that increases in Ao are increases in the fractional utility of the asset, where the total utility is the total satisfaction that the user receives over the life of the asset. Given that the total satisfaction must be greater or equal to the total costs for acquiring, operating, maintaining and disposing the asset, a value can be assigned to Ao based on the flight hour costs, $FH_{cost,}$ for the helicopter. The cost per flight hour is calculated as follows:

$$\begin{aligned} &FH\_value \geq FH\_cost \\ &\quad = AAC\_aircraft + DMC\_Engine + DMC\_Aircraft \\ &\quad + Fuel\ cost\ per\ FH \qquad (2) \end{aligned}$$

Here $AAC_{aircraft}$ is the average acquisition cost per flight hour. DMC_{*} is the average direct maintenance cost per flight hour. The average acquisition cost AAC is calculated as:

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$$Avg\ Acq\ Cost = \frac{Aircraft\ average\ acquisition\ cost}{Expected\ aircraft\ lifetime\ in\ FH} \qquad (3)$$

From reference sources, e.g. (Katzomis, 1998), for the Apache and Blackhawk helicopter

$$\begin{aligned} Acquisition\ Cost_{Apache} &= \$43M \\ Acquisition\ Cost_{Blackhawk} &= \$21M \qquad (4) \end{aligned}$$

And assuming an average expected lifetime for helicopters of 62,500 flight hours and a fleet mix of 30% Apaches, 70% Blackhawks, the acquisition cost for the fleet becomes:

$$AAC_{Aircraft} = \frac{0.3 * \$43M + 0.7 * \$21M}{62{,}500\ expected\ lifetime\ FH\ per\ aircraft} = 441\ \$/FH \qquad (5)$$

Next we look at two major factors that cause loss of flight hours.

3.1. Unscheduled Event Model

In our model an unscheduled/unplanned maintenance occurs at the unit level in the following two conditions:

a) A malfunction is not detected until the pre-flight inspection rendering the engine and hence the aircraft unavailable for the mission.
b) A malfunction or an alert is generated during the mission resulting in mission abort.

The model associated with these unscheduled events is expressed as:

$$Unscheduled\ Mx\ event \xrightarrow{leads\ to} \left\{ \begin{matrix} Loss\ of\ flight\ hour\ due\ to\ aircraft\ downtime \\ Economic\ impact\ from\ possible\ mission\ abort \\ Safety\ value\ from\ possible\ loss\ of\ life/aircraft \\ Decrease\ in\ operational\ availability \end{matrix} \right\} \qquad (6)$$

We monetize the net impact of these unscheduled maintenance events using the following method and assumptions:

1. Administrative and logistics delay for an unscheduled event is 8 days. Using the average aircraft utilization rate (based on parameters listed in Table 1), we convert this to equivalent loss of flight hours, X_{TALDT} The monetary value is given by: FH_{value} x X_{TALDT}
2. A mission-abort decision is made mid-way into mission. Using the average aircraft utilization rate (based on parameters listed in Table 1), we convert this to equivalent loss of flight hours, $X_{MA.}$ The monetary value is given by: FH_{value} x $X_{MA.}$ We further multiply this number by the probability of occurrence, *P(engine inflight shutdown|malfunction).*
3. We assume a constant value for a class A accident. Let M_{ACC} denote this constant value. This number is multiplied by *P(class A accident|inflight engine shutdown).* which is usually a very small number.

If a CBM technology can provide an early indication with an adoption rate α and prevent n_{OI} such events, the savings would be:

n_{OI} x α x {FH_{value} x X_{TALDT} +
P(engine inflight shutdown|malfunction) x
FH_{value} x X_{MA} +
P(class A accident|inflight engine shutdown) x

M_ACC} (7)

Next we describe the value capture expression associated with the other factor that causes loss of flight hours.

3.2. Scheduled Event Model

Scheduled Preventative Maintenance, SPM, is defined as activities performed on a periodic basis to keep the aircraft ready for operations. A SPM occurs at a fixed interval T_{SPM}, may involve more than one maintainer and requires L_{SPM} man-hours of activity. T_{SPM} is expected to vary depending on OPTEMPO and mission criticality.

The model associated with a scheduled preventative maintenance event is:

$$\textit{Scheduled Mx event} \xrightarrow{\textit{leads to}} \left\{\begin{array}{l}\textit{Additional burden on maintainer} \\ \textit{Decrease in operational availability}\end{array}\right\} \tag{8}$$

A CBM technology can potentially impact a SPM as follows: (1) It can increase the time interval between two successive scheduled preventative maintenance activities. That is, $T_{SPM,CBM} \geq T_{SPM.}$ (2) It can decrease the time it takes to perform a scheduled preventative maintenance action. That is, $L_{SPM,CBM} \leq L_{SPM}$. The expression for reducing the cost associated with SPM is given by:

$$M_{SPM,CBM} = FH \times \alpha \times \left\{\frac{L_{SPM}}{T_{SPM}} - \frac{L_{SPM,CBM}}{T_{SPM,CBM}}\right\} \times \$AVUM \tag{9}$$

Here \$AVUM is the unit level labor rate and FH is the total flight hours over the evaluation period.

3.3 Economic Impact of an Undetected Fault

The net impact of undesired effects resulting from an inability to detect the initial fault are described in Figure 1.

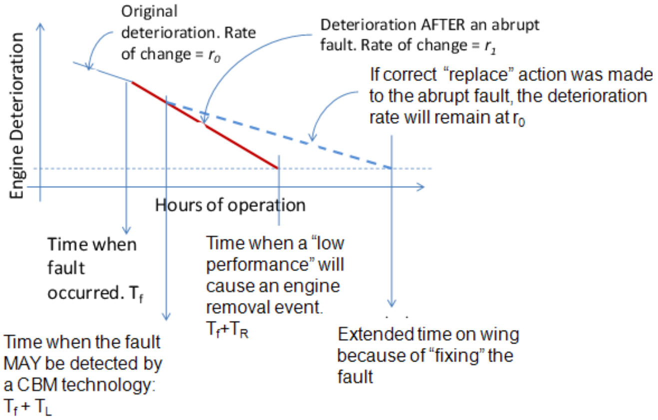

Figure 1. Impact of an undetected abrupt fault

As shown in the Figure 1, an abrupt fault happens at time $T_{f.}$ Here we assume that the source of the abrupt fault is contained within a line replaceable unit LRU. Since this fault is "abrupt", by definition it causes a sudden increase in the engine deterioration rate. The deterioration rate increases from $r_0 \rightarrow r_{1.}$ Since the engine is operating at meeting its power requirements, it is operating inefficiently after the onset of the abrupt fault. This causes a jump in the specific fuel consumption SFC.

In the "to-be" scenario, we assume that we have a CBM technology that can detect the onset of the abrupt fault. This detection is done after a period of latency, T_L. The resulting benefits are expressed as:

(a) After the replacement action, the engine continues to operate at its original deterioration rate r_0. This will increase its time on wing. This modeled as a net reduction in DMC_{Engine}.

(b) After the replacement action, the engine continues to operate at its deterioration rate, which implies lower fuel consumption rate. This is modeled as a net reduction in net fuel savings

(c) Secondary damage to other parts. If we can detect the abrupt fault earlier and replace it, we can save an equivalent amount of secondary damage.

(d) Transition from an unplanned to a planned maintenance.

4. AN EXAMPLE – MECHANICAL HEALTH MONITORING

This example discusses how the costs and benefits of a technology referred to as Mechanical Health Monitoring (MHM) can be estimated. MHM consists of the sensors and algorithms needed to collect and fuse data from Oil Debris Monitoring (ODM) and vibration monitoring. The ODM system consists of a sensor that counts individual metallic particles and the associated signal processing electronics and software. The vibration monitoring system consists of multiple accelerometers and the hardware and software required to generate Condition Indicators (CIs) for advanced mechanical diagnostics. The MHM algorithms include a progressive on-board indicator and on-ground indications that enable maintenance to be planned when an incipient fault is detected while the engine continues to be operated. In evaluating the costs and benefits of MHM, two different options are considered. In option 1 an ODM system is compared to the chip detector (Figure 2). Option-2 includes an advanced capability of fusing ODM and vibration indicators is compared to a baseline design of a chip detector. Figure 3 illustrates the system with the addition of vibration monitoring. This comparison enables an evaluation of the additional cost of including vibration monitoring and the increased benefits that come from ODM and vibration fusion.

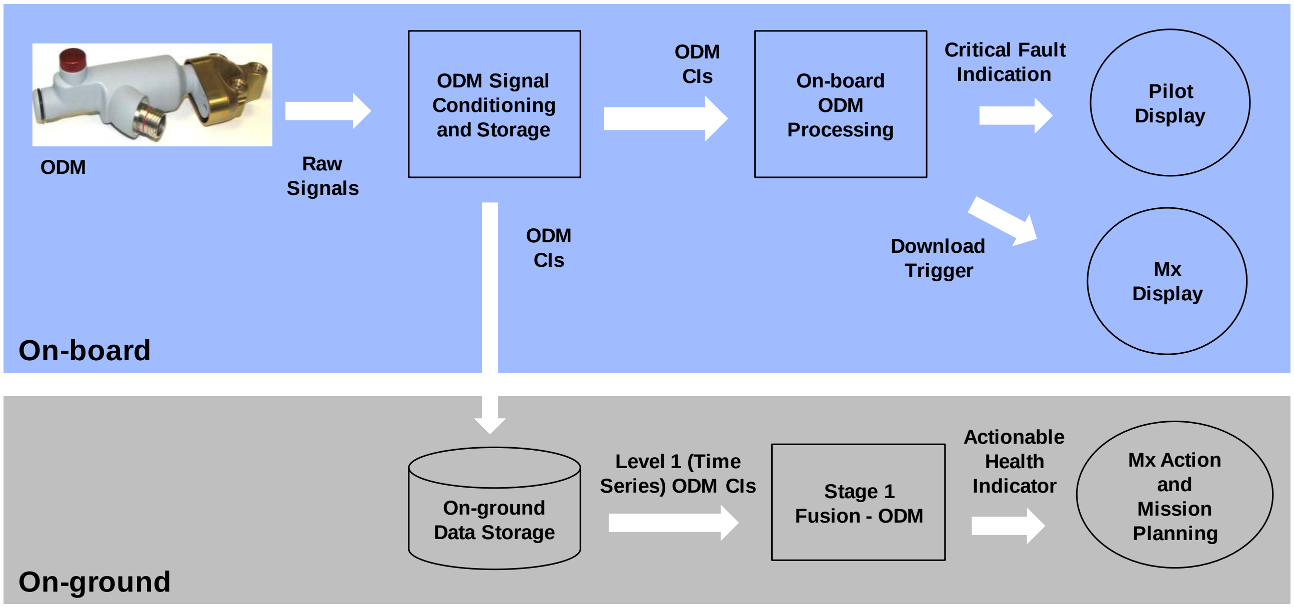

Figure 2. Option 1: ODM system

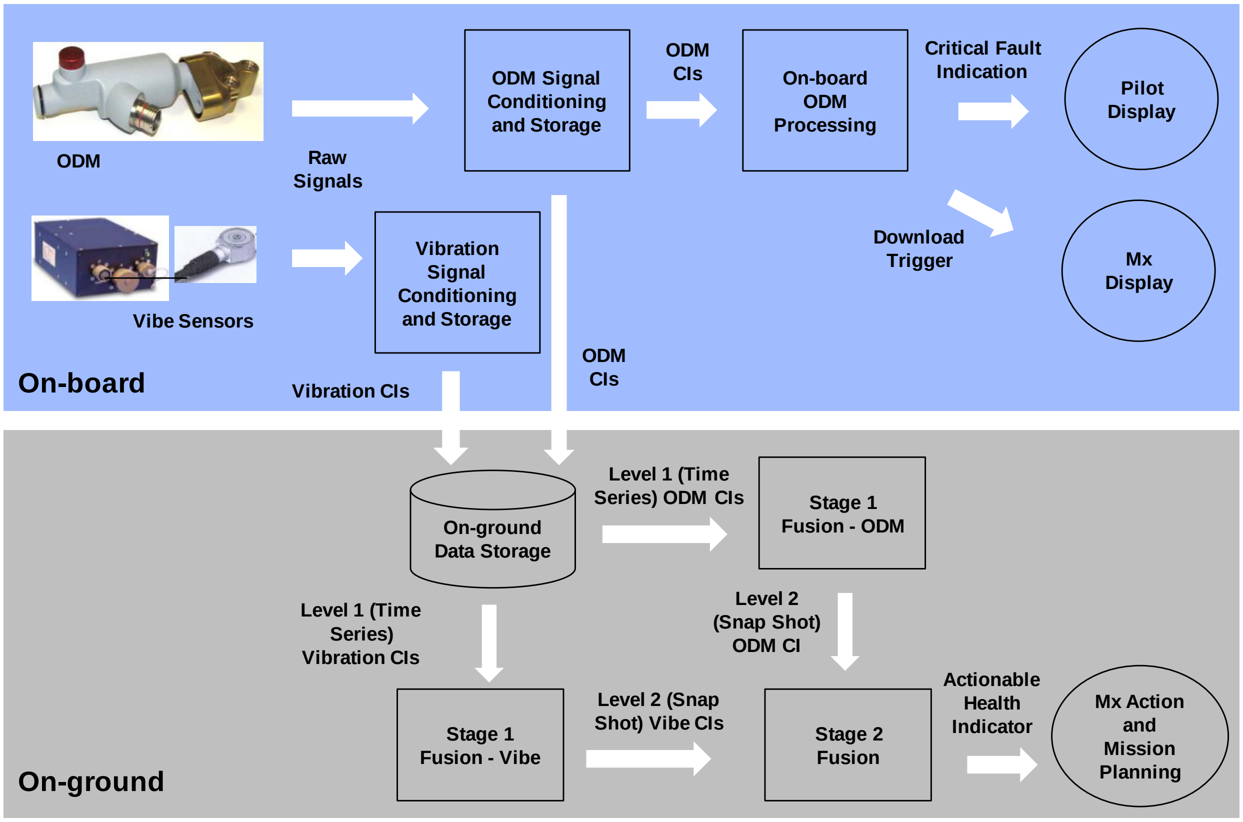

Figure 3. Option 2: ODM and vibration fusion

The benefits for each option are derived from the following value areas:

1) Reduction in hours spent investigating and dispositioning false chip detections
2) Reduction in mission aborts caused by chip indications in flight
3) Converting unscheduled engine replacements to planned maintenance
4) Increased aircraft availability due to conversion to planned maintenance
5) Minimized secondary damage
6) Converting unscheduled LRU-related maintenance actions to planned maintenance (option 2 only)
7) Reduction in depot repair costs through fault isolation and smart workscoping (option 2 only)

One of the significant improvements in using these systems is the operational benefits of the transition from unscheduled to planned maintenance, i.e. being able to prepare for maintenance before the aircraft has to be removed from service. This improves availability and avoids additional expenses for expediting shipping, overtime, etc. There can be large variation in how unscheduled maintenance affects operations. In some scenarios, an aircraft being removed from service can have minimal operational impact. In other scenarios, it can be very disruptive. To quantify the value of avoiding these disruptions, we estimate the average additional flight hours that an aircraft is down for unscheduled maintenance and multiply this by our cost per flight hour rate.

The key metric that enables maintenance to transition from unscheduled to planned is the amount of advanced notice (in operating hours) between high confidence detection of the incipient fault , and annunciation that the engine should no longer be operated. Option 2 is typically able to reach a given levels of detection confidence earlier than option 1. This is because an independent vibration indication along with a relatively small amount of debris enables higher confidence early in the fault progression. Alternatively, with ODM only, the fault must progress farther before there is enough debris to reliably distinguish between normal and faulted conditions. To model this in the value equation, an engineering estimate is made that Option 1 will provide enough advanced notice to enable planned maintenance 50% of the time. It is assumed that Option 2 will enable planned maintenance 95% of the time. These assumptions are consistent with seeded-fault test data and analysis results. In the instances where there is not enough advanced notice to enable fully planned maintenance, the ground system is designed to indicate the need for immediate maintenance. This case is considered to be equivalent to a present state of the art chip detector operational baseline. This difference in advanced notice is one of the primary differences between the two options, and leads to significant value that justifies the additional cost of the vibration and fusion functionality.

Figure 4 shows how the consolidated cash flow was developed for the illustrative CBM functions, MHM-I and MHM –II. The cost elements follow a cost element structure echoing the outline provided in Appendix D of the Report of the OSD CBM+ Action Group 2010 Summer Study (Secretary of Defense, 2010). At the top level, the cost elements include research and development, infrastructure investment, operation and sustainment of the technology and final disposal. We also explicitly track and monetize a cost for the additional weight incurred for the engine integrated elements of the technology solution.

5. CONCLUSIONS AND SIGNIFICANCE

Integrating an advanced health monitoring system on a new engine platform must exhibit both operational and economic benefits. The objectives of decreasing the Maintenance Burden on the Soldier and reducing Operations & Support (O&S) Costs are financial benefits that are relatively easy to account for in a cash flow model. In this paper we presented an approach for calculating some of qualitative benefits. Specifically, we focused on monetizing the benefits associated with increased availability Ao arising from reducing downtime and fuel savings arising from reducing inefficient engine operations. Key to these value expressions is the concept of a simple life-cycle model that estimates the minimum cost per aircraft flight hour. The key contribution lies in this relatively simple equation that makes minimal assumptions and readily calculated using available design data such as those used to evaluate a new engine procurement option. Since the value must be greater than equal to the cost, we use this to calculate the marginal benefits that can derived by an increase in Ao.

The impact of abrupt undetected faults on engine fuel consumption forms the basis for monetizing inefficient operations. Again we assume a typical engine degradation model used to estimate performance-based maintenance intervals.

We illustrated the cost model and its application to evaluate two CBM options available for mechanical health monitoring. While our intent was not to describe the underlying technologies, but illustrate the cost and benefit elements that were used to evaluate the two options with respect to each other.

	Costs ($M)	Technology		
Cost Elements		MHM - I	MHM-II	Other
	Development cost	med	med	med
	Unit Cost	low	low	low
	Common Unit Cost	shared across integrated suite		
	Sustainment cost	shared across integrated suite		
	Lifetime Investment	med	med	med
	Comm. Lifetime invest	shared across integrated suite		
	Weight Penalty (lbs) & cost penalty ($)	small low	med low	med low
Army CBM Objectives	**Benefits ($M)**			
Decrease Maintenace Burden	Maintainer Burden reduction	small	small	small
Increased Platform Availability & Readiness	Increased Availability (Ao) Utility Value	small small	med med	small small
	Mission abort savings	med	med	
Enhanced Safety	Accident avoidance	med	med	
Reduced Operations and Support (O & S) Costs	% DMC change Cost saving			small
	Fuel saving			
	Unscheduled→planned Mx	small	med	med
	Depot part/labor savings	small	small	small
	Net Cash Savings ($M)	med	large	med

Figure 4. Summary table for presenting CBA results

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BIOGRAPHIES

Grant A. Gordon is a Staff Engineer in the Engine Systems group within Honeywell's Advanced Technology division. He has received three degrees in engineering culminating with a Ph.D. in Engineering Science and Mechanics from The Pennsylvania State University in 1995. At Honeywell, he leads programs to develop prognostic and diagnostic tools for condition based maintenance of airframes and engines. He has published more than 50 technical articles and holds ten patents. He is a certified Program Management Professional (PMP), a member of the American Helicopter Society, serves as an elected chairman on the SAE aerospace G-11 standards committee and on various conference committees.

Chris Hickenbottom is a senior systems engineer in Honeywell Aerospace's Condition-Based Maintenance (CBM) Center of Excellence. His background is primarily with propulsion systems for Honeywell's Business and General Aviation (BGA) and Defense and Space (D&S) products. Chris has been involved in many development programs, including the AS907/HTF7000 propulsion engine, the Power and Thermal Management System (PTMS) for the Joint Strike Fighter, and the Zing™ system for the TFE731 Remote Monitoring Service. Chris received his BSME from the University of Arizona.

Dr. Dinkar Mylaraswamy joined Honeywell in 1997 after completing his PhD from Purdue University. As the CBM Technology fellow he is responsible for identifying and maturing strategic health management technologies that cut across multiple products and services. He has served as the technical lead on various health management programs—across Petrochemical, Building and Aerospace business within Honeywell as well the US Army, NASA, UK-MOD, and Navair programs. He routinely works with academic institutes and serves on industry panels. He has authored over 30 papers and holds 18 patents in the area of fault diagnosis and its applications.