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The Analysis of Return on Investment for PHM Applied to Electronic Systems

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***Abstract*—Prognostics and Health Management (PHM) provides an opportunity for lowering sustainment costs, improving maintenance decision-making, and providing product usage feedback into the product design and validation process. However, support for PHM is predicated on the articulation of clear business cases that quantify the expected cost and benefit of its implementation. The realization of PHM requires implementation at different levels of scale and complexity. The maturity, robustness, and applicability of the underlying predictive algorithms impact the overall efficacy of PHM within an enterprise. The utility of PHM to inform decision-makers within tight scheduling constraints and under different operational profiles likewise affects the cost avoidance that can be realized. This paper discusses the calculation of Return on Investment (ROI) for PHM activities and presents a case study conducted using a stochastic discrete event simulation model to determine the potential ROI offered by electronics PHM. The case study of a multifunctional display in a Boeing 737 compared the life cycle costs of a system employing unscheduled maintenance to the same system using a precursor to failure PHM approach.**

***Index Terms*—avionics, cost modeling, electronics PHM, PHM, return on investment**

I. INTRODUCTION

ALL PHM approaches are essentially the extrapolation of trends based on recent observations to estimate Remaining Useful Life (RUL), [1]. The value obtained from PHM can take the form of advanced warning of failures; increased availability through an extension of maintenance cycles and/or timely repair actions; lower life-cycle costs of equipment from reductions in inspection costs, downtime, inventory, and no-fault-founds; or improved system qualification, design, and logistical support of fielded and future systems [2]. In order to justify the adoption of PHM approaches, its value often must be articulated in the form of a business case. An economic justification is the cornerstone of persuasive business cases and Return On Investment (ROI) is a useful means of gauging the economic merits of adopting PHM.

The determination of the ROI allows managers to include quantitative and readily interpretable results in their decision-making. ROI analysis may be used to select between different types of PHM, to optimize the use of a particular PHM approach, or to determine whether to adopt PHM versus more traditional maintenance approaches.

The economic justification of PHM has been discussed by many authors, e.g., [3-20]. Although the existing PHM ROI assessments described in this section contain valuable insight into the cost drivers, most cost analyses and cost-benefit analyses are application-specific; and in most cases they do not provide a general modeling framework or consistent process with which to approach the evaluation of the application of PHM to a system. Furthermore, existing approaches provide primarily “point estimates” of the value based on a set of fixed inputs when, in reality, many of the critical inputs are uncertain. Accommodating the uncertainties in the PHM ROI calculation is at the heart of developing realistic business cases that address prognostic requirements.

The ROI associated with PHM approaches have been examined for specific non-electronic military applications, including ground vehicles, power supplies and engine monitors [3-5]. NASA studies indicate that the ROI of prognostics in aircraft structures may be as high as 0.58 in 3 years for contemporary and older generation aircraft systems assuming a 35% reduction in maintenance requirements [6]. Simple ROI analyses of electronic prognostics for high reliability telecommunications applications (power supplies and power converters) have been conducted, including a basic business case for the BladeSwitch voice telecommunications deployment in Malaysia [7].

ROI predictions of the costs of PHM implementation and the potential for cost avoidance have been evaluated and an analysis of PHM for JSF aircraft engines was developed using a methodology that employed Failure Modes, Effects, and Criticality Analysis (FMECA) to model hardware [8,9].

Byer et al. [10] and Leao et al. [11] describe processes for conducting a cost-benefit analysis for prognostics applied to aircraft subsystems.

The cost-benefit analysis of PHM for batteries within ground combat vehicles was modeled using the Army Research Laboratory’s Trade Space Visualizer software tool [12]. Banks and Merenich [12] found that ROI was maximized when the time horizon (prognostic distance) was greatest and when the number of vehicles and the failure rates were largest. A comparison of the ROI of prognostics for two types of military ground vehicle platforms was performed using data from Pennsylvania State University’s battery prognostics program [13]. Non-recurring development costs

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were estimated for the prognostic units developed for the batteries of the Light Armored Vehicle (LAV) and the Stryker platform used in the Stryker Brigade Combat Team (SBCT) family of vehicles. ROI was calculated as 0.84 for the LAV and 4.61 for the SBCT based on estimates of the development and implementation costs. When combined with known data about battery performance across the Department of Defense (DoD), the total ROI of battery prognostics for the DoD was calculated as 15.25 over a 25-year period.

The Boeing Company developed a life cycle cost model for evaluating the benefits of prognostics for the Joint Strike Fighter program. The model was developed by Boeing's Phantom Works division to enable cost-benefit analysis of prognostics for the fighter's avionics during system demonstration and then enhanced to permit life cycle cost assessment of prognostic approaches [14]. Cost influencing parameters in addition to economic factors were incorporated into a cost benefit analysis [15].

II. CALCULATING RETURN ON INVESTMENT (ROI)

ROI measures the 'return,' the cost savings, profit, or cost avoidance that result from a given use of money. In general, ROI is the ratio of gain to investment. Equation (1) is a way of defining a ROI over a system life cycle.

$$ROI = \frac{Return - Investment}{Investment} = \frac{Avoided\ Cost}{Investment} - 1 \quad (1)$$

The central ratio in (1) is the classical ROI definition and the ratio on the right is the form of ROI that is applicable to PHM assessment. In the case of PHM, the investment includes all the costs necessary to develop, install and support a PHM approach in a system; while the avoided cost is a quantification of the benefit realized through the use of a PHM approach. Note, not all researchers that quote ROI numbers for the application of PHM to systems define ROI in the same way. Equation (1) is the standard definition used by the financial world for return on investment.

Constructing a business case for PHM does not necessarily require that the ROI be greater than zero ($ROI > 0$ implies that there is a cost benefit), i.e., in some cases the value of PHM is not directly quantifiable in monetary terms but is necessary in order to meet a system requirement that could not otherwise be attained, e.g., an availability requirement. However, the evaluation of ROI (whether greater than or less than zero) is still a necessary part of any business case developed for PHM [21].

For PHM, ROI must be measured relative to whatever methodology is currently used to manage the system. For electronic systems, a common management approach is unscheduled maintenance (defining the investment cost associated with unscheduled maintenance to be zero). Following an unscheduled maintenance policy, systems are operated until failure and are then repaired or replaced. Applying (1) to a baseline of unscheduled maintenance, the ROI is given by,

$$ROI = \frac{C_{us} - \left(C_{PHM} - I\right)}{I} - 1 \quad (2)$$

where C_{us} is the total life cycle cost of the system with an unscheduled maintenance policy, C_{PHM} is the total life cycle cost of the system employing a particular PHM approach and I is the investment in the PHM approach. Equation (2) measures ROI relative to unscheduled maintenance; if C_{PHM} is equal to C_{us}, then ROI equals 0, the breakeven point.[1]

The investment cost is the effective cost per socket[2] of implementing PHM and then using it to guide maintenance planning. It is calculated as,

$$I = C_{NRE} + C_{REC} + C_{INF} \quad (3)$$

where C_{NRE} are the PHM non-recurring costs, C_{REC} are the PHM recurring costs, and C_{INF} are the annual infrastructure costs associated with PHM. The costs of false alarm resolution, procurement of more LRUs than the unscheduled maintenance quantity, and maintenance costs that differ from unscheduled maintenance are not included in the investment cost because they are the result of the investment and are reflected in C_{PHM},. C_{PHM} must also include the cost of money differences associated with purchasing LRUs at maintenance events between unscheduled maintenance and a PHM approach, i.e., even if both approaches end up purchasing the same number of replacement LRUs for a socket, they may purchase them at different points in time resulting in different effective costs if the discount rate is non-zero. If replacement LRUs are drawn from an inventory of spares (as opposed to purchased when needed), then there may be no cost of money impact on C_{PHM} associated with the purchase of LRUs.

III. PHM COSTS

The two major categories of cost-contributing activities that must be considered in an analysis of the ROI of PHM are implementation costs and cost avoidance. These categories represent the 'Investment' portion and the 'Avoided Cost' portion of the ROI calculation in (1) respectively.

A. Implementation Costs

Implementation costs are the costs associated with the realization of PHM in a system, that is, the technologies and support necessary to integrate and incorporate PHM into new or existing systems. The costs of implementing PHM can be categorized as recurring, non-recurring, or infrastructural

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[1] Equation (2) is only valid for comparison of ROI to unscheduled maintenance, which is a convenient well defined solution to measure ROI from. Using (2), one can compare the relative ROIs of multiple PHM approaches measured from unscheduled maintenance; however, the ROI of one PHM approach relative to another is not given by the difference between their ROIs relative to unscheduled maintenance. In order to evaluate ROI relative to a baseline other than unscheduled maintenance, appropriate values of Avoided Cost and Investment must be substituted into (1).

[2] A *socket* is a unique instance of an installation location for an LRU. One instance of a socket occupied by an engine controller is its location on a particular engine. The socket may be occupied by a single LRU during its lifetime (if the LRU never fails), or multiple LRUs if one or more LRUs fail and needs to be replaced.

depending on the frequency and role of the corresponding activities. The implementation cost is the cost of enabling the determination of Remaining Useful Life (RUL) for the system.

Non-recurring costs are associated with one-time only activities that typically occur at the beginning of the timeline of a PHM program—although disposal or recycling non-recurring costs would occur at the end. Non-recurring costs can be calculated on a per-LRU, per-socket, or per a group of LRUs or sockets basis. The specific non-recurring cost is calculated as:

$$C_{NRE} = C_{dev\_hard} + C_{dev\_soft} + C_{training} + C_{doc} + C_{\text{int}} + C_{qual} \quad (4)$$

where C_{dev_hard} is the cost of hardware development; C_{dev_soft} is the cost of software development; $C_{training}$ is the cost of training; C_{doc} is the cost of documentation; C_{int} is the cost of integration; and C_{qual} is the cost of testing and qualification.

Recurring costs are associated with activities that occur continuously or regularly during the PHM program. As with non-recurring costs, some of these costs can be viewed as an additional charge for each instance of an LRU or for each socket (or for a group of LRUs or sockets). The recurring cost is calculated as:

$$C_{REC} = C_{hard\_add} + C_{assembly} + C_{test} + C_{install} \quad (5)$$

where C_{hard_add} is the cost of PHM hardware added to each LRU (e.g., sensors, chips, extra board area) and may include the cost of additional parts or manufacturing or the cost of hardware for each socket (such as connectors and sensors); $C_{assembly}$ is the cost of assembly, and installation of the hardware in each LRU or the cost of assembly of PHM hardware for each socket or for each group of sockets; C_{test} is the cost of recurring functional testing of PHM hardware for each socket or for each group of sockets; and $C_{install}$ is the cost of installation of PHM hardware for each socket or for each group of sockets, which includes the original installation and re-installation upon failure, repair, or diagnostic action.

Unlike recurring and non-recurring costs, infrastructure costs are associated with the support features and structures necessary to sustain PHM over a given activity period and are characterized in terms the ratio of money to a period of activity (i.e., dollars per operational hour, dollars per mission, dollars per year). The infrastructure costs are calculated as:

$$C_{INF} = C_{prog\_ma\text{int}enance} + C_{decision} + C_{retraining} + C_{data} \quad (6)$$

where C_{data} is the cost of data management, including the costs of data archiving, data collection, data analysis, and data reporting; $C_{prog\_maintenance}$ is the cost of maintenance of the prognostic devices; $C_{decision}$ is the cost of decision support; and $C_{retraining}$ is the cost of retraining costs to educate personnel in the use of PHM.

B. *Cost Avoidance*

Prognostics provide estimations of Remaining Useful Life (RUL) in terms that are useful to the maintenance decision making process. The decision process can be tactical (real-time interpretation and feedback) or strategic (maintenance planning, or feedback into the product design or verification process). Unfortunately, the calculation of RUL alone does not provide sufficient information to form a decision or to determine corrective action. Determining the best course of action requires the evaluation of criteria such as availability, reliability, maintainability, and life cycle cost. Cost avoidance is the value of changes to availability, reliability, maintainability, and failure avoidance.

The primary opportunities for obtaining cost avoidance from the application of PHM to systems are failure avoidance and minimization of the loss of remaining system life. Field failure of systems is often very expensive. If all or some fraction of the field failures can be avoided, then cost avoidance may be realized by minimizing the frequency of unscheduled maintenance. Avoidance of failures can also increase availability, reduce the risk of loss of the system, and may increase human safety depending on the type of system considered. Failures avoided fall into two types: 1) real-time failure avoidance during operation that would otherwise result in the loss of the system or loss of the function the system was performing (i.e., loss of mission), and 2) warning of future (but not imminent) failure that allows preventative maintenance to be performed at a place and time that are convenient.

C. *Maintenance Planning Cost Model [22]*

Interpretation of RUL results from PHM activities is a decision making under uncertainty problem. Without comprehending the corresponding measures of the uncertainty associated with the calculation, RUL projections have little practical value, [1]. In order to perform effective maintenance planning and calculate corresponding life cycle costs, a method that captures and includes data uncertainties must be used. A stochastic discrete event simulation model [22] is used to compute the total life cycle cost of sockets when unscheduled and PHM management approaches are used, i.e., computes C_{us} and C_{PHM} in (2). The model follows the history of a single socket (or a group of sockets) from time zero to the end of support life for the system. To generate meaningful results, a statistically relevant number of sockets (or systems of sockets) are modeled and the resulting cost and other metrics are generated in the form of histograms. The model treats all inputs to the discrete event simulation as probability distributions, i.e., a stochastic analysis is used, implemented as a Monte Carlo simulation. Various maintenance interval and PHM approaches are distinguished by how sampled TTF values are used to model PHM RUL forecasting distributions.

Since the case study in this Section IV of this paper focuses on the application of a precursor to failure PHM approach, only the details of how this particular PHM approach is modeled by the maintenance planning model are included here. The treatment of other PHM approaches appears in detail in [22].

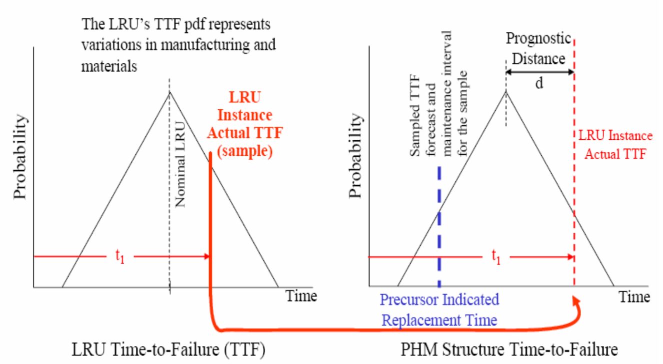

Fig. 1. Precursor to failure monitoring modeling approach (triangular distributions are used for illustration purposes) from [22].

Precursor to failure monitoring, the approach used in the case study in Section IV, employs fuses or other monitored structures that are manufactured with or within the LRUs or as monitored precursor variables representing non-reversible physical processes, i.e., they are coupled to the manufacturing or material variations of a particular LRU. Health Monitoring (HM) and LRU-dependent fuses are examples of precursor to failure methods. A parameter to be determined from analysis is prognostic distance. The prognostic distance is a measure of how long before system failure the prognostic structures or prognostic cell is expected to indicate failure (in operational hours for example). The precursor to failure monitoring methodology forecasts a unique time to failure (TTF) distribution for each instance of an LRU based on the instance's TTF.[3] For illustration purposes, the precursor to failure monitoring forecast is represented as a symmetric triangular distribution with a most likely value (mode) set to the TTF of the LRU instance minus the prognostic distance, Figure 1.

The LRU TTF probability density function (pdf) and the Precursor to failure TTF pdf on the left and right of Figure 1, respectively, could have different distribution shapes and parameters; symmetric triangular distributions were chosen for illustration. The precursor to failure monitoring distribution has a fixed width measured in the relevant environmental stress units (e.g., operational hours in our example) representing the probability of the prognostic structure indicating the precursor to a failure. As a simple example, if the prognostic structure was a LRU-dependent fuse that was designed to fail at some prognostic distance earlier than the system it protects, then the distribution on the right side of Figure 1 represents the distribution of fuse failures (the TTF distribution of the fuse).

The model proceeds in the following way: for each LRU TTF distribution sample (t_1) taken from the left side of Figure 1, a precursor to failure monitoring TTF distribution is created that is centered on the LRU TTF minus the prognostic distance (t_1-d). The precursor to failure monitoring TTF distribution is then sampled and if the precursor to failure monitoring TTF sample is less than the actual TTF of the LRU instance, the precursor to failure monitoring is deemed successful. If the precursor to failure monitoring distribution TTF sample is greater than the actual TTF of the LRU instance then precursor to failure monitoring was unsuccessful. If successful, a scheduled maintenance activity is performed and the timeline for the socket is incremented by the precursor to failure monitoring sampled TTF. If unsuccessful, an unscheduled maintenance activity is performed and the timeline for the socket is incremented by the actual TTF of the LRU instance. At each maintenance activity, the relevant costs are accumulated.

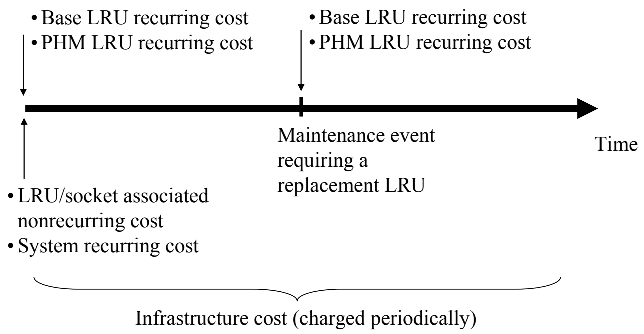

Fig. 2. Temporal ordering of implementation cost inclusion in the discrete event simulation.

The scheduled and unscheduled costs computed for the sockets at each maintenance event are given by,

$$C_{socket\ i} = fC_{LRU\ i} + (1-f)C_{LRU_{repair\ i}} + fT_{replace\ i}V + (1-f)T_{repair\ i}V \tag{7}$$

where $C_{socket\ i}$ is the life-cycle cost of socket i; $C_{LRU\ i}$ is the cost of procuring a new LRU; $C_{LRU\ repair\ i}$ is the cost of repairing an LRU in socket i; f is the fraction of maintenance events on socket i that require replacement of the LRU in socket i with a new LRU; $T_{replace\ i}$ is the time to replace the LRU in socket i; $T_{repair\ i}$ is the time to repair the LRU in socket i; and V is the value of time out of service.

Note, the values of f and V generally differ depending on whether the maintenance activity is scheduled or unscheduled. For simplicity, (7) is written assuming that quantity of replaced LRUs in socket i is one; however, in general, the socket could receive many LRUs during its lifetime.

As the discrete event simulation tracks the actions that affect a particular socket during its life cycle, the implementation costs are inserted at the appropriate locations, Figure 2. At the beginning of the life cycle, the non-recurring cost is applied. The recurring costs at the LRU level and at the system level are first applied here and subsequently applied at each maintenance event that requires replacement of an LRU ($C_{LRU\ i}$, as in (7)). The recurring LRU-level costs include the base cost of the LRU regardless of the maintenance approach. Discrete event simulations that compare alternative maintenance approaches to determine the ROI of PHM must include the base cost of the LRU itself without any PHM-specific hardware. If discrete event simulation is used to calculate the life-cycle cost for a socket under an unscheduled maintenance policy, then the recurring LRU-level cost is

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[3] In this model, all failing LRUs are assumed to be maintained via replacement or good-as-new repair, therefore, the time between failure and the time to failure are the same.

reduced to the cost of replacing or repairing an LRU upon failure. Under a policy involving PHM, the failure of an LRU results in additional costs for the hardware, assembly, and installation of the components used to perform PHM. The infrastructure costs are distributed over the socket's life cycle.

See [22] for additional model implementation details, including a flow chart that describes the simulation process.

IV. CASE STUDY

The scenario for this business case example considers the acquisition of PHM for an electronics LRU in a commercial aircraft used by a major commercial airline. The representative LRU is a multifunction display (MFD), two of which are present in each aircraft. A fleet size of 502 aircraft was chosen to reflect the quantities involved for a technology acquisition by a major airline, in this case, Southwest Airlines [23]. The Boeing 737 300 series was chosen as the representative aircraft to be equipped with electronics PHM.

The implementation costs reflect a composite of technology acquisition cost benefit analyses (CBAs) for aircraft and/or for prognostics. The implementation costs are summarized in Table 1. All values are in 2008 U.S. dollars; all conversions to year 2008 dollars were performed using the Office of Management and Budget (OMB) discount rate of 7% [24]. The discount factor was calculated as $1/(1 + r)^t$ where r is the discount rate (0.07) and t is the year ($t = 0$ represents 2008).

Maintenance costs vary greatly depending on the type of aircraft, the airline, the amount and extent of maintenance needed, the age of the aircraft, the skill of the labor base, and the location of the maintenance (domestic versus international, hangar versus special facility). The maintenance costs in the model are assumed to be fixed; however, the effects of aging are known to produce increases in maintenance costs [25].

Koch, *et al.* [26], give the maintenance cost per hour for Boeing 737-100 and -200 series aircraft as 12% of the hourly operating cost, noting that the ratio of maintenance costs per hour to aircraft operating costs per hour has remained between 0.08 and 0.13 since the 1970s. The numerical average of the direct hourly operating costs for major airlines summarized in [27] was used. This cost is treated as the cost of scheduled maintenance per hour, which is equivalent to the cost of unscheduled maintenance that can performed during the downtime period, (see Table 2), after the flight segments for the day have been completed.

The cost of unforeseen failures that require immediate attention during a flight can vary depending on the interpretation and on the subsequent actions required to correct the problem. Unscheduled maintenance that would require a diversion of a flight can be extremely expensive. The cost of a problem requiring unscheduled maintenance that is detected before the aircraft has left the ground (during a flight segment but not airborne) can be highly complex to model if the full value of passenger delay time and the downstream factors of loss of reputation and indirect costs are included [28].

For the determination of the cost of unscheduled maintenance during a flight segment, it is assumed that such an action typically warrants a flight cancellation. This represents a more extreme scenario than a delay; the model assumes that unscheduled maintenance that occurs between flight segments (during the preparation and turnaround time) would be more likely to cause a delay, whereas unscheduled maintenance during a flight segment would result in a cancellation of the flight itself. The Federal Aviation Administration provides average estimates of the cost of cancellations on commercial passenger aircraft that range from $3,500 to $6,684 per operational hour [29].

The operational profile for this example case was determined by gathering information for the flight frequency of a typical commercial aircraft. A large aircraft is typically flown several times each day; these individual journeys are known as flight segments. The average number of flight segments for a Southwest Airlines aircraft was seven in 2007 [23]. Although major maintenance, repair, and overhaul operations (MROs) call for lengthy periods of extensive inspections and upgrades as part of mandatory maintenance checks, a commercial aircraft may be expected to be operational up to 90% to 95% of the time for a given year [30]. A median airborne time for commercial domestic flights was approximately 125 minutes in 2001 [24]. A representative support life of 20 years was chosen based on [24]. A 45-minute turnaround time was taken as the time between flights based on the industry average [31]. Using this information, an operational profile was constructed whose details are summarized in Tables 2 and 3.

Table 1. Implementation Costs and Categories

Frequency	Type	Value
Recurring Costs	Base cost of an LRU (without PHM)	$25,000 per LRU
Recurring Costs	Recurring PHM cost	$155 per LRU $90 per socket ($C_{REC}$)
Recurring Costs	Annual Infrastructure	$450 per socket ($C_{INF}$)
Non-Recurring Engineering	PHM cost	$700 per LRU ($C_{NRE}$)

Table 2. Unscheduled Maintenance Costs and Modes

Maintenance Event	Probability	Value (V)
Before mission (during preparation)	0.19	$2,880/hour
Maintenance event during mission	0.61	$5,092/hour (mean of range in [29])
Maintenance event after mission (during downtime)	0.20	$500/hour

Table 3. Operational Profile

Factor	Multiplier	Total
Support life: 20 years	2,429 flights per year	= 48,580 flights over support life
7 flights per day	125 minutes per flight	= 875 minutes in flight per day
45 minutes turnaround between flights [31]	6 preparation periods per day (between flights)	= 270 minutes between flights/day

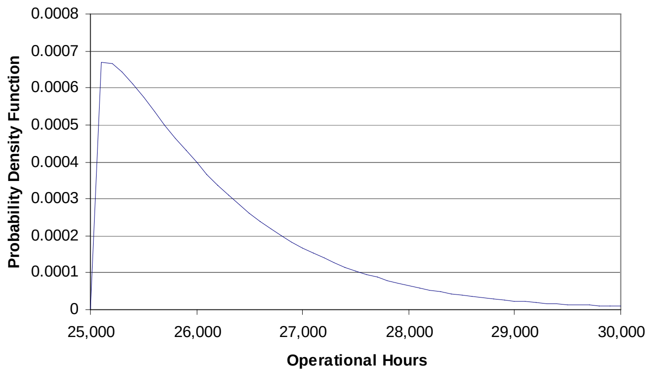

Fig. 3. Weibull distribution of TTFs (β=1.1 [35], η= 1,200 [33] and γ = 25,000 hours).

Reliability data was based on [32] and [33], which provide models of the reliability of avionics with exponential and Weibull distributions, commonly used to model avionics [34]. The assumed TTF distribution of the LRUs is provided in Figure 3. In an analysis of over 20,000 electronic products built in the 1980s and 1990s, [35] shows that Weibull distributions with shape parameters close to 1, i.e., close to the exponential distribution, are the most appropriate Weibull distributions for modelling avionics. Upadhya and Srinivasan, [36], models the reliability of avionics with a Weibull shape parameter of 1.1, consistent with the common range of parameters found in [35]. Although [35] found exponential distributions to be the most accurate, failure mechanisms associated with current technologies, [37] suggest that the Weibull may prove to be more representative for future generations of electronic products. The location parameter was chosen based on the typical avionics unit being considerably shorter-lived than ten years that is a common life assumption within the aerospace industry, [35].

A. *ROI Calculation*

To enable the calculation of ROI, an analysis was performed to determine the optimal prognostic distance for the example case, shown in Figure 4. For the combination of PHM approach, implementation costs, reliability information, and operational profile assumed in this example, a prognostic distance of 475 hours yielded the minimum life cycle cost over the support life. The TTF distribution of the prognostic structure monitored with the precursor-to-failure approach was a triangular distribution with a width of 500 hours was chosen (right side of Figure 1).

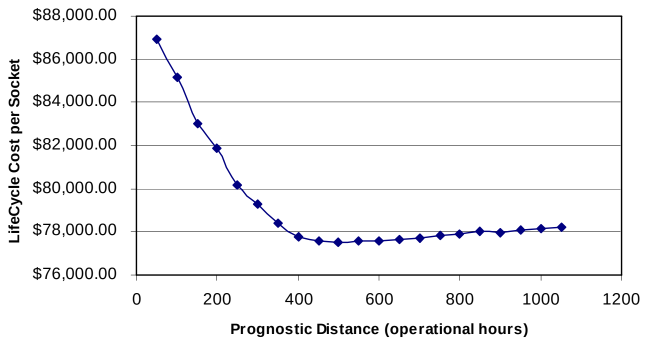

Fig. 4. Variation of life cycle cost with precursor to failure PHM prognostic distance. Small prognostics distances cause PHM to miss failures; large precursor to failure is too conservative.

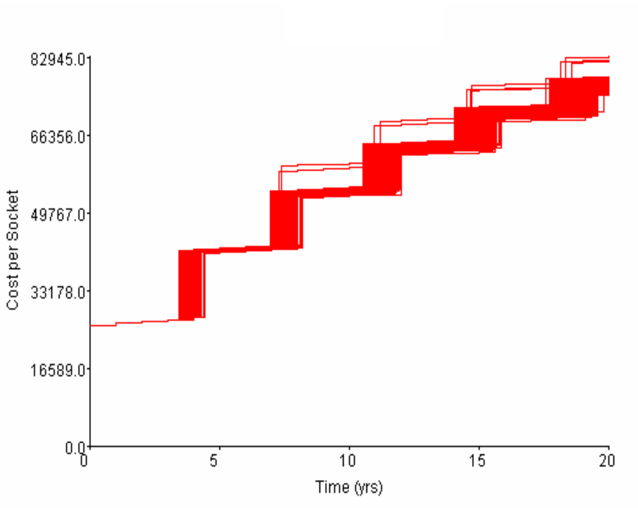

Fig. 5. Socket cost histories over the system support life.

Using a prognostic distance of 475 hours, a discrete event simulation was performed under the assumptions of negligible random failure rates and false alarm indications. Figure 5 illustrates the cumulative cost per socket as a function of time. The graph of life cycle cost intersects the vertical axis at the point corresponding to the initial implementation cost; as maintenance events accumulate over the support life, the cost rises, culminating at the end of the 20 years. Each socket required a replacement of five LRUs on average, corresponding to the distinct steps in cost every ~3.8 years. The small step increases between LRU replacements (most clearly seen between year 0 and 3) represent annual PHM infrastructure costs. For this case study, 1,000 sockets were simulated; divergence in life cycle cost due to randomness and variability of parameters can be seen as the support life progresses.

Using this PHM approach, 91% of failures were avoided[4] and the total life cycle cost per socket was C_{PHM} = \$77,319 with an effective investment cost per socket of I = \$5,512, representing the cost of developing, supporting, and installing PHM. This cost was compared to an unscheduled maintenance policy in which LRUs are fixed or replaced only upon failure. Preserving all simulation details not particular to the PHM approach, the life cycle cost per socket under an unscheduled maintenance approach was C_{us} = \$96,815. Following (2), the ROI of PHM was calculated as [\$96,815 – (\$77,319 – \$5,512]/ \$5,512 – 1, approximately 3.537.

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[4] Sockets with LRU failures not detected by the PHM approach appear in Figure 5 as the histories above the majority of the data set (these first appear at approximately 7.8 years). These sockets incur and unscheduled maintenance event that is more expensive.

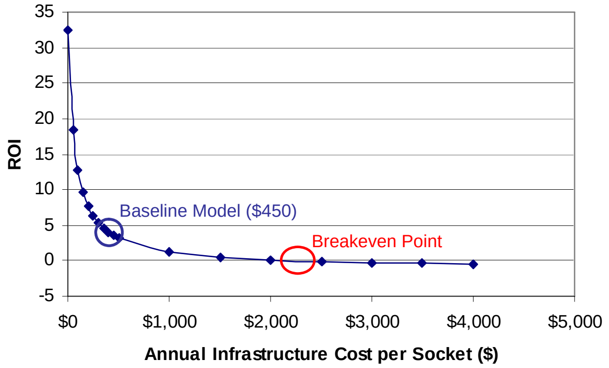

Fig. 6. ROI as a function of the annual infrastructure cost of PHM per LRU.

Figure 6 contrasts the ROI with the annual infrastructure cost of implementing PHM on a per-socket basis, including the costs of hardware, assembly, installation, and functional testing. The intersection with the abscissa represents the breakeven point at which PHM no longer yields a positive return on investment. In this instance, the breakeven point occurred at $2271 per LRU; Figure 7 illustrates the relationship between ROI and the TTFs of the LRUs for three annual infrastructure costs. The TTF parameter varied is the location parameter used in the Weibull distribution; the shape and scale parameters were kept constant. For large TTFs, the reliability of the LRUs is such that PHM is no longer beneficial to the program; LRUs with smaller TTFs provide the opportunity for greater ROI.

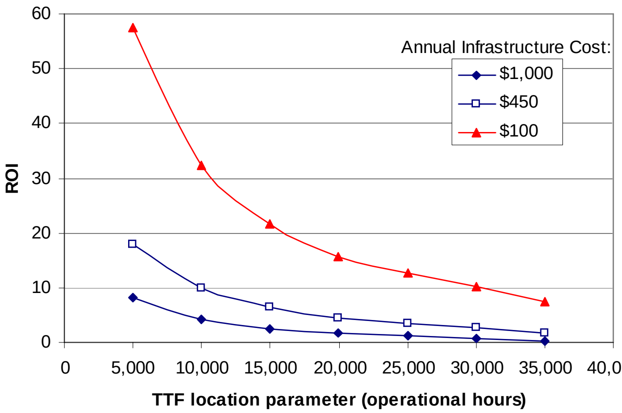

Fig. 7. ROI versus TTF (Weibull, β=1.1 [35], η= 1,200 [33]) for various annual infrastructure costs (C_{INF}).

The ROIs in (2) can be calculated statically using values of C_{us}, C_{PHM} and I that are averaged over the whole population of sockets (the value of 3.537 above was obtained this way). However, in reality, a population of sockets will result in a distribution of ROIs (every socket has a different ROI). In order to calculate the distribution of ROIs, each member of the population has to be independently tracked through an unscheduled <u>and</u> PHM maintenance scheme (i.e., using identical samples in the Monte Carlo analysis from the distributions that represent the member's characteristics and maintenance costs) – in this manner, a separate ROI is calculated for each member of the population. When the process is repeated on an entire population of sockets, a histogram of ROIs results, Figure 8. Using this histogram (distribution), valuable business case parameters can be extracted, such as: assuming we have estimated the uncertainties in the input parameters appropriately, this case study indicates that we can have an 80% confidence that the ROI is greater than 3.17.

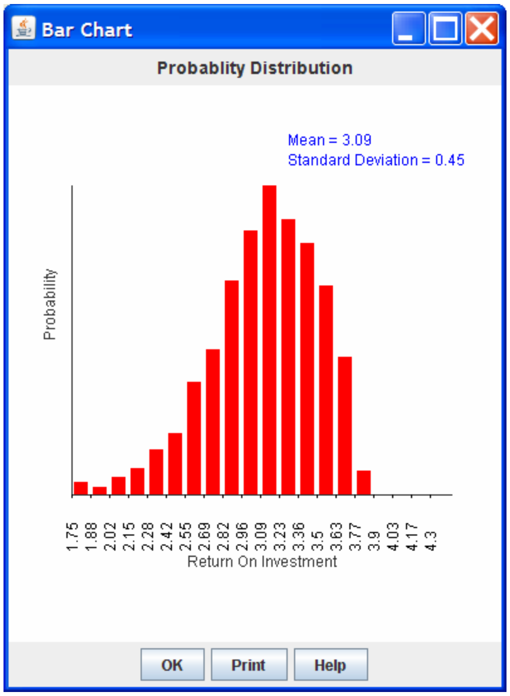

Fig. 8. Histogram of ROIs for a 3000 socket population.

The example provided in this section demonstrates the conditions under which a positive return on investment can be obtained using a precursor to failure approach. In reality, for the time-to-failure distribution assumed in Figure 3, potentially larger ROIs may be possible using a fixed schedule maintenance interval, however, it is not generally true that fixed schedule maintenance interval maintenance will always result in higher ROIs than other PHM-based approaches.

V. SUMMARY AND CONCLUSION

PHM can be used within the maintenance decision-making process to provide failure predictions, to lower sustainment costs by reducing the costs of downtime, for inspection, for inventory management, to lengthen the intervals between maintenance actions, and to increase the operational availability of systems. PHM can be used in the product design and development process to gather usage information and to provide feedback for future generations of products.

A business case was presented that demonstrated a positive ROI to adopting PHM based on Monte Carlo simulations that accounted for uncertainties in both the performance of the PHM approach and the various costs involved in the calculation. PHM would likely be used to maintain groups of dissimilar LRUs within a larger system, requiring an expanded analysis to include reliability, age, and cost information for multiple components. Furthermore, the results presented here are specific to a precursor to failure PHM approach; they may not be consistent with the ROI of using life consumption monitoring methods (LRU independent methods) and are not specific to a particular precursor to failure device.

The model used in this paper does not address the total impact of PHM that would be experienced at the system level, such as the time needed for the maintenance and logistics communities to fully adapt to PHM. For example, the cost of the necessary cultural changes in the maintenance community is not included (and difficult to quantify). In addition there may be quantifiable costs associated with availability changes that result from the inclusion of PHM that are not included in the model described in this paper, as well as, costs associated with spares inventories and spare replinishment. Although the model in [22] can incorporate false alarms and failures that are outside the scope of the PHM approach, they were not considered in the business case example included in this paper.

To determine the ROI requires an analysis of the cost-contributing activities needed to implement PHM and a comparison of the costs of maintenance actions with and without PHM. Analysis of the uncertainties in the ROI calculation is necessary for developing realistic business cases. Allowance for variability in cadence, false alarm, random failure rates, and system complexity enables a more comprehensive treatment of PHM to support acquisition decision making.

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