ABSTRACT

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Prognostics and Health Management (PHM) provides the potential to lower sustainment costs, to improve maintenance decision-making, and to provide product usage feedback into the product design and validation process. A case analysis was developed using a discrete event simulation to determine the benefits and the potential cost avoidance resulting from the use of PHM in avionics. The model allows for variability in implementation costs, operational profile, false alarms, random failure rates, and system composition to enable a comprehensive calculation of the Return on Investment (ROI) in support of acquisition decision making. The case analysis compared the life cycle costs using unscheduled maintenance to the life cycle costs using two types of PHM approaches.

ELECTRONIC PROGNOSTICS AND HEALTH MANAGEMENT: A RETURN ON INVESTMENT ANALYSIS

By

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Dedication

To my family

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Chapter 1: Introduction

Prognostics and Health Management (PHM) is the process of estimating the remaining life of a product and utilizing this estimation to affect maintenance decision making or to improve product design and reliability. PHM allows for the measurement of a product's *in situ* conditions and for the assessment of its reliability. PHM can be used within the maintenance decision making process to provide failure predictions and to lengthen the intervals between maintenance actions. PHM may allow for better inventory management, improved inspection, increased operational availability of systems, lowered sustainment[1] costs, and reduced downtime. PHM can be used in the product design and development process to gather usage information and to provide feedback for future generations of products. Proponents of PHM have prophesied that its success may one day obviate the need for redundant components in systems, but the transition to a full PHM approach requires extensive validation and verification.

1.1. The Benefits of Prognostics and Health Management

The aim of using PHM is cost avoidance —the reduction or elimination of costs that would have otherwise been incurred— which may be realized in monetary or non-monetary outcomes. Types of cost avoidance include failure avoidance,

[1] 'Sustainment' in this context describes technological sustainment, i.e., the activities necessary to preserve the functionality of an existing system to satisfy its operational requirements [1].

increased availability, reduced risk of catastrophic loss (such as the loss of human life or the loss of an entire system) and increased safety or airworthiness. Cost avoidance may be manifested by improved utilization of a product to minimize the amount of remaining useful life (RUL) when a component is thrown away by a scheduled maintenance action. Cost avoidance in a logistical capacity may take the form of a reduction in the logistics footprint, better inventory control, less external test equipment, and improved spares management (including storage, quantities, and refreshes). In terms of repair, PHM may allow for better fault isolation, decreasing the time needed for inspection and troubleshooting. It may also reduce the amount of collateral damage incurred in repairing an item and may lower the number of misdiagnosed problems. End-of-life (EOL) cost avoidance may be realized by more efficient disposal, lower take-back costs, and decreased disposal quantities.

The potential benefits of PHM are substantial for the military and commercial sectors; the U.S. Air Force estimates that successful health monitoring of the Minuteman III strategic missile fleet could cut its life cycle costs in half [2]. In addition to other forms of cost avoidance, the highly competitive commercial aviation industry may be able to use PHM to reduce the number of maintenance and diagnostics personnel and the need for diagnostic tools.[2] The economic justification of PHM has been discussed by several authors, e.g., [5-8]. The Return on Investment (ROI) associated with PHM approaches have been examined for non-electronic military applications, including ground vehicles and engine monitors [9, 10]. A full assessment of the benefits of electronics PHM (e-PHM) for commercial and military

[2] Wages for skilled avionics technicians have increased steadily in recent years, with a 27% increase between 2004 and 2005 [3], while the estimated annual global market for diagnostic tools within commercial aviation maintenance is in excess of $1 billion [4].

aircraft requires knowledge of industry practices and regulations, the inclusion of scheduling policies, an understanding of the underlying PHM component technologies, and an assessment of their accuracy.

The purposes served by a PHM program may be tactical, strategic, or observational. Tactical PHM provides real-time feedback and interpretation of the information collected by prognostic devices. Strategic PHM supplies information for maintenance planning for the short term or for longer time horizons. Observational PHM is conducted to gain insight and gather data about specific components and their use conditions. The level of confidence needed for reliance on PHM is greatest for tactical purposes and lower when PHM is used in an observational capacity, that is, a tactical purpose would require a high level of trust in PHM and may be associated with safety critical components, while observational PHM is essentially passive and does not influence an immediate course of action. A PHM program may serve multiple purposes simultaneously or may shift with changing user requirements. PHM may initially be used for data monitoring and may have added functionality later to aid in maintenance planning.

1.2. Prognostics and Health Management Applications

PHM methods have been applied to estimate equipment life in a diverse array of applications, including gearboxes, actuators, nuclear power plant equipment, and other mechanical devices [11-13]. Early applications of traditional maintenance modeling include production equipment [14] and the hardware portions of engines and other propulsion systems [15]. Although PHM has been widely applied to civil engineering structures and to mechanical systems, electronic systems have not historically been the subjects of PHM for several reasons. Electronic parts contain a high level of complexity and functionality in relation to their physically small scale, rendering PHM more difficult; furthermore, the Time to Failure (TTF) of electronic parts is assumed to be substantially longer than the lifetimes of the systems containing them.

PHM is a growing area of interest within the government sector for use in military applications. The 1990s witnessed a transition within the electronics supply chain from parts designed to military specifications (Mil-Spec) to Commercial off the Shelf (COTS) parts for long field life systems such as military ground vehicles and aircraft. The expected lifetimes of COTS parts are shorter than the expected lifetimes of Mil-Spec parts and are shorter than the lifetimes of many military systems; thus, wear-out and fatigue are more problematic and relevant issues for electronics than when Mil-Spec parts were available [16].

The military faces costly maintenance problems that are exacerbated by the use of aircraft whose operational lives exceed their expected design lifetimes ('life extension'). The degraded performance of components in aging aircraft has been studied extensively [17, 18]. Department of Defense (DoD) guidelines require acquisition Program Managers (PMs) to "optimize operational readiness through affordable, integrated, embedded diagnostics and prognostics, and embedded training and testing" among efforts to improve system performance and to decrease the cost of ownership [19]. The primary DoD areas for prognostic applications are ground vehicles, ship programs, and fixed wing and rotary wing aircraft; the military has also examined the application of prognostics to advanced artillery systems [20-21].

Electronic devices have emerged as candidates for prognostics as knowledge of electronic failure modes and behavior has increased and as the potential for cost avoidance is explored. Electronics prognostics have been developed for power supplies, aircraft wiring, avionics circuit boards, and switch-mode power supplies [22]. Higher-level electronics PHM applications include satellite communications, unmanned aerial vehicles, and radar systems [23, 24]. Computer servers —essential to the data management of PHM— have themselves been studied as PHM candidates [25].

1.3. Approaches to Prognostics and Health Management

The estimation of RUL is at the core of prognostic and health assessments for maintenance decision making. The methods for determining RUL vary but all involve extrapolating and analyzing the data collected by PHM. RUL estimates are best used in conjunction with measures of the corresponding uncertainties; that is, maintenance decisions are more accurate when the uncertainties associated with RUL prediction are included [26]. Methods have been developed to estimate the uncertainties of RUL predictions that are based on fuse structures linked to specific failure mechanisms, as in health monitoring, and the uncertainties associated with RUL for PHM [27]. The inclusion of uncertainties with RUL estimates is necessary for objective and comprehensive business cases for PHM.

The PHM approaches used to calculate RUL include Health Monitoring (HM) and Life Consumption Monitoring (LCM). A Line Replaceable Unit (LRU) is a generic part (here, a ‘black box’ electronics unit) that is usually designed to common specifications and are readily replaceable on the ‘line,’ i.e., in the field. Precursor to Failure methodologies refer to methodologies that are dependent on the specific LRU instance to which they are applied [28]. Included in this category of PHM approaches are Health Monitoring (HM) and LRU-Dependent fuses. LRU-Dependent fuses are assumed to be fabricated concurrently with specific instances of LRUs, e.g., they are assumed to share LRU-specific variations in manufacturing and materials and would track specific failure mechanisms [29].

LRU-Independent methodologies technologies are designed to perform irrespectively of the specific LRU instance to which they are applied. Included in this category of PHM approaches are Life Consumption Monitoring (LCM) and LRU-Independent fuses. LCM produces RUL estimates by collecting environmental stress data and using it as the input to a Physics-of-Failure (PoF) model of a nominal system, [30]. LRU-Independent fuses are fabricated separately from the LRUs and assembled into the LRUs; they do not share any LRU-specific variations in manufacturing and materials.

Canaries, a type of expendable fuse device, serve as harbingers of product failures by wearing out earlier than the product itself. The term ‘canary’ is derived from the use of canaries in mine pits to alert miners of hazardous conditions [31]. Thus the action of alerting, triggered by their failure, may correspond to costs from subsequent grounding or inspection of the aircraft and from replacement of the failed canary. Canary devices may be LRU-Dependent fuses that are fabricated as part of the LRU itself; such a device is a product of the same manufacturing processes and materials that characterize the LRU. LRU-Independent fuses are fabricated separately from the LRUs that they are later coupled to during assembly. They do not share any LRU-specific variability in reliability that derives from manufacturing or material variations.

A majority of PHM approaches involve Precursor to Failure monitoring, a form of Health Monitoring that has been widely applied to mechanical systems [15, 28]. Health Monitoring for electronics has had relatively fewer applications [32]. Precursor to Failure approaches require that the precursor of interest has a deterministic relationship with a specific system failure, but they do not require that the system failures themselves be deterministic, i.e., non-stochastic. In contrast, LCM harnesses the deterministic properties of system failures to use in failure models. LCM employs empirical life cycle loading information in tandem with PoF models to calculate the amount of damage experienced by a component and then compute its RUL [30].

As a PHM approach that does not depend on precursors, LCM does not utilize measures that fully correspond to the state of a specific instance of a system and represents a form of imperfect monitoring. LCM approaches cannot rely on the assumption of perfect monitoring that is often used within maintenance planning models. Perfect monitoring assumes that monitoring occurs without uncertainty and that the scope of the monitoring is complete, that is, it is suitable and sufficient to model all units identically and perfect knowledge exists about the state of any unit at a given time. Imperfect monitoring has been previously examined in [28] and [33], while perfect, but partial monitoring has been treated in [34]. Numerous models for single and multi-unit maintenance planning have appeared [35, 36] that use the assumption of perfect monitoring; for electronic systems in particular, perfect monitoring may be extremely difficult to achieve while the uncertainties are high and the conditions for perfect monitoring may not exist.

PoF is a scientific approach to reliability assessment that uses modeling and simulation based on knowledge of the system architecture, life cycle load profile, and material properties of electronics in addition to knowledge of the underlying causes of failure such as corrosion, wear, fatigue, and fracture. Empirical life cycle loading information can include environmental conditions —among them, humidity, temperature, shock, and vibrations— and operational parameters, including power dissipation, voltage, and current. For instance, temperature cycling is a known source of fatigue failure for interconnects; PoF models have been used to predict the Time to Failure (TTF) distributions of interconnects within known confidence intervals and to predict the RUL of interconnects in electronic packages [37]. Among the objectives of PoF are the improvement of the design and manufacturing practices, the inclusion of reliability in the design process, identification of potential failure mechanisms, and the reduction of operational failures [38].

1.4. Adoption of Prognostics and Health Management

The adoption of PHM approaches requires consideration and planning for integration into new and existing systems, operations, and processes. PHM must provide a significant advantage in order to provide added value for the future product development process or for the maintenance process; commitments to implement and support PHM approaches cannot be made without the development of supporting business cases. 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 a technology enterprise. The utility of PHM to inform decision-makers within tight scheduling constraints and under different operational profiles likewise affects cost avoidance.

1.4.1. Return on Investment

One important attribute of most business cases is the development of an economic justification. Return on investment (ROI) is a useful means of gauging the economic merits of adopting PHM. Constructing a business case for PHM does not necessarily require that the ROI be greater than zero, that is, that there is a cost benefit. In some cases, the value of PHM is not quantifiable in monetary terms; PHM may be 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 or not it indicates that there is a cost benefit, is still an important component of any business case developed for PHM [39].

ROI measures the 'return,' the savings, the profits or the cost avoidance that result from a given use of money. Types of ROI include the cost savings, the avoidance, and the growth in profits [40]. At the enterprise level, ROI may reflect how well an organization is managed. In regards to specific organizational objectives such as gaining market share, retaining and attracting customers, or improving availability, the ROI may be measured in terms of how a change in practice or strategy results in meeting these goals. In general, ROI is the ratio of gain to investment. Equation (1.1) defines a ROI calculation over a system life cycle.

$$ROI = \frac{Return - Investment}{Investment} = \frac{Cost\ Avoidance - Investment}{Investment} \tag{1.1}$$

ROI allows for enhanced decision-making regarding the use of investment money and research and development efforts by enabling comparisons of alternatives. However, its inputs must be accurate and thorough in order for the calculation itself to be meaningful. 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 return is a quantification of the benefit realized through the use of a PHM approach. The determination of the ROI allows managers to include quantitative and readily interpretable results in their decision-making [41]. 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 traditional maintenance approaches.

1.4.2. Review of Economic Analyses of Prognostics and Health Management

NASA studies indicate that the use of prognostics in aircraft structures may be produce positive ROIs within a period of 3 years for contemporary and older generation aircraft systems assuming a sharp reduction in maintenance requirements [42]. One of the most prominent defense applications of PHM is the Joint Strike Fighter (JSF), a major multi-national acquisition program intended to comprise three quarters of the American tactical aircraft fleet by 2020 [43, 44]. PHM is the principle component in the JSF's Autonomic Logistics[3] system. 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 [46, 47]. The effectiveness of the PHM devices in detecting and isolating each of the failures was determined and evaluated against unscheduled maintenance and scheduled maintenance approaches.

Ashby and Byer [47] employed a logistic simulation model to assess impacts on availability within military flight scheduling for an engine control unit (ECU) equipped with PHM for different subcomponents and to determine the maintenance and cost avoidance savings. PHM, when applied to suitable subcomponents, offered substantial monetary and non-monetary benefits, specifically in increased safety and improved sortie generation rates (the sustainable number of aircraft launches in a given time period).

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[3] 'Autonomic logistics' describes an automated system that supports mission reliability and maximizes sortie generation while minimizing costs and logistical burden, [45].

The Boeing Company developed a life cycle cost model for evaluating the benefits of prognostics for the JSF 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 [48]. The model allowed for selection of standard mission profiles or definition of custom mission profiles. Cost-influencing parameters in addition to economic factors were incorporated into a cost benefit analysis [49]. For a notional airframe mounted accessory drive (AMAD), a substantial 'prognostic payback ratio' was estimated that included a sensitivity analysis with respect to prognostic approach and TTF parameters. Embraer [50] developed a similar model for legacy aircraft.

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 that estimated a positive ROI [51]. The BladeSwitch ROI was based on the assumption that the cost of the prognostic unit would be approximately 10% of the LRU's cost for simple forms of PHM. The authors anticipate that the avoidance of the 'soft costs' of worsened reputation and the penalties and fines for malfunctioning systems resulting in downtime has the potential to increase the ROI for BladeSwitch significantly.

Byer *et al.* [52] describe a process for conducting a cost benefit analysis for prognostics applied to aircraft subsystems. The definition of a baseline system without PHM and the aircraft system with PHM is the first step in the analysis.

Secondly, reliability and maintainability predictions for the components of the aircraft are developed. Next, the measures of PHM effectiveness are defined and the corresponding metrics associated with these measures of effectiveness are established. The impact of PHM on training, support equipment, the cost of consumables, and manpower are then assessed. The overall non-recurring and recurring costs of providing PHM are estimated. The results are then computed for the cost benefits. The process is then repeated for PHM benefits that are not denominated in monetary units, including sortie generation capability, reduction in the frequency of accidents, and the change in footprint.

As supplemental information and for model refinement, Byer *et al.* [51] use FMECA, line maintenance activity costing, and legacy field event rates in addition to scheduling matrices and cost data on parts to produce life cycle costs and operational impact assessments. The detailed inputs present an improvement over the more general information contained in typical military maintenance databases, which may have a great amount of historical data overall but lack specific data on the fault diagnostic and isolation times needed to assess the cost avoidance of PHM. The methodology can be used to enhance the accuracy of operational and support costs, even in the absence of PHM technologies, by creating a more rigorous framework for the examination of maintenance costs.

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 [53]. The analysis was performed by conducting a study of asset failure behavior, calculating the cost of PHM technology development and integration, estimating the benefits of the technology implementation, and calculating decision metrics. The initial analysis focuses on isolating the subcomponents that contribute to the degradation of the larger components or the system itself. FMECA can then be used to classify the failure mode and determine which prognostics technology could be used to monitor it. This information is then extended into a fleet operations framework in which a user can select variables of parameters, such as the system's availability, the battery failure rate, or the logistic delay time. These parameters can be optimized to achieve a given ROI, or the user can set values for these parameters and then calculate the ROI for different scenarios. Banks and Merenich [53] found that ROI was maximized when the time horizon —the distance between the indication of upcoming failure by the prognostic device and the actual subcomponent failure— 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 [54]. Non-recurring development costs 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 for the LAV and for the SBCT based on estimates of the development and implementation costs. The difference in ROI is attributed to a shorter period of benefit over which the costs of PHM development would be absorbed for the LAV in addition to a smaller quantity of batteries. The implementation costs considered were manufacturing of the PHM sensors and their installation in each vehicle. The non-recurring development costs included algorithm development, hardware and software design, engineering, qualification, and testing, vehicle system integration, and the development of an integrated data environment (IDE) for data management. 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 over a 25-year period. The study found that the ROI was greatest when evaluated across the entire DoD, and that the ROI was several times higher for the SBCT than the LAV.

These efforts have examined the ROI of electronics PHM and contain valuable information on methodologies, approaches, and applications. However, even when these studies provide quantitative ROI estimates, comparison lacks value because there is not a consistently provided basis for the calculation. Therefore, it is difficult to extrapolate these findings to other PHM applications or to arrive at an ROI estimate on the basis of existing studies.

1.5. Enabling a Return on Investment Analysis

Although existing PHM ROI assessments contain valuable insight into the cost drivers, most cost analyses and cost benefit analyses are application-specific; they provide neither a general modeling framework nor a consistent process with which to approach the evaluation of the application of PHM to a new system. Furthermore, existing approaches primarily provide ‘point estimates’ of the value based on a set of fixed inputs when, in reality, the inputs are uncertain. For example, the reliability of a system is best represented as a probability distribution, as are many other inputs to the ROI analysis. 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.

It has been shown that PHM approaches can be suitable for electronic systems [27, 29, 30]; however; the connection between utilization of PHM and the reduction in life cycle costs has not been examined and quantified in a manner that includes a detailed model of implementation costs. Prognostics sensor technologies and health management are burgeoning areas of research, yet usage methodologies for prognostic information are in early development. Greitzer *et al.* emphasize that *how* to do prognostics and then *what* do with prognostic information are distinctly separate issues [55]. An implementation cost model is necessary for the transition from conceptualization to realization of the potential of prognostics and for the cost benefit analysis of PHM.

1.5.1. Thesis Overview

This effort focuses on an implementation model that expands an existing maintenance planning model [56] used to quantify the ROI of PHM. The maintenance planning model incorporates realistic monitoring conditions (i.e., imperfect and partial) and addresses the uncertainties that exist in the prediction of RUL. The maintenance planning model addresses the disparate operational profiles of systems under consideration and allows for the inclusion of false alarms and random failures. It is capable of analyzing single- and multiple-socket systems to mimic the use of PHM in the maintenance planning of complex systems. The integration of the implementation model and the maintenance planning model enables a more comprehensive calculation of ROI to support acquisition decision-making.

The second chapter of this thesis describes the methodology for constructing the model and delineates the assumptions followed in its formulation. It describes the incorporation of the implementation costs and the cost avoidance from maintenance planning into the discrete event simulation. The third chapter discusses the case data used to analyze the ROI of using PHM in comparison to traditional maintenance approaches. The fourth chapter details the analysis of the case data and presents the results. The fifth and final chapter summarizes the contributions of the model and discusses the future of PHM.

Chapter 2: Return on Investment Model Methodology

This chapter describes the methodology used to construct the Return on Investment (ROI) model and describes the assumptions made in its formulation. It details the incorporation of the implementation costs and the cost avoidance from prognostics and health management (PHM) into a discrete event simulation to perform a ROI analysis. The implementation cost represents the 'investment' portion of the ROI calculation, while the cost avoidance from maintenance planning in comparison to a traditional maintenance approach such as unscheduled maintenance without PHM provides the 'return.'

Implementation costs are the costs associated with the realization of PHM in a system, that is, the development of the technologies and support structures necessary to integrate and incorporate PHM into new or existing systems. Within the realm of maintenance planning, the primary areas for cost avoidance from the implementation of PHM are failure avoidance and the minimization of the loss of remaining useful life (RUL). Field failure of systems can be costly; the cost of a mission abort due to system failure in an Unmanned Aerial Vehicle (UAV) is an estimated $15,000 [47]. If all or some fraction of field failures can be avoided, then maintenance planning may facilitate cost avoidance by minimizing the cost of unscheduled maintenance. Failure avoidance has the benefits of increased availability and reduced risks of catastrophic losses such as the loss of human lives or the loss of the entire system.

2.1. Model Terminology

The following definitions are used throughout the discussion of the implementation and maintenance planning portions of the model.

A Line Replaceable Unit (LRUs) is an essential support item that can be removed and replaced at field level in order to restore an item to operational readiness [57]. LRUs are distinguished from Shop Replaceable Units (SRUs) and Depot Replaceable Units (DRUs), which may require additional time, resources, and equipment for replacement and maintenance.

A socket, sometimes referred to as a 'block' in reliability engineering [58], is a unique instance of an installation location for an LRU. One instance of a socket occupied by an engine controller is the controller's 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. Cushing [59] supplies the example of a light bulb installed in a particular light fixture. The light bulb is the LRU of interest, and the light fixture where it is installed is the socket. Replacing the light bulb at specific intervals has no impact on the intrinsic reliability of the bulb but increases the availability of the socket.

Unscheduled maintenance refers to operating a system until failure and then taking appropriate maintenance actions to replace or repair the failure. The opposite of unscheduled maintenance is preventative maintenance in which a maintenance action is taken prior to failure at a scheduled interval or in response to an indication provided by a PHM approach. A fixed-schedule maintenance interval is the interval at which scheduled maintenance is performed. The fixed-schedule maintenance interval is kept constant for all instances of the LRUs occupying all socket instances throughout the system life cycle. The common wisdom that oil should be changed every 3,000 miles for personal vehicles represents a fixed-schedule maintenance interval policy.

Section 2.9 discusses the two categories of PHM methods —Precursor to Failure methodologies that rely on specific LRUs, and LRU-Independent methodologies that are independent— in greater detail within the context of their implications for the maintenance planning performed in the model. Table 1 contrasts common approaches to maintenance planning.

Table 1. Maintenance Processes [60]

Type	Reactive	Proactive		
Category	Run to Fail	Preventative	Predictive	
Subcategory	**Fix when it breaks**	**Scheduled**	**Condition-Based Maintenance (CBM)**	**Prognostic**
		Static	Dynamic	
When Scheduled	No Scheduled Maintenance	Maintenance based on a fixed time schedule for inspection, repair, and overhaul	Maintenance based on current condition	Maintenance based on forecast of remaining useful life
Why Scheduled	No Scheduled Maintenance	Failure modes and equipment maintenance requirements predicted during design	Maintenance is needed now based on real-time evidence to prevent equipment degradation	Maintenance need is probable within mission time
How Scheduled	No Scheduled Maintenance	Modeling and simulation; no real-time feedback loop	Continuous collection of condition data	Forecast of remaining useful life based on actual stress conditions

2.2. Implementation Costs

'Implementation' may be decomposed into many separate activities at different levels of complexity and detail. The following sections discuss the major groups of implementation costs while maintaining generality and breadth. This broadness reflects the incorporation of implementation costs into ROI models for PHM; an organization will likely not be able to put an exact price tag on specific activities. Implementation cost models can and should be adapted to meet the needs of a particular application and can be expanded as knowledge of the PHM devices and their use increases.

Implementation activities are categorized as occurring at either the LRU level or at the program or system level (i.e., a group of sockets). LRU-level implementation costs are unique to a group of identical LRUs or to a single representative LRU. Within the government sector, a program is a distinct effort to procure a new or improved capability in order to satisfy the needs of a mission. The program level is where cost-contributing activities that are relevant to the overall acquisition occur; a program may include a number of either new or legacy systems. Examples of systems include Armored Personnel Carriers (APCs) or Unmanned Aerial Vehicles (UAVs).

The costs of implementing PHM can be categorized as non-recurring, recurring, or infrastructural depending on the frequency and role of the corresponding activities. The following sections describe these activities and their significance within the implementation cost model framework. Section 2.10 discusses the formulation of the implementation cost model itself and its integration with the maintenance planning model.

2.3. Non-Recurring LRU Level Costs

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 or per-socket basis, or per a group of LRUs or sockets. The development of hardware and software are the most prominent non-recurring costs (within the context of technology acquisitions, such costs are often termed Non-Recurring Engineering (NRE) costs). Hardware cost modeling will vary depending on manufacturing specifications, country of origin, level of complexity, and materials. LRU-dependent prognostics are manufactured concurrently with the device whose failure they are intended to indicate; if a general cost model can be developed for the electronic components of interest, it may be a reasonable assumption that the costs of materials, parts, and labor for the manufacturing of the prognostic device will be equivalent. This simplifies the cost modeling of the LRU-dependent prognostics but not the LRU-Independent approaches, which need not have anything in common with the device they are monitoring.

The development of PHM software may be outsourced and treated as a single contract amount or may be modeled according to standard software cost models such as COCOMO [61]. COCOMO and other software cost models provide cost estimates based on the Source Lines of Code (SLOC), the programming language used, and the manpower needed for development. Both hardware and software design include testing and qualification to ensure performance, compatibility with existing architectures, and compliance with standards and requirements.

Other non-recurring costs include the costs of training, documentation, and integration. Training costs arise from the need to develop training materials to instruct and educate maintainers, operators, and logistics personnel as to the use and maintenance of PHM, in addition to the cost of removing these workers from their ordinary duties to attend training. PHM hardware and software must have documentation to serve as guides and as usage manuals, while integration costs refer to the costs of modifying and adapting systems to incorporate PHM.

The specific non-recurring cost is calculated as:

$$Non-Recurring\ Cost = C_{dev\_hard} + C_{dev\_soft} + C_{training} + C_{doc} + C_{int} + C_{qual} \qquad (2.1)$$

in which,

C_{dev_hard} = the cost of hardware development
C_{dev_soft} = the cost of software development
$C_{training}$ = the cost of training
C_{doc} = the cost of documentation
C_{int} = the cost of integration, and
C_{qual} = the cost of testing and qualification, including the cost of functional testing for hardware and software components.

2.4. Recurring Costs

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.

The recurring cost at the LRU level is calculated as:

$$Recurring\ Cost_{\ (per\ LRU)} = C_{LRU} + C_{hard\_add} + C_{assembly} + C_{install} \qquad (2.2)$$

in which,

C_{LRU} = the base cost of an LRU without any PHM-specific hardware or software included

C_{hard_add} = the cost of hardware in each LRU (such as sensors, chips, extra board area)

$C_{assembly}$ = the cost of assembly of the hardware in each LRU, and

$C_{install}$ = the cost of installation of hardware for each LRU, including the original installation and re-installation upon failure, repair, or diagnostic action.

The recurring cost at the system level is calculated as:

$$Recurring\ Cost_{\ (per\ system)} = C_{hard\_add\_sys} + C_{install\_sys} \tag{2.3}$$

in which,

$C_{hard\_add\_sys}$ = the cost of additional parts and manufacturing or the cost of hardware for each socket (such as connectors or sensors), and

$C_{install\_sys}$ = the cost of installation of hardware for each socket or for each group of sockets, which includes the original installation and re-installation upon failure, repair, or diagnostic action.

2.5. Infrastructure Costs

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 of the ratio of money to a period of activity (e.g., dollars per operational hour, dollars per mission, dollars per year). During a mission or a period of use, the PHM device may be collecting, processing, analyzing, storing, and relaying data. These activities constitute the data management needed to implement PHM and are continual throughout the life of the PHM program. PHM necessitates the compilation of extensive data in the pre-processing phrase; the tradeoff between the data rate and the error probability [62] is an additional factor in the post-processing data management. The addition of PHM to an LRU imposes a cost associated with the extra time for maintainers, diagnosticians, and other personnel to read and to relay the information provided by PHM to render a decision about the timing and the content of maintenance actions. As with the LRUs that they monitor, PHM devices may also require maintenance over their life cycles, including repairs and upgrades. Maintenance of the PHM devices may require the purchase of repair expendables (consumables) or ordering of new parts. The labor required for such maintenance contributes to the infrastructure costs. Lastly, re-training or 'continuous education' is an infrastructure cost, ensuring that personnel are prepared to use and maintain the PHM devices as intended.

The infrastructure costs are calculated as:

$$Infrastructure\ Cost = C_{prog\_maintenance} + C_{decision} + C_{retraining} + C_{data} \tag{2.4}$$

in which,

C_{data}	= the cost of data management, including • Cost of data archiving • Cost of data collection • Cost of data analysis • Cost of data reporting
$C_{prog\_maintenance}$	= the cost of maintenance of the prognostic devices
$C_{decision}$	= the cost of decision support, and
$C_{retraining}$	= the cost of re-training costs to educate personnel in the use of PHM.

2.6. Financial Costs

Many of the acquisition programs that are suitable for PHM applications have support lives that may span decades. Relevant business cases, therefore, must examine the ROI over a long-term period. The cost of money must be included in the ROI calculation due to the longer time period over which the analysis is being performed. Financial costs are among the aspects of engineering economics that are part of technology acquisitions, capital allocations, and budgeting.

With respect to engineering product design and development, financial costs can be examined when evaluating alternative investment prospects and determining the best uses of organizational resources. An interest charge is applied when money is borrowed; resource allocation analysis requires consideration of these charges, the value of money over time, depreciation, and the inflation over a system's life cycle. Economic equivalence correlates the cash flows associated with different usage alternatives to produce meaningful comparisons for investment decision-making. Concepts such as Present Value may be used to evaluate the value of money in the present time and its value at points in the future in a meaningful way that allows for an 'apples to apples' comparative basis.

Ignoring inflation, the present value of an investment worth V_n, n years from the present with a constant discount rate (rate of ROI on the money expected by the lender or expected as return from an alternative investment) of r is given by,

$$Present\ Value = \frac{V_n}{(1+r)^n} \tag{2.5}$$

Using (2.5), a cost of V_n can be shifted n years into past or future for comparison purposes. Other forms of the present value calculation exist for various assumptions about the growth of money over time.

2.7. Other Costs

The implementation of PHM imparts additional burdens onto systems that cannot always be easily measured and considered in monetary terms. The physical hardware apparatuses used in PHM will consume volumetric space and alter the weight (loading) of the systems where they are installed. The time needed for PHM data to be processed, stored, and analyzed to render a maintenance decision is an additional metric of importance. Space, weight, time, and cost (SWTC) are the dimensions in which PHM activities could be fully expressed. Considering each of these dimensions may not be useful or needed for a particular analysis; however, awareness of these physical and time-related factors can be leveraged to calculate the non-monetary impositions and potential benefits associated with PHM. Examples of these non-monetary quantities are provided in Table 2.

Table 2. Non-Monetary Considerations

Category	Example
Space (Volume or Area)	Footprint within the LRU
	Footprint of external equipment needed to support PHM
	Dimensions of electronics content and integration with existing equipment (e.g., number of connector pins, boards per panel)
Weight	Weight of PHM equipment on-board or on system
	Weight of external equipment needed to support PHM
Time	Time to collect data
	Time to analyze data
	Time to render a decision
	Time to communicate decision
	Time to take action

2.8. Cost of Adaptation to Prognostics and Health Management

Maintenance culture has been studied to identify areas of improvement following accidents or failures, to determine the most effective ways of training maintenance crews, and as part of resource management, with 12-15% of accidents in the commercial aviation industry attributable to maintenance errors [63]. Analyses of the maintenance culture underscore the complexity of decision-making within the industry and point to the underlying difficulties of effecting organizational changes [64, 65].

Organizations seeking to implement changes within their daily operations are confronted by direct and tangible impacts such as new equipment and fewer personnel that can be correlated to different costs. However, the role of seemingly intangible elements has proved important to the practices and business culture of productive and efficient organizations and has been studied within the contexts of industrial and organizational psychology, group dynamics, human factors, and team and training effectiveness [66].

The aviation workplace culture has been examined as an environment in which high-pressure, safety-critical decisions must be made in a team atmosphere [67]. PHM represents a departure from traditional maintenance procedures; to implement it will require a change the maintenance culture such that maintainers are comfortable and educated to use PHM as intended. Little or no value can be derived from PHM if maintainers fail to accept it and go about maintaining systems as they would have in the past. This cost of changing the maintenance culture may be quantified as part of continuous education cost beyond standard training. System architects and designers would eventually transition to having greater confidence in PHM, ultimately to remove redundancy and to make other changes necessary to allow the full value of PHM to be realized. While this is not an easily quantifiable or engineering cost, it is nonetheless a real factor contributing to the adoption of PHM.

Continuous education is needed as part of a full transition to PHM. While the focus of the majority of human factors programs within the American aviation maintenance industry has been instituting cultural change, Patankar and Taylor [63] note that these programs typically fail to deliver even modest changes. ‘Learning curves’ quantify the known time for changes to take effect within a sociotechnical system. Patankar and Taylor [63] propose that an effective strategy for change includes education that focuses on both awareness of the purposes for change and the accompanying behavior, improved communication and skill set development, and proactive training that educates maintenance technicians before accidents occur rather than in their aftermath.

2.9. Maintenance Planning (portions adapted from [56])

Maintenance optimization uses mathematical models to quantify the costs and benefits of maintenance and to determine a maintenance schedule such that a favorable (near-optimal) balance between the two is obtained. Maintenance optimization has been studied since the 1960s [68]. and is one of the principal motivations behind PHM. However, maintenance modeling has not been widely applied to electronic systems and is a relatively recent development. Previously, electronics failures were presumed random and usually modeled as an unscheduled maintenance activity, while wear-out was assumed to be beyond the end of the system's support life. Electronic devices have become candidates for prognostics as knowledge of electronic failure modes and behavior has increased and as the potential for cost avoidance is evaluated.

Discrete event simulation has been widely applied to maintenance modeling, e.g., [69-71], and is a popular tool within traditional operational research and within different industries, including manufacturing, finance, and medicine [72, 73]. PHM activities have been modeled using discrete event simulation [74]. Discrete event simulation consists of an assortment of techniques to characterize the behavior of a dynamical system as it progresses over an evolutionary unit of interest that may be temporal or physical (e.g., load cycles or any of the physical phenomena behind the failure mechanisms that are considered by the PHM approach). Discrete event simulation captures changes in system behavior as separate events rather than a continual transition. The U.S. Air Force developed the Logistics Composite Model (LCOM) in the late 1960s to use discrete event simulation to address maintenance staffing, sortie generation rates, sparing and equipment, and other key logistic support issues while incorporating variability in resources and in needs [75].

2.9.1. Maintenance Planning Model

The maintenance planning model uses Monte Carlo methods to analyze the costs associated with a variety of maintenance approaches. The maintenance planning model enables the evaluation of the cost avoidance from maintenance planning with prognostic approaches in contrast to non-PHM approaches. The maintenance planning model employs a discrete event simulation to track individual the points at which an LRU could be installed (i.e., individual sockets) from the beginning of their field lives upon initial installation of the first LRU to the end of the operation and support, culminating in disposal. The LRUs installed at these socket locations may have variable TTFs and variable RUL estimates. If the LRU originally installed in a socket never fails, the socket will only contain one LRU in its life cycle; alternatively, it may have many LRUs installed as they fail and require replacement. The discrete event simulation applies to both single and multiple sockets within the larger system.

The maintenance approaches that can be compared are (a) a fixed-schedule maintenance interval; (b) a variable maintenance interval schedule for LRUs based on inputs from a Precursor to Failure methodology; (c) a variable maintenance interval schedule for LRUs based on an LRU-Independent methodology, and (d), unscheduled maintenance. The intrinsic reliability of the LRU is defined in terms of its Time to Failure (TTF). Approaches (b) and (c) involve adopting PHM, while (a) and (d) are traditional (and extant) methods.

In the precursor to failure models, the TTF distribution associated with the PHM structure (or sensor) is unique to each LRU instance, whereas in the LRU-Independent models the TTF distribution associated with the PHM structure is linked to the nominal LRU and is independent of any manufacturing or material variations between LRU instances.

2.9.2. Precursor to Failure Monitoring

Precursor to failure monitoring approaches utilize fuses or other monitored structures that are manufactured with or within the LRUs or as a monitored precursor variable that represents the manufacturing or material variations of a particular LRU. Health Monitoring (HM) and LRU-dependent fuses are examples of precursor to failure methods. The parameter to be determined is the prognostic distance, the time interval between the identification of failure by the PHM device and the failure of the LRU. The precursor to failure monitoring methodology forecasts a unique time to failure (TTF) distribution for each instance of an LRU based on the LRU's TTF.

The precursor to failure monitoring distribution has a fixed width measured in the relevant environmental stress units (here, operational hours) representing the probability of the prognostic structure accurately indicating the precursor to a failure. The parameter to be optimized in this case is the prognostic distance assumed for the precursor to failure monitoring forecasted TTF.

The model proceeds in the following way: for each LRU TTF distribution sample (t_1) taken such that t_1 is less than the TTF of the nominal LRU, a precursor to failure monitoring TTF distribution is created that is centered on the LRU TTF minus the prognostic distance (t_1-d). Figure 1 illustrates the TTF based on precursor to failure monitoring as assuming a symmetrical triangular distribution with a mode at this location. Figure 1 depicts symmetrical triangular distributions for the probability density functions (pdfs) of the TTFs of the LRU and of the precursor to failure predictions; however, these are separate pdfs that may assume different shapes and sizes.

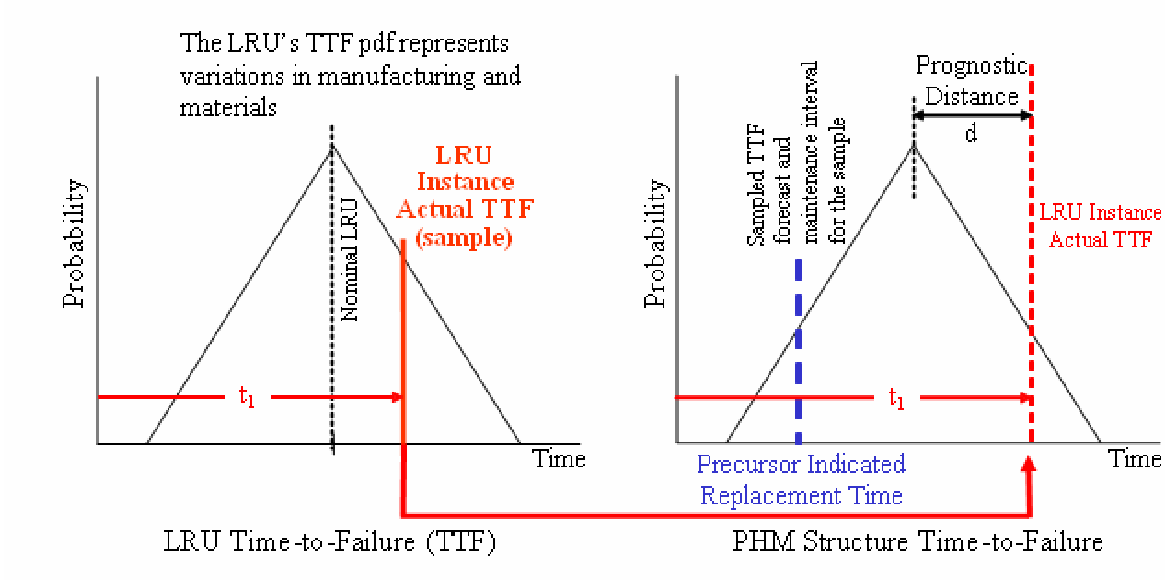


Figure 1. Precursor to Failure Monitoring Modeling Approach with Symmetrical Triangular Distributions [56]

The precursor to failure monitoring TTF distribution is 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. The costs of performing the necessary maintenance actions are accrued.

2.9.3. Life Consumption Monitoring

In LRU-Independent PHM methods, the PHM devices are manufactured independently of the LRUs, i.e., the PHM structures are not coupled to a particular LRU's manufacturing or material variations. An example of a LRU-Independent method is Life Consumption Monitoring (LCM). LCM is the process by which a history of environmental stresses, such as thermal loads or vibrations, is used in conjunction with physics of failure (PoF) models to compute damage accumulated and thereby forecast RUL. The LRU-Independent methodology forecasts a unique TTF distribution for each instance of an LRU based on its unique environmental stress history; Vichare et al. [27] has demonstrated that this distribution may also be derived from recorded environment history. The shape and width of the LRU-Independent method distribution is influenced by the uncertainties associated with the sensing technologies and uncertainties in the prediction of the damage accumulated. The variable to be optimized in this case is the safety margin assumed on the LRU-Independent method forecasted TTF, i.e., the length of time (e.g., in operation hours) before the LRU-Independent method forecasted TTF the unit should be replaced.

The LRU-Independent model proceeds in the following way: for each LRU TTF distribution sampled, an LRU-Independent method TTF distribution is generated that is centered on the TTF of the nominal LRU less the safety margin, illustrated in Figure 2 using symmetrical triangular distributions for the pdfs of the TTFs for the LRU and the prediction from the LRU-Independent approach. The LRU independent method TTF distribution is then sampled; if the LRU-Independent method TTF sample is less than the actual TTF of the LRU instance, then LRU-Independent method was successful (failure avoided). If the LRU-Independent method TTF distribution sample is greater than the actual TTF of the LRU instance, then LRU-Independent method was unsuccessful. If successful, a scheduled maintenance activity is performed and the timeline for the socket is incremented by the LRU-Independent method 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.

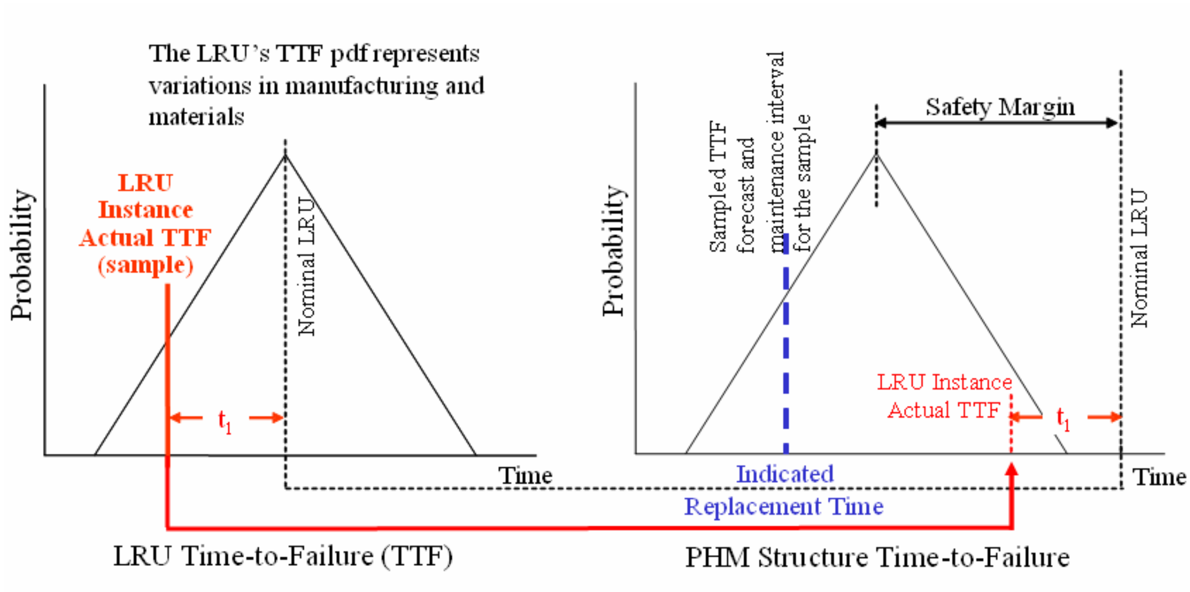


Figure 2. LRU-Independent Modeling Approach with Symmetrical Triangular Distributions [56]

2.10. Model Integration

Several key concepts differentiate the modeling of cost avoidance using maintenance planning from implementation cost modeling. First, the temporal order of events in the lifetime of an LRU or socket affect the calculation of cost avoidance (this is true whether financial costs are included or not). The cost avoidance is heavily influenced by the sequencing (in time) of failures and maintenance actions, whereas implementation costs are not time-sequence dependent and can be modeled independently of each other in many cases, despite sharing cost-contributing factors.[4] Secondly, irrespective of the combination of criteria for cost avoidance under consideration, corresponding measures of the uncertainty associated with the calculation must be incorporated. It is the inclusion and comprehension of the corresponding uncertainties — decision making under uncertainty— that is at the heart of being able to develop a realistic business case that addresses prognostic requirements.

Equation (2.6) describes the underlying calculation that the model performs to find the cost per socket of scheduled and unscheduled maintenance. The model is capable of following single sockets or groups of sockets from the beginning of their field lives to the end of the system support life; however, for simplicity, (2.6) is presented for the single-socket case with one LRU occupying the socket. In order to construct histograms of metrics of interest, such as life cycle cost, a sufficiently large number of sockets should be modeled.

$$C_{socket\ i} = fC_{LRU\ i} + (1-f)C_{LRU\ i\ repair} + fT_{replace\ i}V + (1-f)T_{repair\ i}V \qquad (2.6)$$

in which,

$C_{socket\ i}$	= Life cycle cost of socket *i*
$C_{LRU\ i}$	= Cost of procuring a new LRU for socket *i*
$C_{LRU\ i\ repair}$	= Cost of repairing an LRU in socket *i*
f	= Fraction of maintenance events on socket *i* that require replacement of the LRU in socket *i* with a new LRU
$T_{replace\ i}$	= Time to replace the LRU in socket *i*
$T_{repair\ i}$	= Time to repair the LRU in socket *i*
V	= Value of time out of service

[4] Note, not being time-sequence dependent does not mean that the costs are not time-dependent. The effective cost does depend on when it is incurred (financial costs, i.e., time value of money), but if there is no time-sequence dependence then the order of events is not important to the model.

Equation (2.6) incorporates the implementation costs as an additional cost per socket and does not reflect the implementation costs at the program or platform level. The costs of repairing an LRU in socket *i* and the time to repair an LRU in socket *i* approach zero if *f*, the fraction of maintenance events on socket *i* that require replacement, approaches unity. These terms may be omitted from (2.6) if it is not possible to repair the LRU or if the maintenance policy calls for replacement rather than repair. The value of time out of service, *V*, differs for unscheduled and scheduled maintenance; unscheduled maintenance often interferes with operations and imposes a greater burden on an organization to resolve. The capability to perform repair as opposed to replacement may also be different for unscheduled and scheduled maintenance, for example, the tools and equipment to repair a failed LRU may not exist if unscheduled maintenance is required at a small regional airport where an airline has limited resources.

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 on the timeline. Figure 3 illustrates the temporal insertion of the implementation costs along the system life cycle. 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 (2.6)). 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 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 course of the socket's life cycle and are charged periodically.

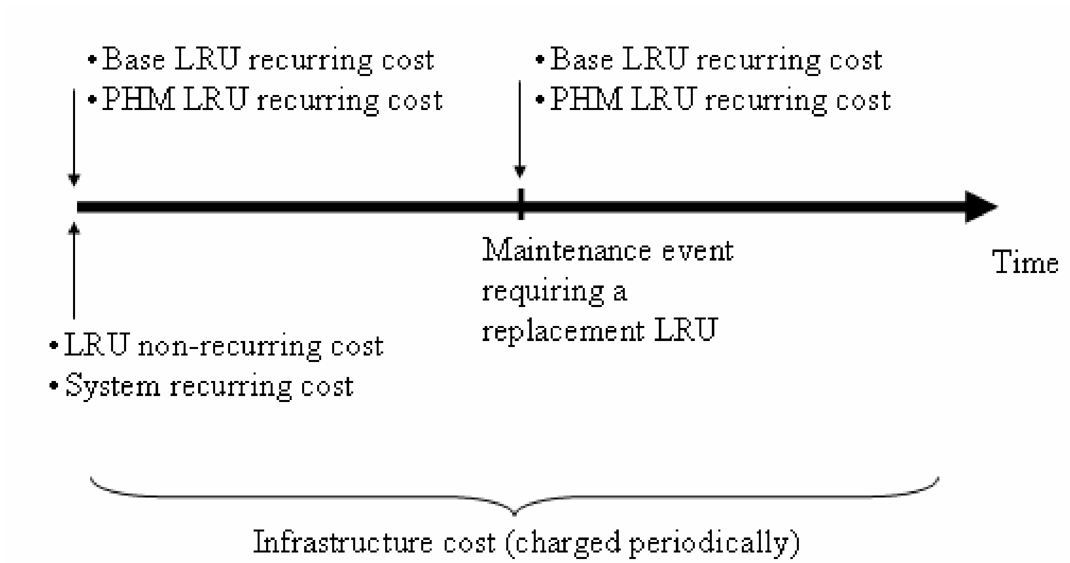


Figure 3. Temporal Order of Implementation Costs

The implementation cost model assumes that a range of possible costs exists for each of the implementation variables. The model accommodates continuous distributions (uniform, triangular, Weibull, normal, lognormal, and exponential) or a fixed value for each variable. For a sample of size m the empirical distribution function is a cumulative distribution function that concentrates probability $1/m$ at each of the m numbers. If $X_1, X_2, \ldots, X_m$ are independent and identically-distributed random variables with the cumulative distribution function $F(x)$. The empirical distribution function is defined as a step function, $F_m(x)$ such that

$$F_m(x) = \frac{1}{m}\sum_{i=1}^{m} I(X_i \le x) \tag{2.7}$$

$I(x)$ is the characteristic (indicator) function defined on a set *X* that indicates the membership on an individual element x in a subset A, with $I_A = \begin{cases} 1 \text{ if } x \in A, \\ 0 \text{ if } x \notin A \end{cases}$. For fixed *x*, the characteristic function is a Bernoulli random variable with parameter $p = F_m(x)$ and $mp = mF_m(x)$, a binomial random variable with mean $\mu = mF_m(x)$ and variance $Var(x) = mF_m(x)(1 - F_m(x))$. For each of the four categories of implementation costs, an empirical distribution function is constructed and utilized according to the process illustrated in Figure 4.

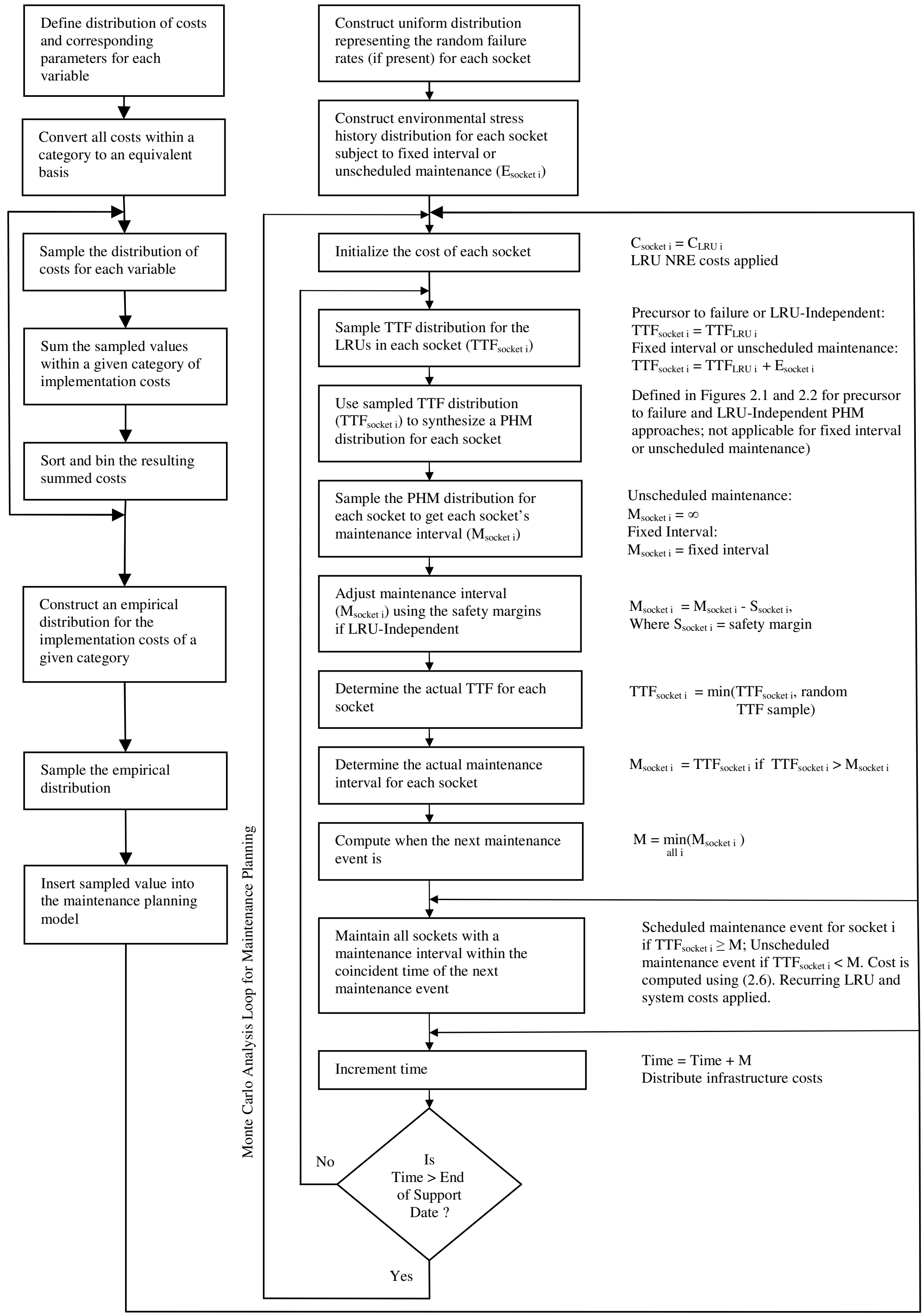


Figure 4. Implementation Cost and Maintenance Planning Model Integration, adapted from [56].

2.11. Operational Profile

The operational profile of systems equipped with PHM dictates how the information provided by PHM may be used to affect the maintenance and usage schedules. The effective costs associated with maintenance actions depend on when actions are indicated relative to some operational cadence. Cadences may be proscribed by business constraints, regulations or mission requirements, and may be subject to change as user requirements shift. The cadence may be best described according to a probabilistic model rather than a timeline, i.e., a defined probability of a maintenance request being issued before, during, or after a mission or particular type of use. The implications of the safety margins or prognostics distances will vary with the difference in cadence to affect the timing of maintenance actions.

The operational profile is reflected in the maintenance modeling by varying the value of the parameter V in (2.6). V, the value of an hour out of service, is set to a specific value if the maintenance is scheduled, but if the maintenance is unscheduled, the value of V is given by the data in Table 3.

Table 3. Data Defining Unscheduled Maintenance Operational Profile

Mode	Probability	*V*
Maintenance event before mission (during preparation)	P_b	V_b
Maintenance event during mission	P_d	V_d
Maintenance event after mission (during downtime)	P_a	V_a

“Before mission” represents maintenance requirements that occur while preparing to place the system into service, i.e., while loading passengers onto the aircraft for a scheduled commercial flight. “During mission” means that the maintenance requirement occurs while the system is performing a service and may result in interruption of that service, i.e., making an emergency landing, or abandoning a High Mobility Multipurpose Wheeled Vehicle (HMMWV) by the side of the road during a convoy. "After mission" represents time that the system is not needed, i.e., the period of time from midnight to 6 AM when the commercial aircraft can sit idle at a gate.

When an unscheduled maintenance event occurs, a random number generator is used to determine the portion of the operational profile the event is in and the corresponding value (*V*) is used in the analysis. This type of valuation in the discrete event simulation is only useful if a stochastic analysis that follows the life of a statistically relevant number of sockets is used.

2.12. Return on Investment Calculation

The ROI calculation is performed by running simulations that differ only in the choice of maintenance approach used, i.e., with all other parameters equal. The investment cost of PHM and the cost per socket are calculated and then compared to the cost per socket of unscheduled maintenance. Equation (2.8) is used to calculate the ROI and represents the application of (1.1) to PHM.

$$ROI_{PHM} = \frac{C_{us} - \left(C_{PHM} - I\right)}{I} - 1 \qquad (2.8)$$

in which,

C_{us}	= the cost per socket using unscheduled maintenance
C_{PHM}	= the cost per socket using a PHM approach, and
I	= the effective investment cost of using a PHM approach per socket

Equation (2.9) is used to calculate *I*, the effective investment cost per socket.

$$Investment\ Cost\ = C_{NRE} + C_R + C_{FA} + C_{ELRU} + C_M + C_J \qquad (2.9)$$

in which,

C_{NRE}	= the PHM non-recurring costs
C_R	= the PHM recurring costs
C_{FA}	= the false alarm resolution costs
C_{ELRU}	= the procurement of LRUs above the unscheduled maintenance quantity
C_M	= the maintenance cost including repair above the unscheduled maintenance (may be <0)
C_L	= the annual infrastructure costs associated with PHM

2.13. Summary

The Return on Investment Model uses Monte Carlo methods to simulate the life cycles of sockets where LRUs are installed. The implementation cost variables are selected to reflect the primary non-recurring, recurring, and infrastructure (sustainment) costs relevant for technology acquisitions. Fixed scheduled maintenance, precursor to failure monitoring and LRU-Independent method models are implemented as stochastic simulations in which a statistically relevant number of sockets are considered in order to construct histograms of costs, availability, and failures avoided. The life cycle costs are accumulated and comparable for different maintenance approaches, investment costs, and operational profiles.

The Return on Investment model is implemented in JAVA language and allows for user definition of the implementation costs described above, the operational profile details, discount rate, the maintenance repair and replacement costs, and of the PHM specifications for precursor to failure monitoring and LRU-Independent modeling approaches. The JAVA implementation of the model accepts the specification of disparate LRUs to mimic the potential implementation of PHM within a system. Additional details are provided in the Appendix.

Chapter 3: Analysis Case Data

This chapter describes the analysis case used to construct a business case to evaluate the Return on Investment (ROI) of Prognostics and Health Management (PHM) for maintenance planning. It describes the assumptions and values used in the modeling of implementation costs and maintenance planning. These values serve as the baseline data for analysis and calculation of the ROI. The analysis case outlined in this chapter is used in Chapter 4 to illustrate how the ROI may be calculated for an actual PHM program and how the implementation costs can be estimated.

A business case evaluates the economic justifications for taking a given course of action, be it the decision to acquire a new technology, to remain with old technology, or to select among many alternative investment options. A business case is constructed for the scenario described in this chapter. Although PHM may be valuable to an organization seeking to improve its knowledge of electronic component reliability or to gather information for their design process, a maintenance planning application was chosen to determine the cost avoidance over a system life cycle.

The receptivity towards and established interest in PHM for avionics is such that prognostics have been termed a 'grail' to be sought [76]; the scenario for this business case considers the acquisition of PHM for a commercial aircraft by a major commercial airline. Much commercial aircraft business data is kept proprietary; when possible, data for the same type of aircraft was used to preserve consistency in the case study.

3.1. Implementation Costs

The implementation costs reflect a composite of technology acquisition cost benefit analyses (CBAs) and estimates for aircraft and for prognostics. The implementation costs are summarized in Table 4. All values are in base year 2007 dollars ($); any conversions to year 2007 dollars were performed using the Office of Management and Budget (OMB) discount rate of 7% [77]. The discount factor is calculated by (3.1).

$$Discount\ Factor = \frac{1}{(1+r)^n} \qquad (3.1)$$

in which,

r = the annual interest rate (the discount rate), and
n = the number of years.

An avionics display unit was selected as the base LRU. These components serve the critical tasks of displaying terrain maps, topographic maps, navigation data, and traffic information. A COTS product, the Sandel ST3400, featuring a high-resolution with full color in a single panel-mounted unit, was selected, with a base price of $25,000 (prices range depending on version and other features, [78]). Figure 5 illustrates the Sandel ST3400 as installed on a Boeing 737. Table 4 summarizes the investment cost data.

Figure 5. Sandel ST3400 in a Boeing 737 (identified in center), [79]

Patankar and Taylor supplied technology training cost information for a major airline that considered the cost of developing training materials and the cost of pulling users away from their regular job functions to attend training, [63]. This cost came to approximately \$250,000 for 191 maintenance employees; data from Southwest Airlines indicates that they had approximately 1,643 maintenance employees in 2006, [80]. Assuming that 70% of the maintenance workforce would have some activities involving PHM, the training cost would come to \$1,500,000 annually. The Bureau of Labor Statistics found that, on average, aircraft and avionics equipment mechanics and service technicians earned approximately \$23.00 per hour in 2006; typically, those working for major airlines tend to earn slightly more [81]. This figure was used in determining the inputs for the installation, assembly, and maintenance portions of the implementation costs.

Table 4. Implementation Costs

Implementation Costs		
Description	Cost ($)	Units
Recurring LRU-Level Costs		
Base Cost per LRU	$25,000	per LRU
Hardware	$25.00	per LRU
Assembly	$65.00	per LRU
Installation	$65.00	per LRU
Non-Recurring Engineering (NRE) Costs		
Hardware Development	$1,000,000	per fleet
Software Development	$200,000	per fleet
Integration	$200,000	per fleet
Documentation	$100,000	per fleet
Training	$1,500,000	per fleet
Testing and Qualification	$900,000	per fleet
Infrastructure Costs per Socket		
Maintenance of Prognostic Unit	$50.00	per year
Data Management	$200.00	per year
Decision Support	$100.00	per year
Continuous Education	$100.00	per year
Recurring System Level Costs		
Hardware	$65.00	per socket
Installation	$25.00	per socket

3.2. Maintenance Planning Costs

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 specialized facility). The maintenance costs in this model are assumed to be fixed; however, the effects of aging are known to produce increases in maintenance costs [82].

Koch, *et al*. give the maintenance cost per hour for a Boeing 737-100 or -200 series aircraft as $231 as 12% of the operating cost of $1,923 per hour, 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 [83]. 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, V_a, after the flight segments for the day have been completed.

The cost of unforeseen failures that require immediate attention during a flight can vary from scheduled maintenance costs 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 caught while the aircraft has not left the ground (when it still during a flight segment, 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 [84].

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 [85].

3.3. Operational Profile Data

The operational profile for the business 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 [86]. 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 [87]. A median airborne time for commercial domestic flights was approximately 125 minutes in 2001 [77]. A representative support life of 20 years was chosen based on [77]. A 45-minute turnaround time was taken as the time between flights based on the industry average [88].

Using this information, an operational profile was constructed whose details are summarized in Table 5. The operational profile data and the maintenance planning information were combined to determine the relationship between the operational mode cadence and the costs of maintenance, given in Table 6.

Table 5. Determination of Operational Profile

Factor	Multiplier	Total
7 flights per day	0.95(365 days per year) = 347 days per year	**2,429** annual flights
	125 minutes per flight	= **875** minutes in flight per day
Support life: 20 years	(2,429 flights per year)(20 years)	= **48,580** flights over support life
45 minutes turnaround between flights	6 preparation periods per day (between flights)	= **270** minutes between flights/day
875 minutes in flight/day	875/(1440 minutes/day)	= **61**% during flight, P_d
270 minutes between flights per day	270 minuts/1440 minutes/day	= **19**% between flights, P_b
'after flight' time per day	= 1- P_d – P_b	= **20**% after flights, P_a

Table 6. Unscheduled Maintenance Costs and Modes

Mode	Probability	Value *V*
Maintenance event before mission (during preparation)	$P_b = 0.19$	V_b = \$2,880 per hour
Maintenance event during mission	$P_d = 0.61$	V_d = \$5,092 (mean of range in [85])
Maintenance event after mission (during downtime)	$P_a = 0.20$	V_a = \$228.48 per hour

3.4. Reliability Information

Reliability data was based on [89] and [90], which provide models of the reliability of avionics with exponential and Weibull distributions, commonly used to model avionics [76]. The assumed TTF distribution of the LRUs is provided in Figure

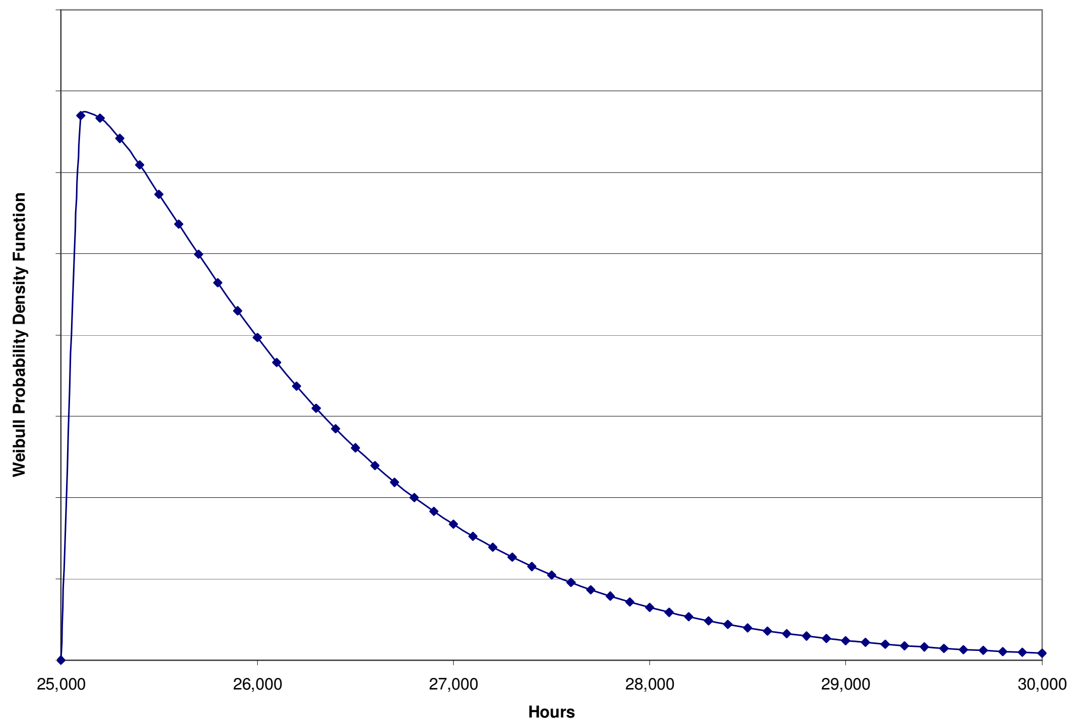


Figure 6. Weibull Distribution of LRU TTF, Case 1 (β = 1.1, η = 1,200 hours, α = 25,000 hours)

6. In an analysis of over 20,000 electronic products built in the 1980s and 1990s, Qin *et al.* [91] show that Weibull distributions with shape parameters close to 1, i.e., close to the exponential distribution, are the most appropriate for modeling avionics.

Upadhya and Srinivasan, [92], model the reliability of avionics with a Weibull shape parameter of 1.1, consistent with the common range of parameters found in [91]. Although Qin *et al.* [91] found exponential distributions to be the most accurate, failure mechanisms associated with current technologies, Condra [93] suggests that the Weibull may prove to be more representative for future generations of electronic products. The location parameter, α, was chosen to be consistent with assumption within the aerospace industry that a typical avionics LRU will last for approximately 10 years of use, [91]. The scale parameter, η, was selected as 1,200 hours based on

[90], which supplied representative examples of Weibull distributions of the TTFs of various electronic products.

However, larger shape parameters (i.e., closer to the Gaussian distribution) in excess of β > 2 were found to be appropriate for electronic components with multiple failure modes [94]. To examine the relationship between the TTF distribution of the LRU and the ROI, a separate analysis was performed using a shape parameter, β, of 3.0, a location parameter of 0.0, and a scale parameter of 25,000 hours. These Weibull parameters have failures distributed more normally over time and are consistent with the case study in [89]. Figure 7 displays the TTF distribution for the first alternative analysis, and Figure 8 displays the TTF distribution for the first case with a shape parameter of 2.

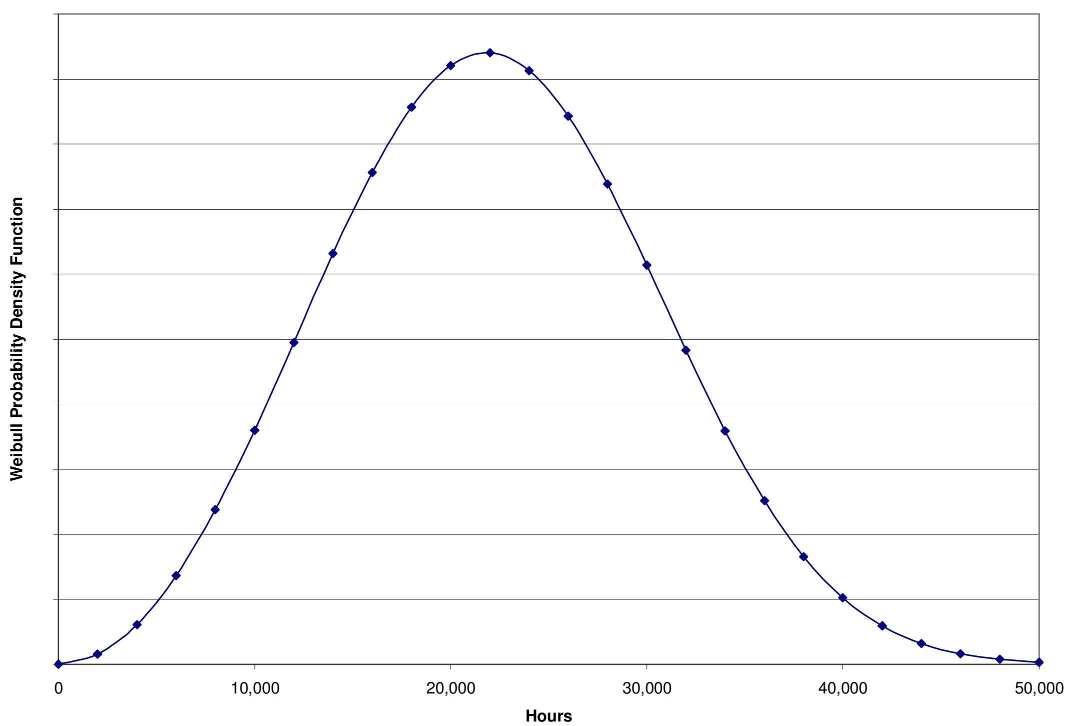


Figure 7. Weibull Distribution of LRU TTF, Case 2
(β = 3, η = 1,200 hours, α = 0)

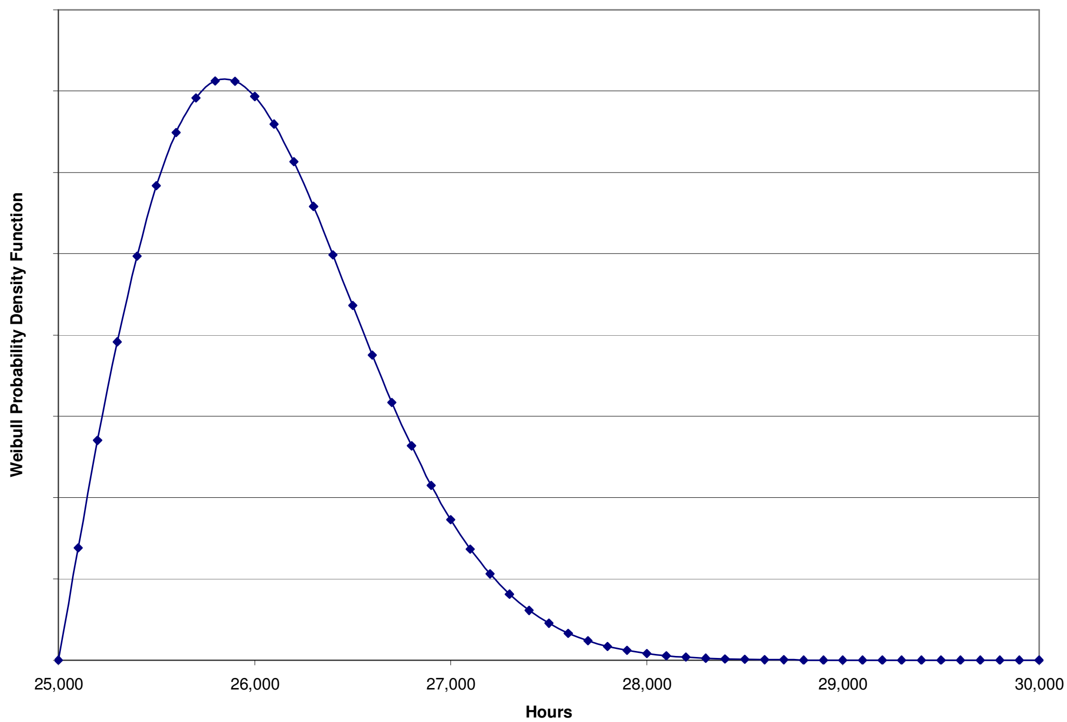


Figure 8. Weibull Distribution of LRU TTF, Case 3
(β = 2, η = 1,200 hours, α = 25,000 hours)

As a system containing multiple electronic components, the PHM structure itself has a reliability profile. In the case of a canary device, the TTF may be deliberately selected to be small with respect to the LRU TTF. However, it is assumed that the electronic components of the PHM structure are less complex than those of the LRU, and, when combined, also have predictably consistent TTFs. In order to allow for variability while utilizing a simple, symmetrical TTF distribution, the TTFs of the prognostic structures were modeled as triangular distributions with a width of 500 hours. Figure 9 illustrates the concept of prognostic distance as it is used by PHM approaches.

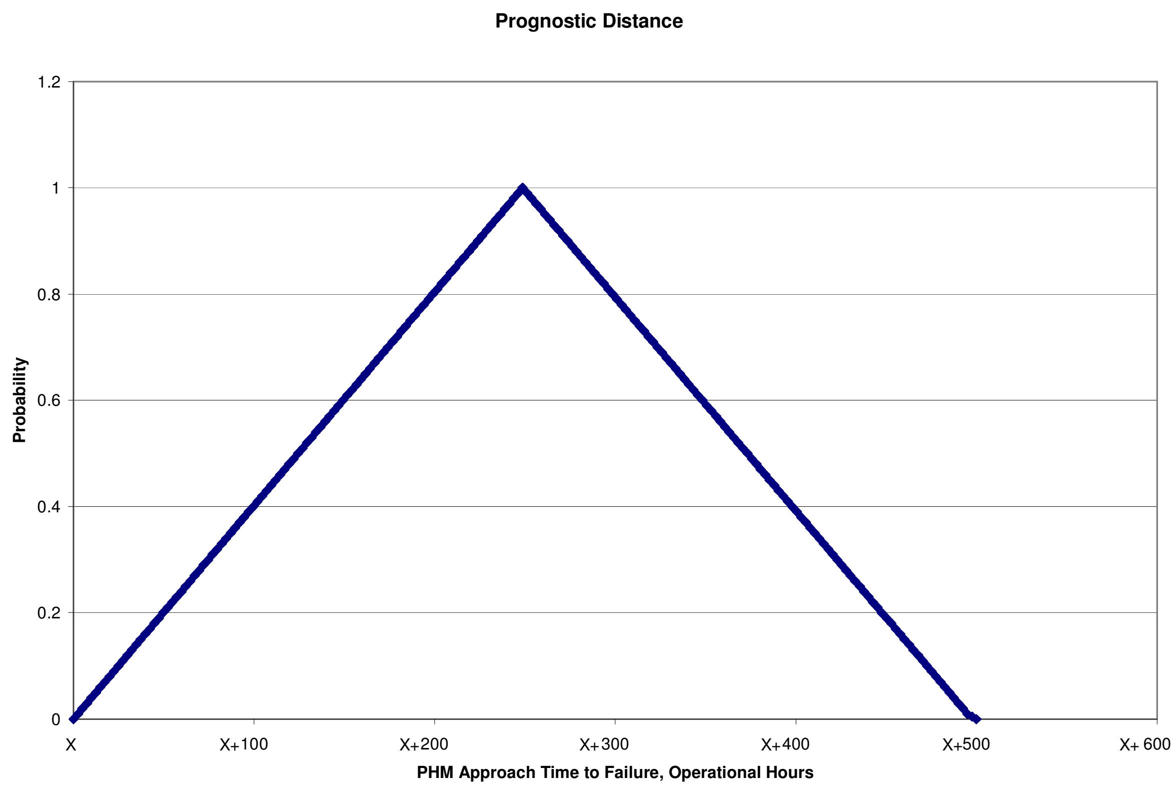


Figure 9. Prognostic Distance for PHM Approach Sustainment Distribution

3.5. Additional Data

The fleet size was chosen to reflect the possible quantities involved for a technology acquisition by a major airline. To maintain consistency with maintenance cost data, the same type of aircraft, the Boeing 737, was chosen. Southwest Airlines has a fleet of 502 Boeing 737s, with 194 737-300-series aircraft, 25 Boeing 737-500s, and 283 737-700s [86]. It is assumed that the airline wishes to retrofit all of their aircraft with PHM. Although aircraft may have multiple display units serving different purposes, it was assumed that each aircraft would have two sockets each dedicated to a Sandel display unit, for a total of 502 aircraft and 1,004 display units.

3.6. Remarks

The data for the analysis case was selected in order to be representative of a contemporary and realistic candidate PHM program. The potential applicability of PHM to the commercial airline industry is apparent in the public familiarity with the problems caused by, but not limited to, maintenance issues. Delays, re-routings, and cancellations of flights are among the tangible and readily visible aspects of traditional maintenance approaches. The data selected for this analysis, including the representative component cost data, maintenance costs, and operational profile, were chosen based on available information from actual programs and flight cadences.

Chapter 4: Case Analysis and Results

4.1. Case Simulation

Following the method described in Chapter 2, and utilizing the data from Chapter 3, business cases were developed for Precursor to Failure and LRU-Independent approaches. This chapter outlines how the analysis was performed and presents the results.

4.2. Optimization of the Prognostic Distance and Safety Margin

For each PHM approach, a sensitivity analysis was performed to determine the prognostic distance that resulted in the lowest total cost. These costs are dependent on the combination of PHM approach, implementation costs, reliability information, and operational profile assumptions and inputs. In comparing the ROI of PHM approaches, the prognostic distance or safety margin that minimized costs were used so that neither approach would have an 'unfair advantage.' Figures 10 and 11 display the relationships between the prognostic distance or safety margin and the total cost for Precursor to Failure and LRU-Independent (Life Consumption Monitoring) approaches, respectively. Table 7 lists the reliability profiles employed. For the first LRU TTF (Case 1), using the Precursor to Failure approach, a prognostic distance of 485 hours yielded the minimum life cycle cost over the support life; for LRU Independent approaches, the safety margin was 490 hours. For the case when β = 3, the prognostic distance for the Precursor to Failure approach was 470 hours, and the safety margin for the LRU Independent approach was 300 hours.

Table 7. Reliability Profiles

Case	Location Parameter, Operational Hours	Shape Parameter	Scale Parameter, Operational Hours
1	25,000	1.1	1,200
2	0	3	1,200
3	25,000	2	1,200

The prognostic distance and safety margin cannot be called truly optimized distances as they are not integrated within other logistics or scheduling constraints and cannot be said to produce the lowest cost on a per-LRU basis at each LRU replacement step across the system support life. They do, however, illustrate that PHM can be useful *within* a schedule: when the prognostic distance or safety margin is overly narrow, there is little time to react and thus cost avoidance opportunities are limited; when the prognostic distance or safety margin is too large, maintenance is performed too soon, losing RUL.

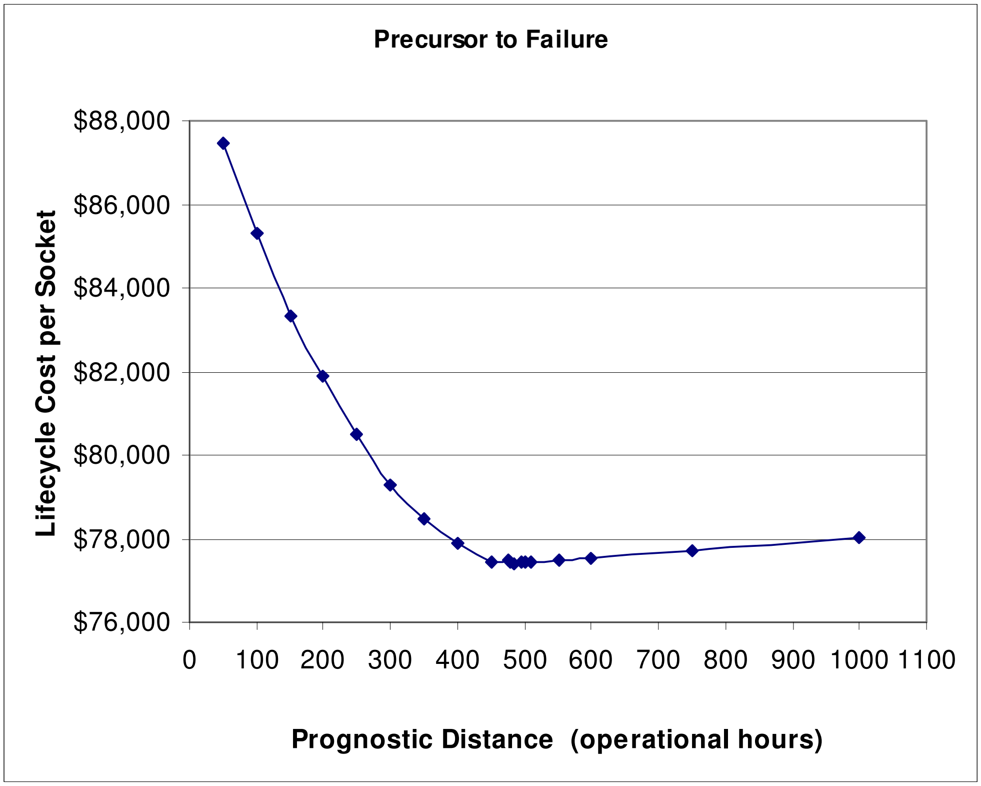


Figure 10. Prognostic Distance for the Precursor to Failure PHM Approach

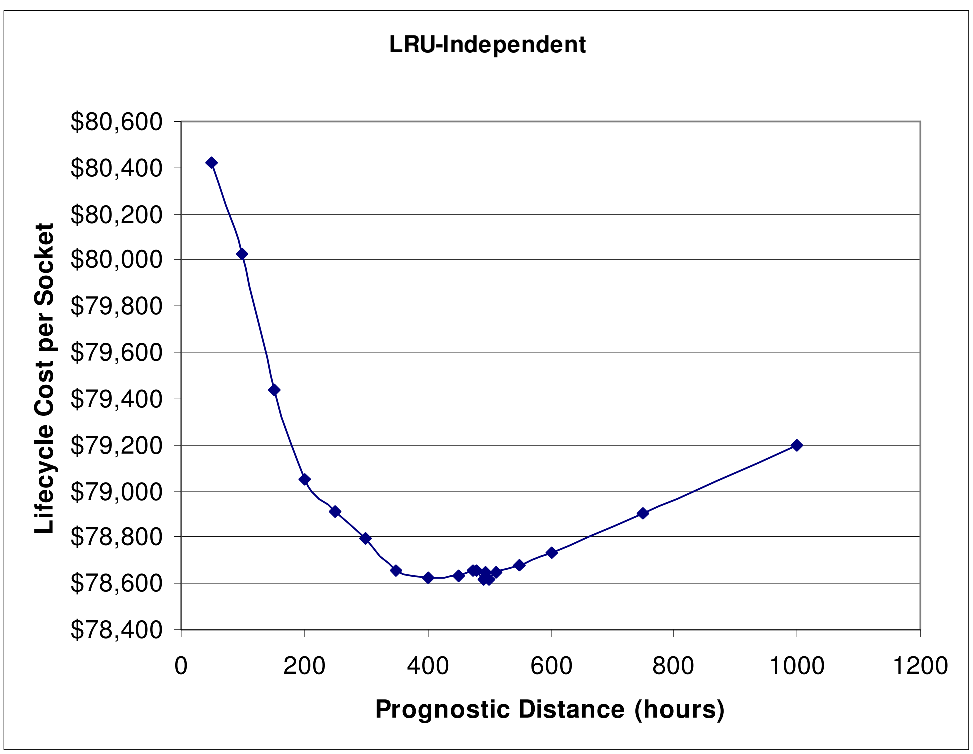


Figure 11. Safety Margin for the LRU Independent PHM Approach

4.3. Lifecycle Cost Accumulation

Following the determination of the prognostic distance or the safety margin, the lifecycle costs were determined for each PHM approach. Figures 12 and 13 illustrate the accumulation of cost over the support life for each PHM approach when $\beta = 1.1$ Figures 14 and 15 display the cost accumulation for the second LRU TTF distribution when $\beta = 3$. Each large jump in cost reflects the replacement of the LRU, while smaller steps represent the charging of the infrastructure costs on an annualized basis and are scaled by the discount rate. One time history line appears on the graph for each of 1000 sockets simulated. The beginning of the time history prior to the first replacement of the LRU displays one small step in cost for each year of infrastructure cost.

On average, 5.98 LRUs were used over the 20 year period following Precursor to Failure PHM, and 6.0 LRUs were used under LRU-Independent PHM for the case when $\beta = 1.1$. For the case when $\beta = 3$, approximately 6.96 LRUs were used under Precursor to Failure and 8.0 LRUs were used under LRU-Independent PHM. These results are expected based on the broader distribution of failures with a Weibull distribution closer in shape to a Gaussian and with a location parameter of zero, spreading failures from the beginning of support life onwards. It would also be expected that the LRU-Independent Approach, relying on PHM structures that lack the intrinsic characteristics of the LRU they are monitoring, would perform worse; i.e., call for more LRU replacements than actually needed.

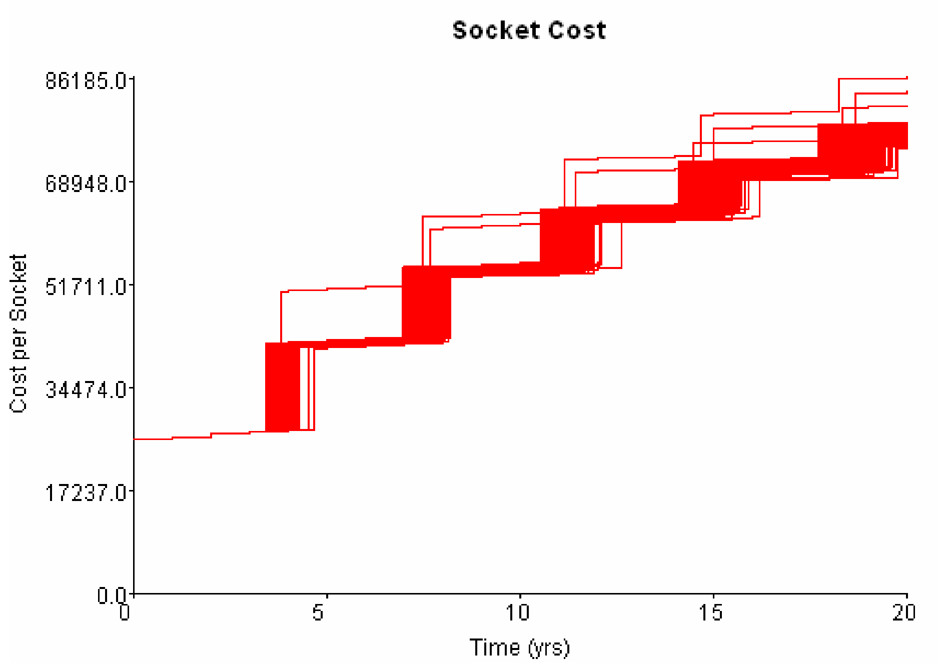


Figure 12. Lifecycle Cost, Precursor to Failure, Case 1

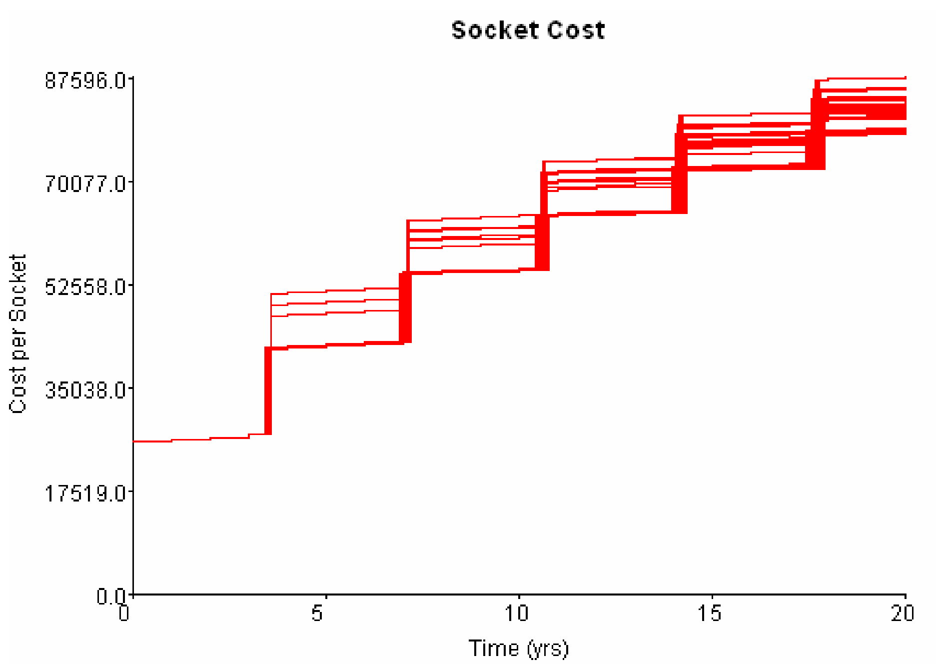


Figure 13. Lifecycle Cost, LRU-Independent, Case 1

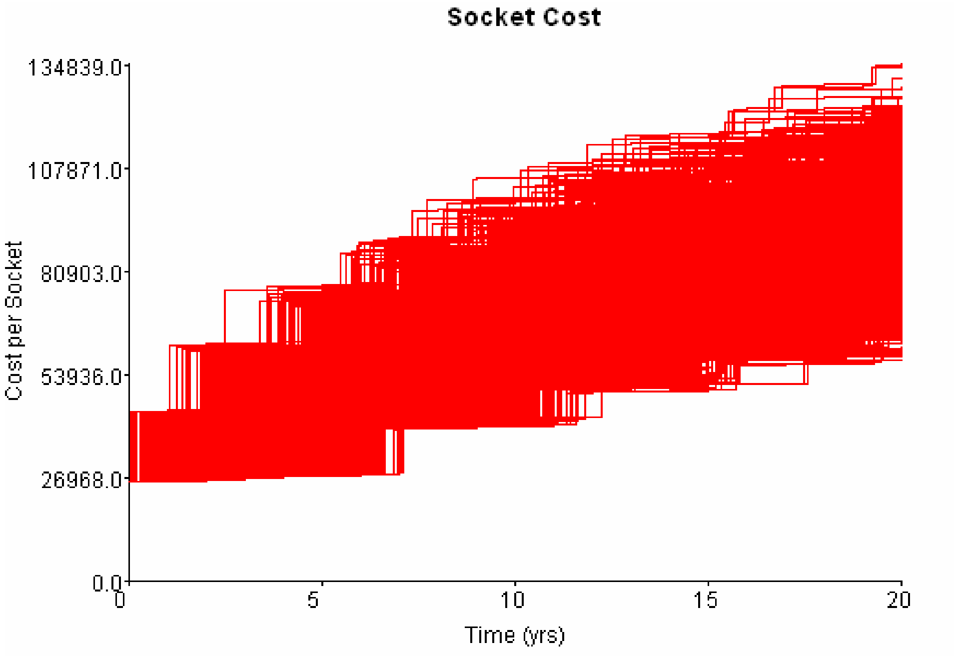


Figure 14. Lifecycle Cost, Precursor to Failure, Case 2

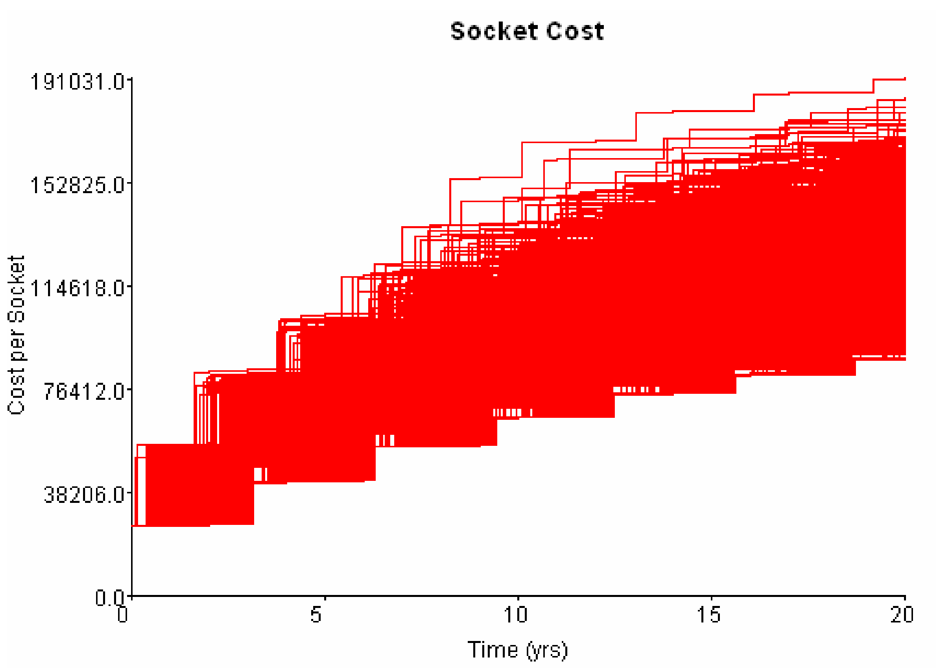


Figure 15. Lifecycle Cost, LRU-Independent, Case 2

The lifecycle cost (time history) plots indicate increased variation in the socket histories when the LRUs had a wider TTF distribution. The homogeneity or consistency of the socket histories —the location of the LRU replacements, the accumulation of cost, and the striations in the graphs— visible in Figures 12 and 13 are in contrast to the multitude of PHM solutions apparent in Figures 14 and 15. The striations that are consistently above the majority of the solutions indicate where the PHM solution did not detect a failure and was penalized.

4.4. Return on Investment Analysis

The ROI was examined as a function of the annual infrastructure cost of PHM. These costs represent the largest portion of the investment costs that are unique to PHM approaches and thus represent a variable of interest against which to calculate ROI. Decision makers have budgetary constraints on the resources that can be committed to PHM; the small recurring costs per LRU used in the case were found to not be as influential on the ROI as the annual infrastructure costs. Figures 16 and 17 display the tradeoffs between ROI and annual infrastructure cost for $\beta = 1.1$; the ROI was calculated to be 3.133 using Precursor to Failure and 2.941 using LRU-Independent PHM. Figures 18 and 19 are for the case when $\beta = 3$; the ROIs were calculated as 2.093 using Precursor to Failure and -0.597 using LRU-Independent PHM. For Case 3, ROI values were lower than Case 1 values but higher than Case 2 values, with an ROI of 3.045 for the Precursor to Failure Approach and 2.504 for LRU-Independent PHM.

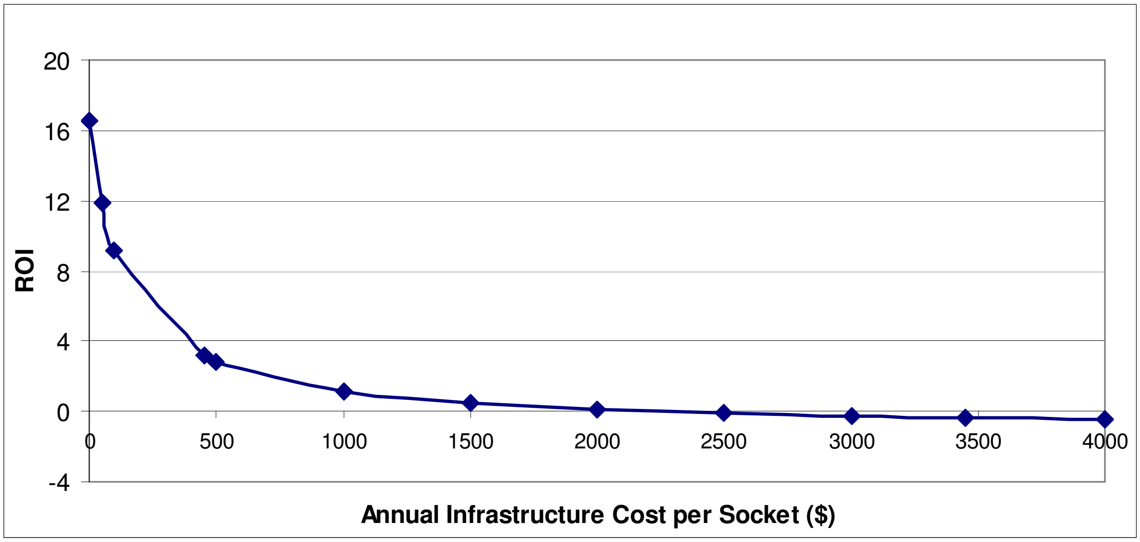


Figure 16. ROI Analysis, Precursor to Failure, Case 1

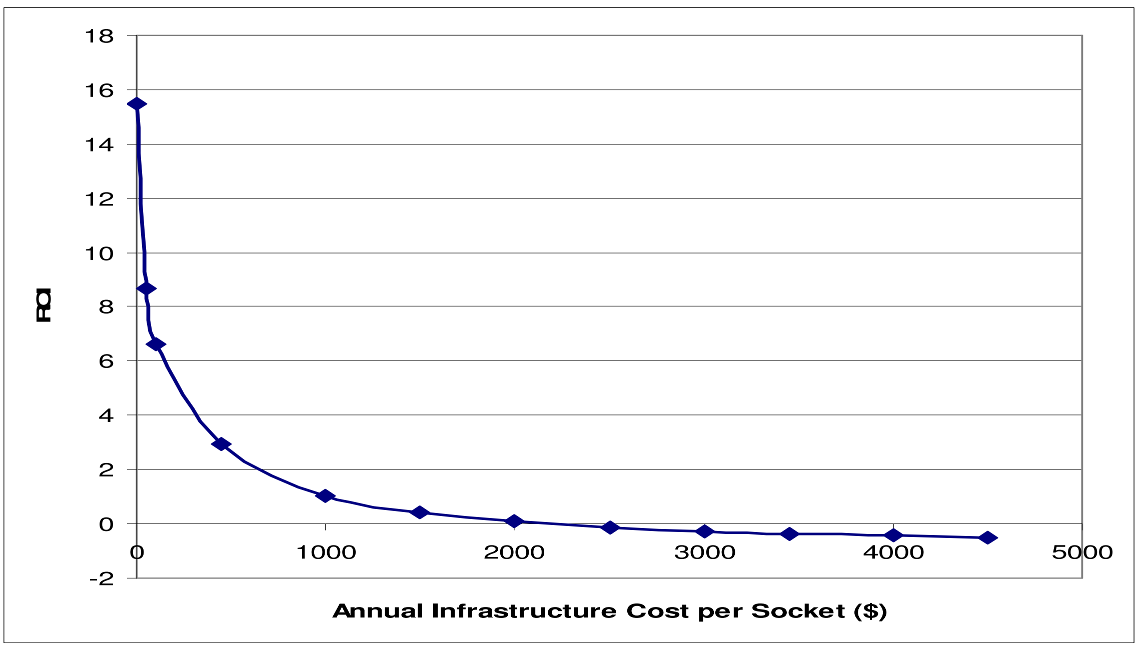


Figure 17. ROI Analysis, LRU-Independent, Case 1

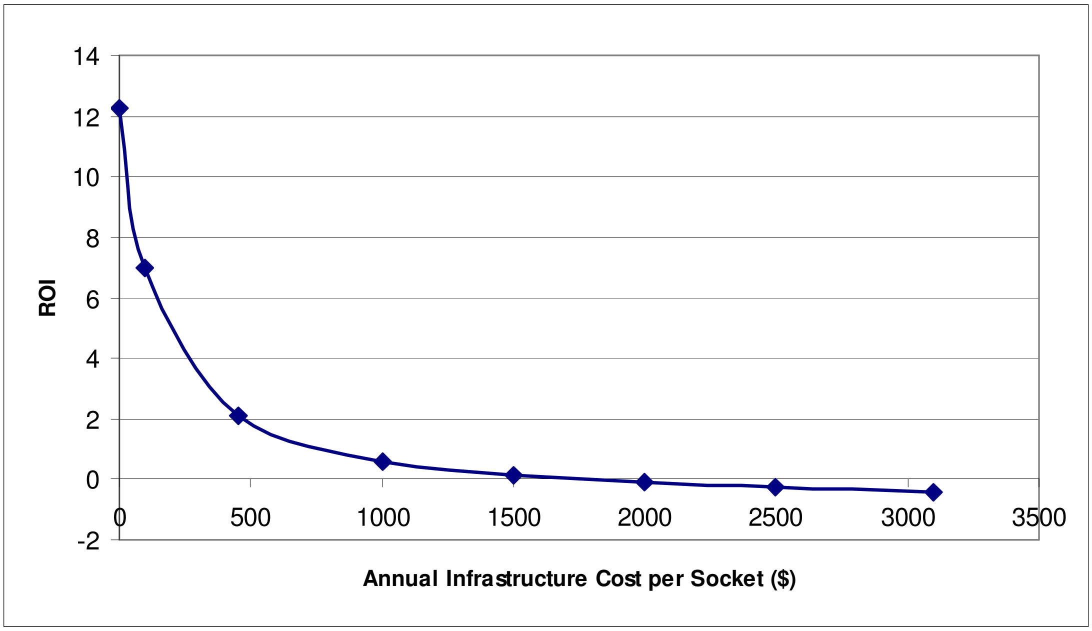


Figure 18. ROI Analysis, Precursor to Failure, Case 2

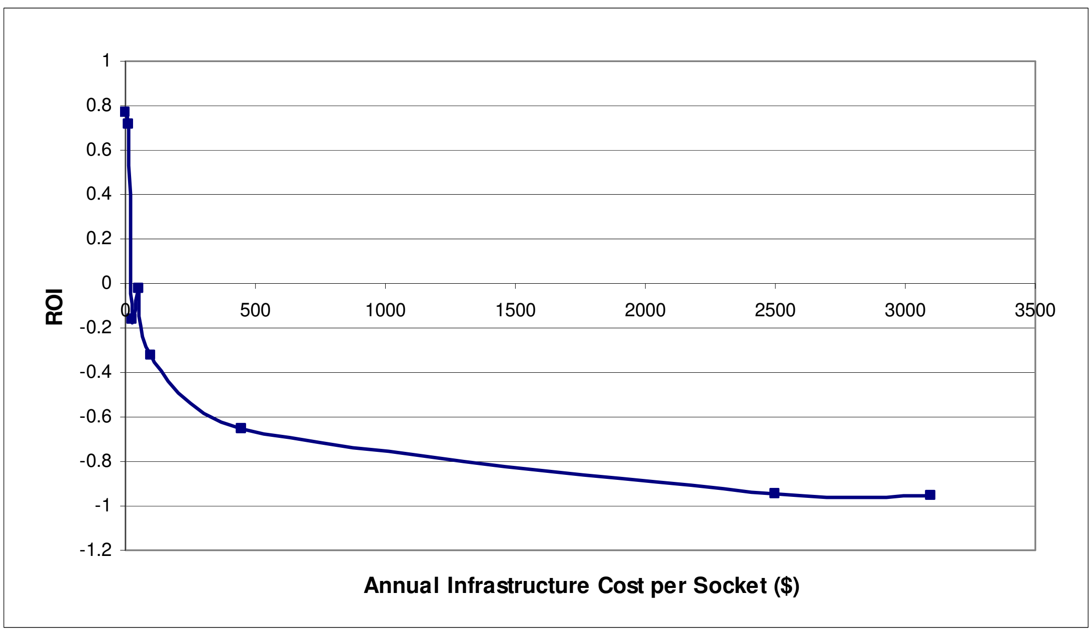


Figure 19. ROI Analysis, LRU-Independent, Case 2

The results show that the ROI of PHM was greatest for the LRU TTF distribution with the shape parameter closest to the exponential, and in which the failures do not commence at the beginning of the support life. When the LRU TTF distribution was wider and failures were more scattered and less predictable, ROIs were consistently lowered. As expected, in both instances, LRU-Independent PHM was inferior to the Precursor to Failure approach ([56] drew this general conclusion). For the larger shape parameter, this behavior was manifested by the breakeven point occurring almost immediately once the annual infrastructural costs grew. Figure 19 indicates that for this particular combination of LRU reliability and PHM approach, a positive ROI would be unrealistic.

4.5. Factors Influencing ROI

The inclusion of two TTF distributions with different Weibull parameters indicates that PHM is highly sensitive to the LRU reliability. However, the width of the PHM approach is also a factor that can determine whether the PHM is indicating maintenance in a timely, pre-emptive manner, whether it is wasting RUL, or whether it misses a required maintenance event entirely. In the analysis, the selected PHM sustainment approach was a symmetrical triangular distribution with a width of 1,000 hours. These results were compared to a PHM distribution width of 3,000 hours, ranging from 1,500 to 4,500 hours. For Precursor to Failure Monitoring, the narrower PHM width produced higher ROI than the wider one; this was expected due to the higher precision. The PHM approach with a width of 3,000 hours could sample its distribution and select a maintenance interval up to 1,500 hours before or after the expected time of the maintenance event. Figure 20 reveals that the LRU-Independent PHM was consistently unlikely to yield a positive ROI irrespective of the PHM width.

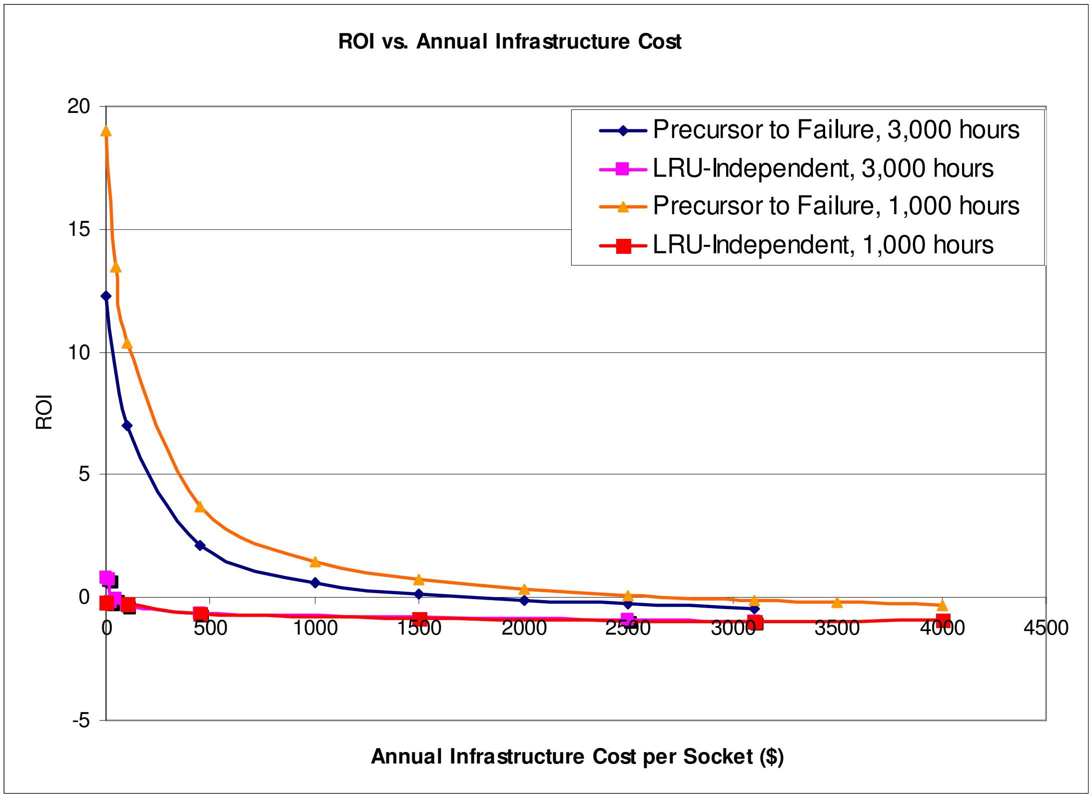


Figure 20. Effect of PHM Width on ROI
Precursor to Failure Monitoring, Case 2

To examine further the effect of the LRU TTF on ROI, the analysis was repeated for TTFs of various location parameters. Figure 20 displays results for TTFs with location parameters, α, of 5,000, 15,000, 25,000, and 35,000 operational hours. The relationship between ROI and the annual infrastructure cost was calculated as a function of location parameter for PHM solutions costing $100, $450 —the baseline case for previous analyses— and $1,000 annually. While the ROI is highest for the PHM solution with the lowest annual infrastructure cost, each of the three solutions exhibited the same behavior as α increased. As α increased, ROI decreased, and the difference in ROI for each of the three costs narrowed. In general, contemporary microelectronics are highly reliable; gains from using PHM would not be expected for LRUs that typically do not experience failures until late in their support lives. The ROI may have begun converging as the TTF location parameter increased because beyond a certain number of operational hours, PHM is of limited utility. This phenomenon is characteristic of a threshold after which there are only diminishing returns; i.e., even when there is still a positive ROI to be had, it either plateaus or declines.

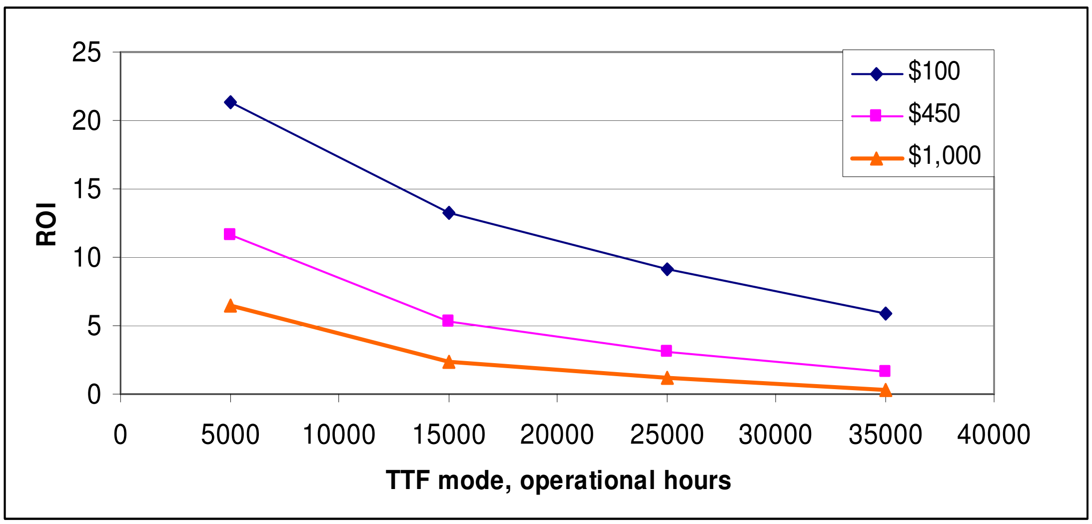


Figure 21. ROI vs. Annual Infrastructure Cost Precursor to Failure Monitoring, Case 1

The relationship between ROI and lifecycle cost was explored. It was found that for the same case data, the lowest ROI on any given run of the simulation did not necessarily correspond to the lowest lifecycle cost per socket. This was assessed by using twenty different prognostic distances for the Precursor to Failure approach and twenty different safety margins using LRU-Independent PHM methods and comparing the ROIs and lifecycle cost results in the set. It was then confirmed by running the simulation with the prognostic distances or safety margins used in the base case and analyzing the outputs from twenty runs of the simulation. This could potentially be due to the presence of factors such as the operational profile -- more LRUs may have been replaced than needed following a PHM solution, for instance, which would increase the lifecycle costs, yet these maintenance actions may always have been done at times that minimized the amount of RUL thrown away. Conversely, the ROI could have been compared against an unscheduled maintenance program in which failures and subsequent maintenance actions occurred during downtime. Such possibilities could give rise to a case where the highest ROI from multiple runs of the simulation would not correspond to the lowest lifecycle cost. However, Figure 21 shows that on average, ROI decreased as lifecycle cost increased for both PHM approaches.

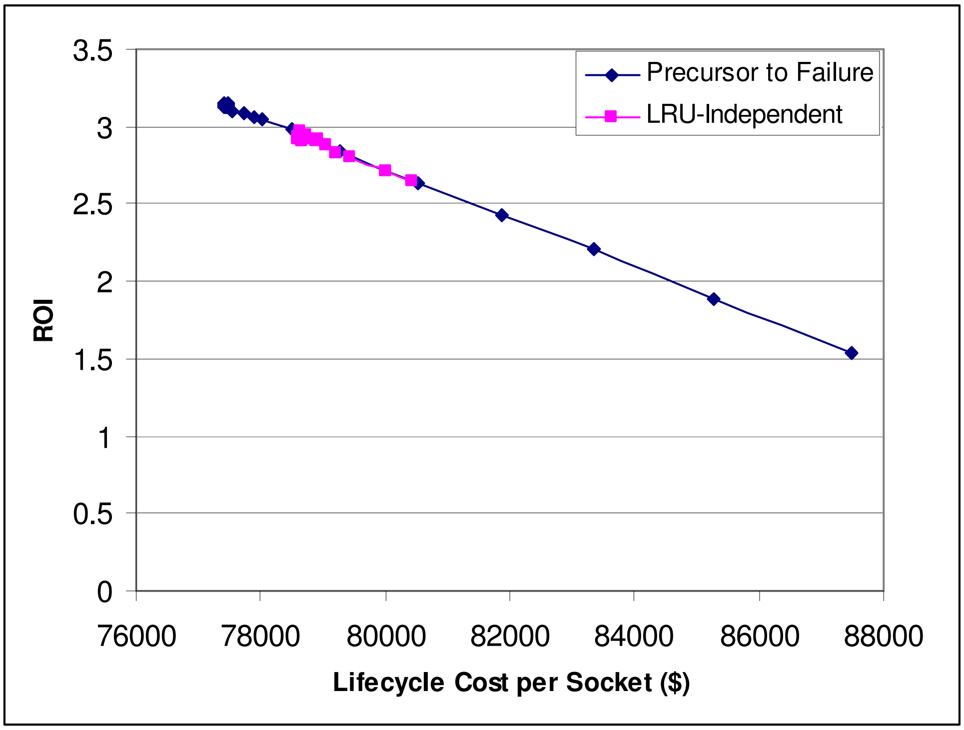


Figure 22. ROI vs. Lifecycle Cost per Socket, Case 1

Lastly, the PHM approaches were compared to Fixed Interval Maintenance. With Fixed Interval Maintenance, if the TTF distribution of the LRU is narrow (i.e., TTF highly predictable), the maintenance interval (i.e., the width of the fixed interval) can be selected in a way that PHM approaches are highly unfavorable. If the LRU TTF is highly likely to occur at 10,000 hours, performing maintenance when convenient and shortly before this time period is extremely advantageous; it would be hard to justify PHM for such an instance. Figure 22 displays a typical relationship between lifecycle costs and the maintenance interval for the distribution in which failures were tightly clustered around α = 25,000 hours. Lifecycle costs are significantly higher than when using PHM; however, the ROI of fixed interval is consistently higher because the implementation costs of PHM are not factored in.

Once the maintenance interval exceeds the TTF, all maintenance becomes unscheduled maintenance and the costs exhibit a plateau. However, for a different LRU TTF in which maintenance could not be as accurately predicted, Precursor to Failure PHM outperformed fixed interval maintenance, shown in Figure 23. An exponential distribution with λ = 20,000 hours was selected. LRU-Independent PHM did not yield a positive ROI; however its resulting ROIs, though negative, were smaller in magnitude than the Fixed Interval Maintenance.

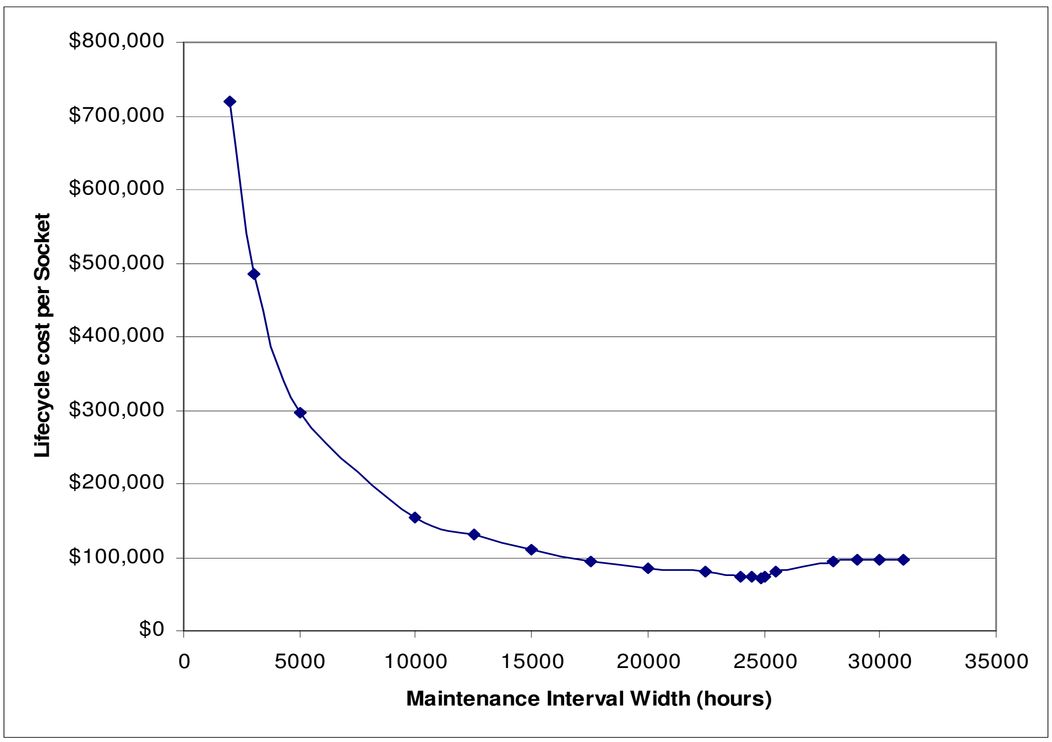


Figure 23. Fixed Interval Maintenance

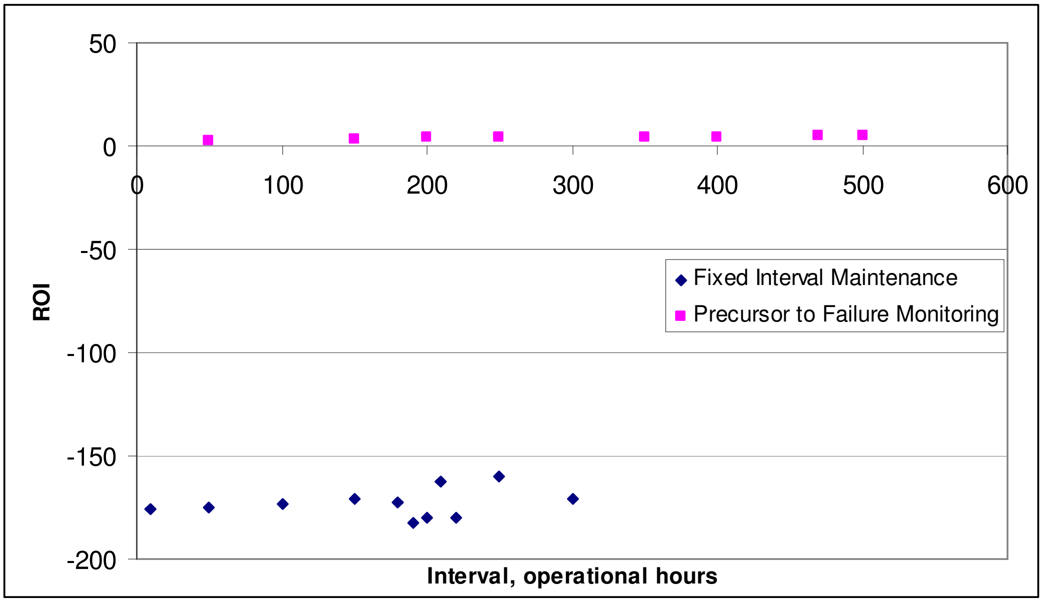


Figure 24. Fixed Interval Maintenance vs. PHM (Note: The interval for Precursor to Failure Monitoring was the prognostic distance used; for Fixed Interval, it was the width of the maintenance interval, divided by a factor of 100 hours on the plot)

4.6. Summary

The case developed in Chapter 3 was analyzed using two different reliability profiles for the LRU. The reliability profile in which Times to Failure were more tightly concentrated was more favorable to PHM than the one in which failures were spread in a more Gaussian distribution across time; however, in both instances, Precursor to Failure monitoring produced positive ROIs. LRU-Independent PHM approaches did not produce as high a ROI as Precursor to Failure, nor did they produce positive ROIs for the latter distribution. ROI was found to be strongly controlled by the reliability profile and affected by the PHM sustainment width and the annual infrastructure cost driver.

Chapter 5: Conclusion

An implementation cost model was integrated with a maintenance planning model to determine the ROI of PHM. A case was developed to analyze the ROI of adapting PHM for avionics. The ROI of using two types of PHM approaches was evaluated. Results indicate that the ROI of Precursor to Failure monitoring is superior to the ROI using LRU-Independent methods. These results are application specific and not applicable to particular avionics LRUs or to groups of mixed LRUs.

5.1. Summary of Contributions

The contributions of this research include:

- The development of a stochastic model for the implementation costs associated with PHM
- The construction of a framework for integrating implementation costs and maintenance planning
- The calculation of ROI to provide meaningful input to acquisition decision-makers, and
- The development of a case analysis to provide insight into the ROI of PHM as applied to avionics used in commercial aviation.

5.2. Areas for Future Research

A major focus of the DoD is the move towards Performance Based Logistics (PBL), which emphasizes the achievement of system readiness. Availability is a key metric examined in PBL; PHM can serve as a maintenance methodology that enables achievement of a specified availability. The path forward for a broader analysis of ROI should include an examination of availability as the ‘return,’ and the relationship between monetary returns and availability.

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 precursor to failure and life consumption monitoring approaches; they may not be consistent with the ROI of using alternative methods and are not specific to a particular PHM device. The analysis could be extended to mimic actual systems to include mixed support lives, not good-as-new repair, and other situations encountered in maintenance. Inputs that are currently entered into the model as static variables or as fixed probabilities, such as the operational profile, could be extended to include probability distributions. A distribution of ROI could be calculated for a given set of inputs.

Appendix: Prognostic and Health Management Return on Investment Tool User's Guide, Version 2.0

1 - Introduction

This document is the user's guide for the CALCE PHM (Prognostics and Health Management) ROI (Return On Investment) analysis software tool. The tool is a stochastic discrete event simulation that can follow the life history of a population of one or more LRUs (Line Replaceable Units) and determine the effective lifecycle costs, availability and failures avoided for sockets.[5] In discrete-event simulation, the operation of a system is represented as a chronological sequence of events. Each event occurs at an instant in time and marks a change of state in the system. The PHM ROI simulator follows individual sockets through their support lives. In order to capture uncertainties in the characteristics of LRUs and in the operation of PHM structures, the simulator follows a population of sockets and determines distributions of lifecycle costs and availabilities.

The formulation of the models used to represent various PHM approaches are contained within [56] and provided as an Appendix to this manual. One important attribute of most business cases is the development of an economic justification. Return on investment (ROI) is a useful means of gauging the economic merits of adopting PHM. 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.

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

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 including the possible cost of purchasing additional Line Replaceable Units (LRUs) due to pre-failure replacement of units; while the avoided cost is a quantification of the benefit realized through the use of a PHM approach.

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

[5] A socket is a unique instance of an installation location for an LRU. For example, 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.

some cases the value of PHM is not easily 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.

2 – Tutorial

This tutorial provides an example that includes creating two different LRUs and analyzing them individually and concurrently to determine the lifecycle cost of the system. It also provides an example of how to save the design to a file. This tutorial assumes that the user is either running an application version of the tool or has accepted the security certificate presented when they entered the web page containing the applet version of the tool.

1) Start the PHM Decision Support Tool. You should obtain an interface like the one shown in Figure 1.
2) Fill out the interface to represent LRU#1 as shown in Figure 2. Note, set the Monte Carlo to "Yes" and choose the sustainment approach first in order to enable all the fields needed to enter the remaining data. Press <OK> in the "Solution Control Details" dialog box after setting Monte Carlo to "Yes".
3) Place the cursor into the "Time to Failure (operational hours)" field and press the <Enter> key to obtain the distribution dialog box and enter the time to failure distribution as shown (also shown in Figure 2). Press <OK> in the "Distribution Details" dialog boxes to close them after setting the data.

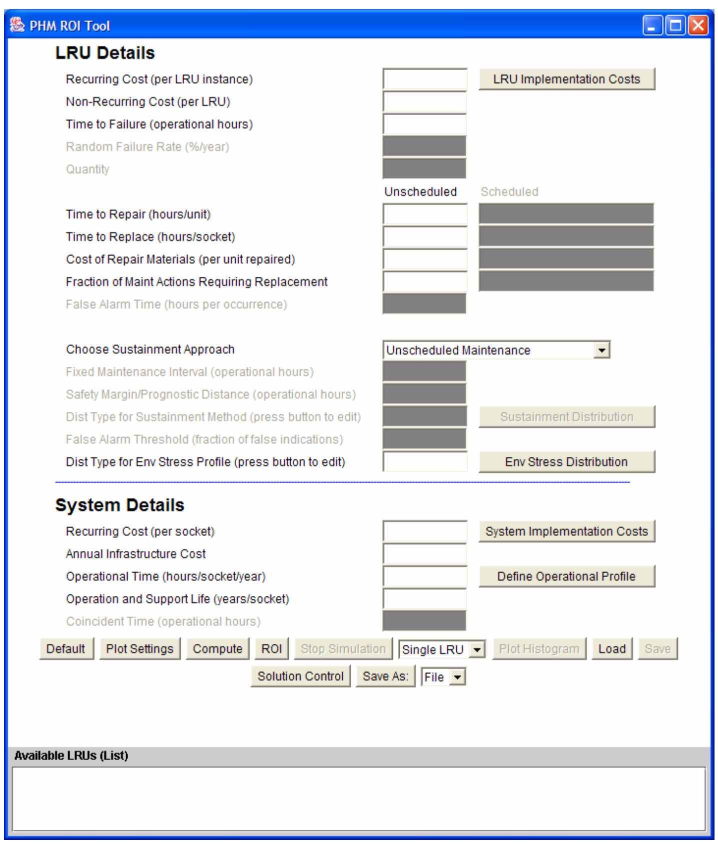


Figure 1 – Initial appearance of PHM ROI tool.

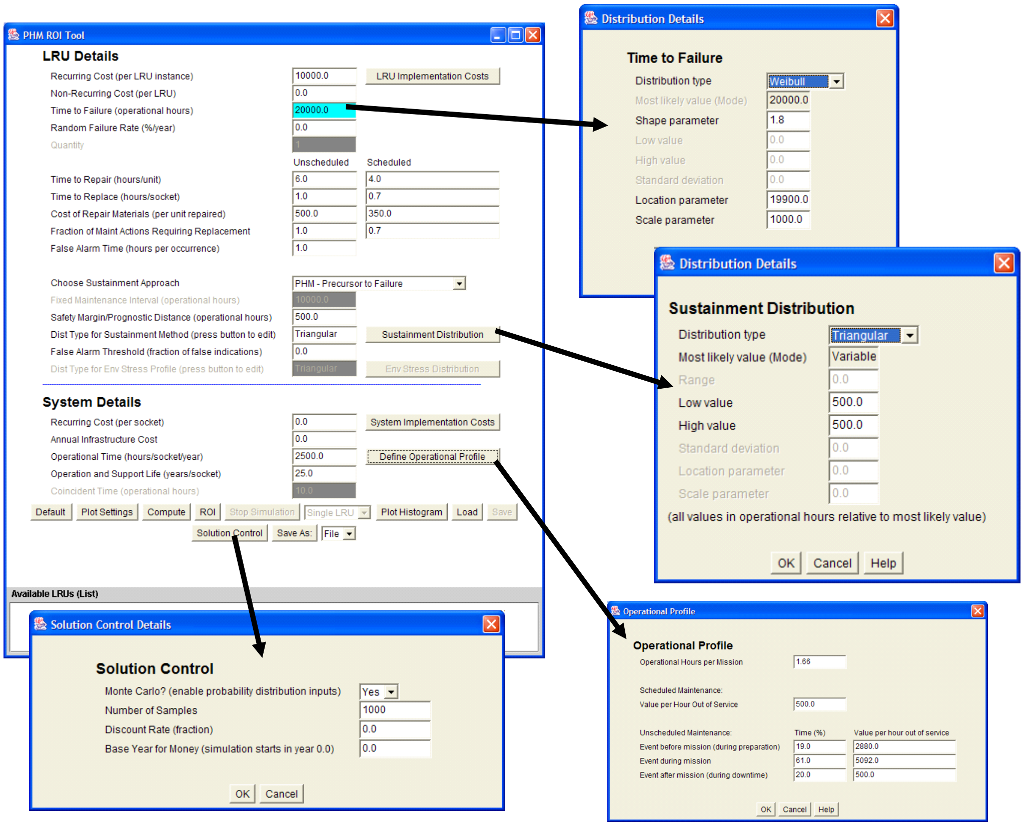


Figure 2 – Data entered to represent LRU#1.

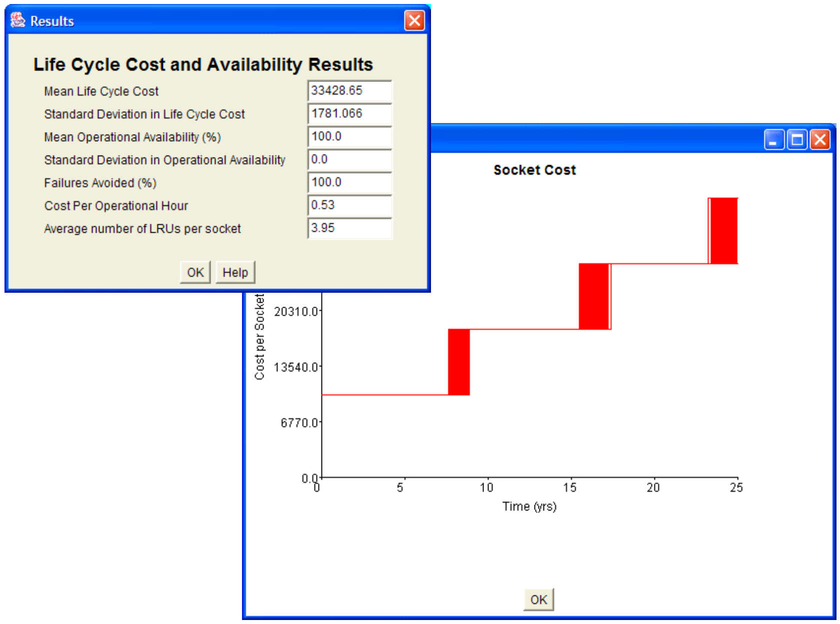
4) Initiate the plotting preferences by pressing the <Plot Settings> button and selecting "Yes" for "Plot Socket Costs?". Press <OK> to close the "Plot unit costs dialog box.

5) Run an analysis of this LRU by pressing the <Compute> button. Select any color you like for the plot when the dialog box appears. A results dialog will appear (Figure 3). Your numbers will be slightly different (and change a bit each time you run the analysis) because it's a stochastic analysis.

6) To save the LRU press the <Save As>. A file dialog will appear where you can enter the name of the file to save the LRU in. Note the file name you enter must end in ".xml". The name of the LRU will appear in the "Available LRUs" box at the bottom of the interface.

7) Now enter data for the second LRU. Fill out the interface to represent LRU #2 as shown in Figure 4. You can just type over the LRU#1 data.

8) When you have finished entering the data, press <Save As> (with "LRU" showing in the adjacent box) and enter a new name for LRU#2. The name of the LRU will appear in the "Available LRUs" box at the bottom of the interface.



9) Notice, you can select either LRU in the “Available LRUs” box at the bottom of the interface and the data in the interface changes to describe the selected LRU.

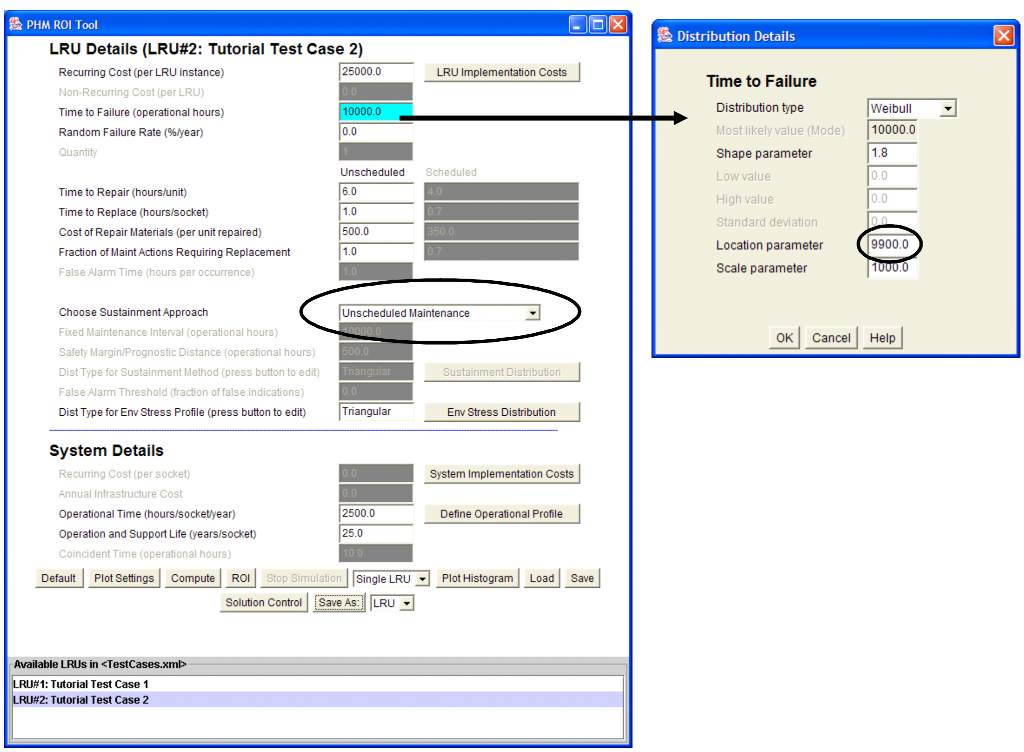


Figure 4 – Data for LRU#2 (note the screen capture above was made after Step 7).

10) Press the <Plot Settings> button and change the "Plot Separately?" to "No".

11) To run an analysis that includes both LRUs, click on the choice box next to the <ROI> button and select "Multi LRUs". You must now enter a value for the "Coincident Time" (put in 1000.0). Press the <Compute> button and select both LRUs to be analyzed in the dialog box (Figure 5).

12) The analysis will run and generate a plot and results dialog just like the single LRU analysis – again, you won't get exactly the results shown in Figure 6 due to the stochastic nature of the analysis.

13) Suppose we wish to make a change to LRU#1 and rerun the analysis. Select LRU#1 from the Available LRUs list; make the data change in the interface (e.g., change the Location Parameter for the Time to Failure from 19900.0 to 8000.0). PRESS THE <Save> BUTTON – NOTE, THIS SAVES THE CHANGE IN YOUR DATA FILE AND IT ALSO RECORDS THE CHANGE FOR THE MULTI-LRU ANALYSIS. Press <Compute> and the new solution is generated – Figure 7.

3 – Field and Button Reference

This section documents all the buttons and fields in the PHM ROI tool. The inputs to the tool are divided into the following two types:

> LRU Details – LRU specific inputs for the LRU selected in the "Available LRUs (List)" at the bottom of the tool interface. If no LRUs appear in the "Available LRUs (List)" then only a single LRU is defined.
>
> System Details – Inputs that describe the lifecycle environment that the LRU(s) are in.

3.1 LRU Details

The LRU Details are shown in the top two thirds of the tool interface shown in Figure 1.

> Recurring Cost (per LRU instance) – The recurring cost per LRU where recurring refers to costs that recur for every instance of the LRU installed in a socket. This should include the recurring cost of implementing any PHM structures that are present on the LRU. Do not include currency symbols. A value can be entered into this field, or alternatively, a value for this field is automatically computed by the LRU implementation cost model, see Section 3.3.
>
> Non-Recurring Cost (per LRU) – The non-recurring cost per LRU where non-recurring refers to costs that occur exactly one time for each LRU (charged in year 0). This should include the design and development cost of PHM structures that are present on the LRU. Do not include currency symbols. A value can be entered into this field, or alternatively, a value for this field is automatically computed by the LRU implementation cost model, see Section 3.3.

In the case of "Unscheduled Maintenance" and "Fixed Interval Scheduled Maintenance" the Non-Recurring Cost (per LRU) is ignored and the Recurring Cost (per LRU instance) is automatically reset to the "Base Cost per LRU" – see Section 3.3. Note, selecting Unscheduled or Fixed Interval Maintenance deletes the results of running the implementation cost model; if you switch from Unscheduled or Fixed Interval Maintenance to one of the PHM approaches, you must either re-enter values into the Recurring and Non-Recurring Cost fields or re-run the implementation cost model.

> Time to Failure (operational hours) - Time to Failure (TTF) for the LRU. The number that appears in the field is the mode of the TTF distribution. This TTF (and its associated distribution) is assumed to be the result of manufacturing and material variations from LRU to LRU. Indications of

these failures mechanisms are assumed to be observable or predictable by the PHM approaches.

Random Failure Rate (%/year) - Percentage of fielded LRUs that will fail per operational year due to failure mechanisms that are not represented in the TTF distribution. These failure mechanisms are NOT observable or predictable in any way by PHM approaches.

Quantity - Disabled (not used at the present time).

Unscheduled/Scheduled - The values of the following four quantities can be different depending on whether the maintenance action is unscheduled or scheduled:

> Time to Repair (hours/unit) - Time in operational hours to either repair a failed LRU or replace a repairable LRU.
>
> Time to Replace (hours/socket) - Time in operational hours to replace the failed LRU with a new LRU.
>
> Cost of Repair Materials (per unit repaired) - Total average cost to repair one LRU.
>
> Fraction of Maint Actions Requiring Replacement - Fraction of LRU maintenance actions that cannot be repaired and require replacement with a new LRU.

False Alarm Time (hours per occurrence) - Number of hours (charged at scheduled maintenance rate) to resolve a false alarm. Only applicable if a PHM sustainment approach is chosen.

Choose Sustainment Approach - Use the choice box to select the sustainment approach to be used for the specific LRU. All the maintenance actions (whether scheduled or unscheduled) can be either repairs or replacements as dictated by the Fraction of Failures Requiring Replacement value:

> Unscheduled Maintenance - No sustainment (maintenance) plan. When the LRU fails, perform an unscheduled maintenance action to fix it.
>
> Fixed Interval Scheduled Maintenance - Perform scheduled maintenance at a fixed interval (defined in operational hours). If the LRU fails prior to the fixed interval, perform unscheduled maintenance.

PHM - Precursor to Failure - The fuse or other monitored structure is manufactured with the LRUs, i.e., it is coupled to a particular LRU's manufacturing or material variations. Health monitoring and LRU dependent fuses are in this category.

PHM - Fuse (LRU Independent) - The PHM structure (or sensors) are manufactured independent of the LRUs, i.e., they are not coupled to a particular LRU's manufacturing or material variations. Life consumption monitoring and LRU independent fuses are in this category.

Fixed Maintenance Interval (operational hours) - The maintenance interval used for fixed interval scheduled maintenance. Only enabled if the Sustainment Approach is "Fixed Interval Scheduled Maintenance".

Safety Margin/Prognostic Distance (operational hours) - The safety margin used for "PHM - Fuse (LRU Independent)" or prognostic distance for "PHM - Precursor to Failure" methods.

Dist Type for Sustainment Method (press button to edit) - The field to the right displays the shape of the distribution assumed. Pressing the <Sustainment Distribution> button pops up a dialog box of collecting the distribution details. These inputs are only enabled if a PHM sustainment approach is chosen.

False Alarm Threshold (frac of false indications) - Fraction of maintenance indications from the PHM approach that are false alarms. This number must be less than 1.0. This input is interpreted as the area under the distribution to the left of the "Threshold Level" in Figure 8. Only applicable if a PHM sustainment approach is chosen.

Dist Type for Env Stress Profile (press button to edit) - The field to the right displays the shape of the distribution assumed. Pressing the <Env Stress Distribution> button pops up a dialog box of collecting the distribution details. These inputs are only enabled if the Unscheduled or Fixed-Interval sustainment approaches are chosen.

3.2 System Details

The LRU Details are shown in the bottom one third of the tool interface shown in Figure 1.

Recurring Cost (per socket) – The recurring cost per socket where recurring refers to costs that recur for every instance of every socket in the system (charged once in year 0). This should include the recurring cost of implementing any PHM structures that are part of the socket (not PHM structures that are part of the LRU). Do not include currency symbols. A value can be entered into this field, or alternatively, a value for this field is automatically computed by the System implementation cost model, see Section 3.3.

Annual Infrastructure Cost – The annual cost charged to each socket in the system to support the PHM infrastructure. Do not include currency symbols. A value can be entered into this field, or alternatively, a value for this field is automatically computed by the System implementation cost model, see Section 3.3.

In the case of “Unscheduled Maintenance” and “Fixed Interval Scheduled Maintenance” the Recurring Cost (per socket) and the Annual Infrastructure Cost are ignored. Note, selecting Unscheduled or Fixed Interval maintenance

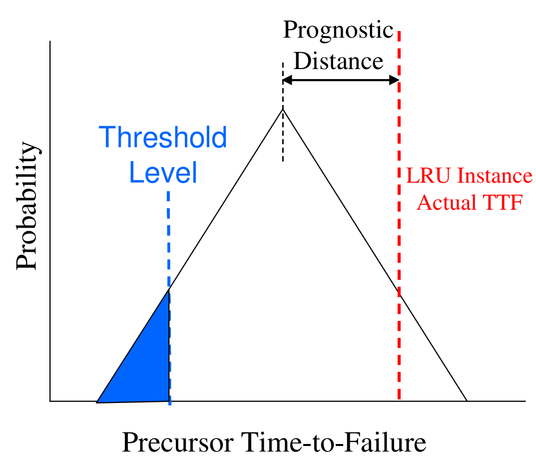


Figure 8 – False alarm interpretation for a precursor to failure PHM example. A triangular distribution is used for illustration purposes only.

deletes the results of running the implementation cost model; if you switch from Unscheduled or Fixed Interval Maintenance to one of the PHM approaches, you must either re-enter values into the Recurring and Annual Infrastructure Cost fields or re-run the implementation cost model.

Operational Time (hours/socket/year) - Average number of operational hours per socket per year.

Operation and Support Life (years/socket) - Operation and support (O&S) lifetime for a socket in years.

Coincident Time (operational hours) - The time interval within which different sockets should be treated by the same maintenance action. Coincident time = 0 means that each LRU is treated independently; Coincident time = infinite means that any time any LRU in the system demands to be fixed, all LRUs are fixed no matter what life expectancy they have. Coincident time is only enabled when multiple LRUs are analyzed.

3.3 LRU and System Implementation Costs

The PHM ROI analysis is performed using only the following four implementation cost fields in the main window (Figure 1): Recurring Cost (per LRU instance), Non-Recurring Cost (per LRU), Recurring Cost (per socket), and the Annual Infrastructure Cost.

The PHM ROI tool provides two utilities that can be optionally used to calculate the inputs for the four implementation cost fields. However, entering inputs into any of the four fields described above overrides information entered into the corresponding calculation utilities. The calculation utilities do not need to be used for the tool to run.

LRU Implementation Costs - Clicking on the <LRU Implementation Costs> button on the main window will open the dialog box shown in the upper left of Figure 9.

The following input fields are included in the LRU-Level Implementation Costs dialog:

> Base Cost per LRU - This value is the cost of an LRU without any PHM functionality or components added. This value should be the equivalent to the recurring cost of a single LRU under a traditional maintenance policy (fixed-value; unscheduled maintenance). This value will be used for the LRU recurring cost if Unscheduled Maintenance or Fixed Interval Scheduled Maintenance are selected as the sustainment approach.

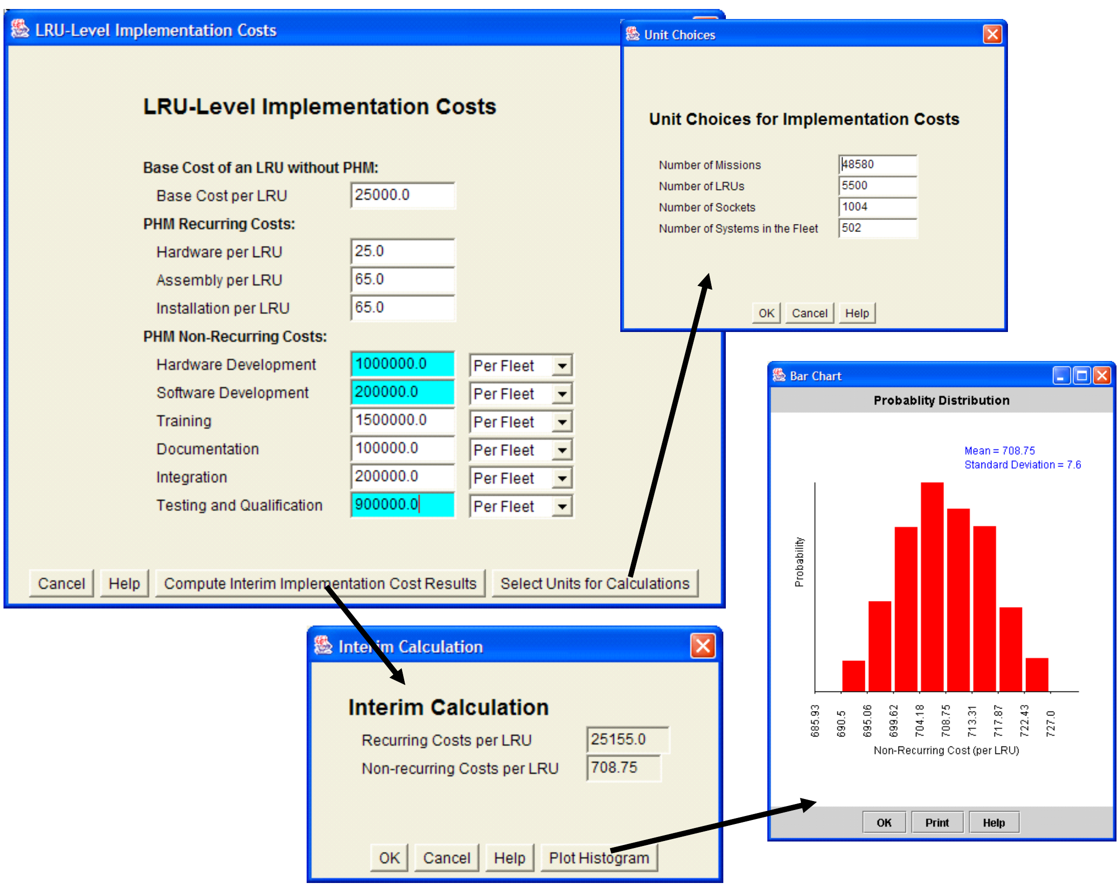


Figure 9 – LRU-level implementation cost calculation utility.

The remaining fields are specific to PHM and are divided into Recurring Costs and Non-Recurring Costs. The Recurring Costs category includes the following three fields:

Hardware per LRU - the cost of PHM hardware for a single LRU instance.

Assembly per LRU - the cost of all labor and/or equipment necessary to assemble PHM components for a single LRU instance.

Installation per LRU - the cost of labor and/or equipment needed to install PHM for a single LRU instance. This assumes that the cost of installation is independent of the LRU's location in a system for a particular type of LRU (i.e., multiple LRUs would be added if the installation cost differed depending on location).

The Non-Recurring Costs can be entered on a per-fleet or per-socket basis. The selection of units is performed using the drop-down menus to the right of each field. The PHM Non-Recurring Costs are:

Hardware Development - the cost of any R&D needed for any of the PHM components or subsystems.

Software Development - the cost of developing any software for performing PHM, including the cost of the software used in data management.

Training - the cost of creating, publishing, and initially instructing PHM user groups and includes the cost of removing users from their normal job functions to attend training.

Documentation - the cost of creating and publishing any training manuals and other technical information for the maintainers, trainers, logisticians, and engineers/programmers, and any other PHM users.

Integration - the cost of any engineering analysis or system modification needed to incorporate PHM.

Testing and Qualification - the total cost of initial testing and qualification for the PHM hardware and software.

<Select Units for Calculations> - At the far right of each Implementation Cost dialog box, there is a button labeled <Select Units for Calculations>. Pressing this button will open the Unit Choices dialog box shown in the upper right corner of Figure 9. The following fields are provided:

Number of Missions - the total number of missions over the support life of all the fielded instances of this LRU.

Number of LRUs - the total number of this LRU produced for all uses.

Number of Sockets - the total number of installation locations for the LRU across the enterprise

Number of Systems in the Fleet - the total number of platforms for the program.

<Compute Interim Implementation Cost Results> - When pressed, the tool will calculate the Recurring Cost per LRU instance and the Non-Recurring Cost per LRU and pop up an Interim Calculation dialog box (Figure 9). The calculated values may not be edited in the interim calculation dialog box. Pressing <Cancel> returns focus to the LRU-Level Implementation Costs dialog box, and pressing <OK> inserts the interim results into the appropriate fields on the main interface. The Interim Calculation dialog box also provides an option to view histograms of each calculated cost. If selected, the user can then determine the number of standard deviations and the number of bars to be used in the histogram. Note, there will only be a histogram to view if Monte Carlo is turned on (see Section 3.6) and distributions are defined on one or more of the implementation cost inputs (see Section 3.8).

System Implementation Costs - Clicking on the <System Implementation Costs> button on the main window will open the dialog box shown in the upper left of Figure 10. System Implementation Costs are divided into Recurring Costs and Infrastructure Costs. Unlike the LRU Implementation Cost dialog box, all fields in this dialog box are specific to using a PHM maintenance approach. The Recurring Costs are:

Installation per Socket - the cost, if any, of preparing an installation point (the socket) for PHM.

Hardware per Socket - the cost of any hardware necessary for preparing an installation point (socket) for PHM.

The Infrastructure Costs are system-level costs on a Per Year or Per Mission basis; the selection is accomplished via the drop-down menus to the right of each field. The four costs in this category are:

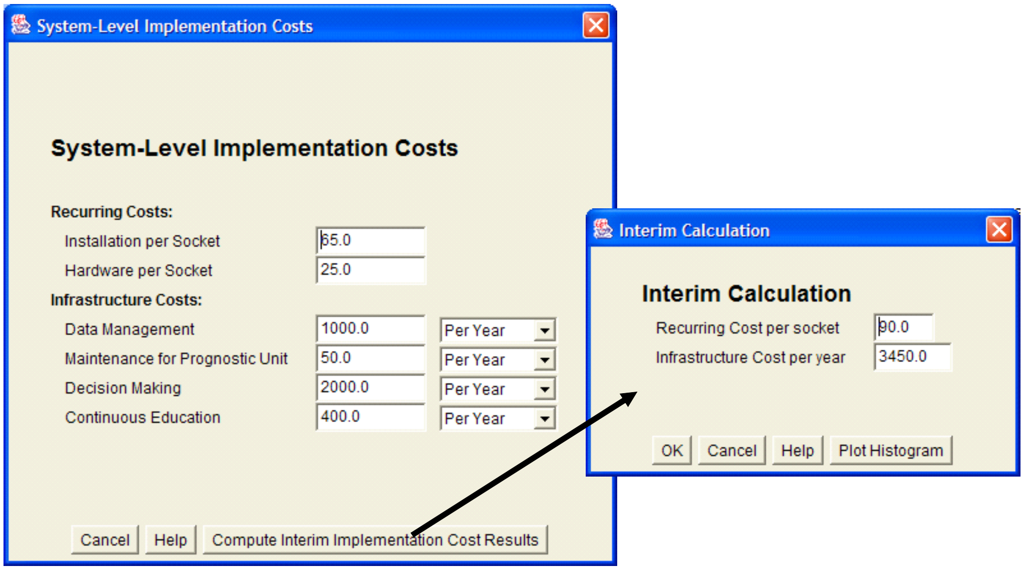


Figure 10 – System-level implementation cost dialog box.

Data Management - the total cost of data collection, processing, reduction, analysis, and storage.

Maintenance for Prognostic Unit - the cost of any maintenance needed on the PHM components

Decision Making - the cost of employing the logisticians, analysts, or mission control officers who utilize PHM to render maintenance decisions

Continuous Education - the cost of periodic re-training of the PHM user group

Common units are used for both the LRU implementation and the system implementation. In order to define the units, press the <Select Units for Calculations> button in the LRU-level Implementation Costs dialog box (see Figure 9).

<Compute Interim Implementation Cost Results> - When pressed, the tool will calculate the Recurring Cost per socket and the Infrastructure Cost per year and pop up an Interim Calculation dialog box (Figure 10). The calculated values may not be edited in the interim calculation dialog box. Pressing <Cancel> returns focus to the System-Level Implementation Costs dialog box, and pressing <OK> inserts the interim results into the appropriate fields on the main interface. The Interim Calculation dialog box also provides an option to view histograms of each calculated cost. If selected, the user can then determine the number of standard deviations and the number of bars to be used in the histogram. Note, there will only be a histogram to view if

Monte Carlo is turned on (see Section 3.6) and distributions are defined on one or more of the implementation cost inputs (see Section 3.8).

If any of the LRU-level or system-level implementation costs are computed with uncertainties, i.e., Monte Carlo is on and input uncertainties defined (as in Figure 9 for example), the implementation costs will be represented by a distribution rather than a number. In this case, when the implementation cost calculators insert values back into the main interface, they will also define a "Custom" distribution which represents the result of the calculator. Note, Custom distributions cannot be defined or modified by the user, they are automatically generated by the implementation cost calculators.

3.4 Operational Profile

The operational profile describes the operational environment experienced by the socket(s). Pressing the <Define Operational Profile> button on the main interface displays the dialog box shown in Figure 11.

> Operational Hours per Mission – Number of operational hours in an average mission. This value is only used if one or more infrastructure cost contributions (see Section 3.3) is described with units of "Per Mission".
>
> Value per Hour Out of Service - Cost of each hour that the system is not in service because a scheduled maintenance action is taking place.

The value per hour out of service for unscheduled maintenance is more complex to describe and depends on the operational profile of the system. The operational profile of systems equipped with PHM dictates how the information provided by PHM may be used to affect the maintenance and usage schedules. The effective costs associated with maintenance actions depend on when (and where) actions are indicated relative to some

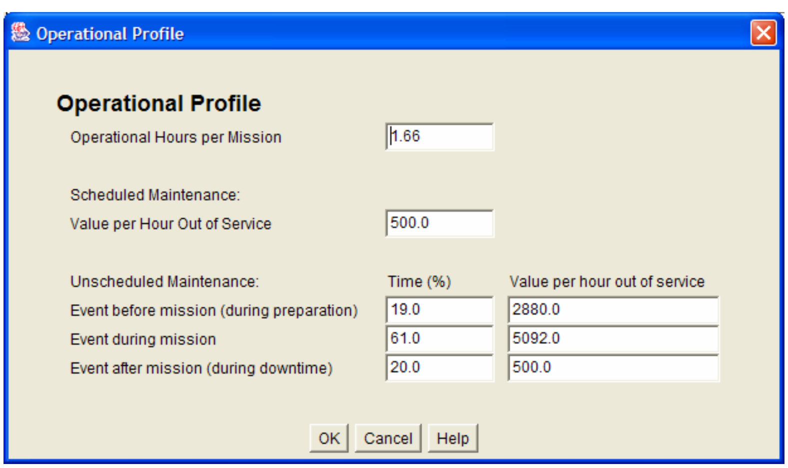


Figure 11 – Operational Profile dialog box.

operational cadence. Cadences may be proscribed by business constraints, regulations or mission requirements, and may be subject to change as user requirements shift. The cadence is best described according to a probabilistic model rather than a timeline, i.e., a defined probability of an unscheduled maintenance request being issued before, during, or after a mission or particular type of use. The implications of the safety margins or prognostics distances will vary with the difference in cadence to affect the timing of maintenance actions. The operational profile is reflected in the maintenance modeling by varying the value of an unscheduled hour out of service and the probability that a particular unscheduled maintenance action falls within a particular period of operation. The periods of operation are defined as:

Event before mission (during preparation) - maintenance requirements that occur while preparing to place the system into service, i.e., while loading passengers onto the aircraft for a scheduled commercial flight.

Event during mission - the maintenance requirement occurs while the system is performing a service and may result in interruption of that service, i.e., making an emergency landing, or abandoning a High Mobility Multipurpose Wheeled Vehicle (HMMWV) by the side of the road during a convoy.

Event after mission (during downtime) - time that the system is not needed, i.e., the period of time from midnight to 6:00 am when the commercial aircraft could sit idle at a gate.

Each period of operation requires two data inputs:

Time (%) – percentage of the non-scheduled, non-operational time that the system is in the period of operation.[6] Note, the percentages entered for the three time periods must add to 100.0 or an error message is generated when exiting the dialog box.

[6] The PHM ROI tool assumes that there are four times: before mission time, during mission time, after mission time, and scheduled non-operational time. These four times add up to (365)(24) = 8760 hours per year. The operational time (hours/socket/year) defined in Section 3.2 is the total of the before and during mission times. Therefore, in order to be consistent, the following inequality must be true,

$$100\left[\frac{O_y}{T_{before}+T_{during}}\right]<8760$$

where

O_y = operational time (hours/socket/year), see Section 3.2
T_{before} = Time (%) before mission
T_{during} = Time (%) after mission.

Value per hour out of service - Cost of each hour that the system is not in service because a maintenance action is taking place. The value in this field is specifically for unscheduled maintenance.

If the PHM approach catches a maintenance action prior to failure, it's always costed as a scheduled maintenance event. This represents a best case assumption that a PHM precipitated maintenance event (prior to failure) can always be moved to a scheduled maintenance period. If the PHM approach fails to precipitate maintenance prior to failure (or an Unscheduled Maintenance approach is used) then a random number generator is used to determine the portion of the operational profile the event is in and the corresponding value per hour out of service is used.

3.5 Analysis Controls

<Default> - Populates all the inputs with a set of default values. This action will destroy all existing data in the tool.

<Plot Settings> - Creates a dialog box (Figure x) that allows control of costs as a function of time. "Plot Socket Costs?" defaults to "No" in which case no plots are created. If "Yes", then a plot should be created each time the tool is run. If "Plot Separately?" is "Yes" then a new plot is created for each analysis, if "No" results are added to the same plot every time an analysis is performed. NOTE - the plots consume a large amount of memory and may cause out of memory errors. The <Clear Plot(s)> deletes all the plots and resets the memory. Plotting unit costs (turned on using the <Plot Settings> button) is temperamental. 1) For plotting to work, Monte Carlo samples should be kept to 1000 or less. 2) If multiple plots are being generated, the number of samples in the first plot generated sets the allowed array size, i.e., don't increase the number of Monte Carlo samples after you start plotting.

<Compute> - Runs an analysis and presents the results in a separate Results dialog box that appears at the end of the analysis. See Section 4 for discussion of results.

<ROI> - Automatically runs a Return on Investment analysis for the selected PHM approach (Sustainment approach) versus Unscheduled Maintenance. See Section 4 for discussion of results.

<Stop Simulation> - Interrupts the simulation. Only enabled if a simulation is running.

Single LRU/Multi LRUs - Single LRU analysis is performed on exactly the data shown in the interface. Multiple LRU analysis is performed on the data that is saved for the LRUs selected. Only enabled if multiple LRUs are defined in the tool. Note, changes made to an LRU in the interface are NOT

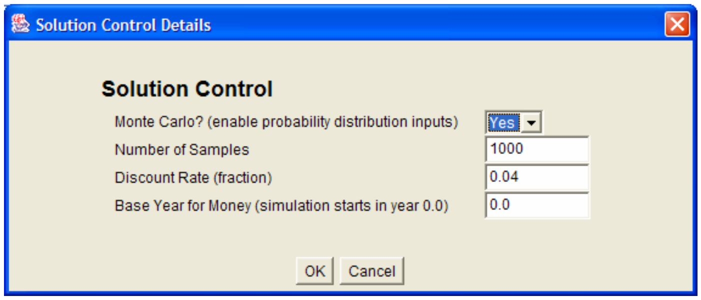


Figure 12 – Operational Profile dialog box.

persistent when you switch between LRUs AND are not used in the analysis, unless you press <Save>. If "Multi-LRUs" is chosen, then a list of LRUs will be presented to the user when they press the <Compute> button - one or more LRUs can be chosen from this list for analysis.

<Plot Histogram> - Allows a histogram of the cost and availability results (and the reliability input) to be created. Only enabled if Monte Carlo analysis is performed.

<Load> - See Section 3.7

<Save> - See Section 3.7

<Solution Control> - See Section 3.6

<Save As:> - See Section 3.7

3.6 Solution Control

Pressing the <Solution Control> button on the main interface launches a dialog box (Figure 12) that includes the following controls:

Monte Carlo? (enable probability distribution inputs) - If "No" Monte Carlo analysis is not performed and the most likely (mode) values that appear in the fields on this interface are used for the analysis. If "Yes" Monte Carlo analysis is performed and distributions are used to optionally describe the inputs.

Number of Samples - Number of samples used in Monte Carlo analysis. Only enabled if Monte Carlo is "Yes".

Discount Rate (fraction) – Discount rate on money. This input along with the next one allows the cost of money to included in the calculation. Set this input to zero if you do not wish to include the cost of money in the calculations.

Base Year for Money (simulation starts in year 0.0) – The year that the calculated costs are indexed to measured from year zero (the start of the simulation). If the discount rate is zero, the value entered into this field is irrelevant.

3.7 Saving and Loading Data

If you are running the tool as a Java applet from the web, you must accept the security certificate presented when you start up the tool in order to save or load data in the tool. If you are running the tool as an application, i.e., from a .exe file that you downloaded, save and load to your local file system will work without any special setup.

<Load> and <Save> - The <Load> button allows you to open a file dialog to choose the file (*.xml) in which LRUs have been previously saved. After you clicked the selected file, all the LRUs included in the file will be listed in the "Available LRUs" field. Clicking on a listed item will cause all the data associated with the selected LRU to be loaded (only the data that is LRU specific is changed, i.e., the data above the blue line). If you make any changes to a specific LRU and want to save them back into the same file, click the <Save> button. Note, changes to an LRU are NOT persistent when you switch between LRUs unless you press <Save>.

When a set of LRUs is loaded (using the <Load> button), the system details and solution control information associated with the first LRU in the list is loaded into the interface. The system details and solution control information is never loaded again. The system details and solution control information that appears on the interface is used when the analysis is performed.

<Save As:> - Click the <Save As:> button to save the LRU shown on the interface as a new LRU in the current file or to save it in a new file by choosing either "LRU" or "File" in the box to the right of the <Save As:> button. Entering data in the interface and pressing <Save As> (with LRU chosen) multiple times will create multiple LRUs. Note, if you are saving to a new file, make sure that the file ends in ".xml" or you won't see the file when you try to reload.

3.8 Stochastic Analysis

The tool is intended to be used with the Monte Carlo analysis turned on - this is the only way that you get a stochastic simulation, which is the primary intent of this tool. The Monte Carlo analysis is enabled by changing the "Monte Carlo?" field to "Yes" and adding distribution information to selected inputs. The two primary inputs to add distribution information to are the "Time to Failure" and the "Sustainment Distribution". Distribution information can be added to the inputs by clicking in the desired field and pressing the "Enter" or

"Return" key. A dialog box will appear that allows the distribution type to be selected and associated data entered. If a particular input has distribution information associated with it, and "Yes" is selected in the "Monte Carlo?" field, the input field will be colored blue.

- When exponential, uniform or Weibull distributions are used, the value entered into the primary field (the "mode") is ignored.
- For uniform distributions the range is the total range (lowest to highest)
- "Fixed Value" uses the value entered into the main interface
- The “Custom” distribution type, which only appears for the Recurring Cost, Non-Recurring Cost, and Annual Infrastructure Cost fields indicates that a custom distribution was generated by the implementation cost analysis and will be used in the system analysis. This distribution can only be automatically generated by the implementation cost model and cannot be entered by the user. The distribution may be viewed by the user, see Section 3.3.

4 – Simulation Outputs

The PHM ROI tools provides three kinds of outputs: 1) means and standard deviations, 2) histograms, and 3) time-history plots.

4.1 <Calculate> Button Outputs

The primary outputs are quantitative and shown in Figures 3, 6 and 7 (produced when the <Compute> button is pressed):

Mean Life Cycle Cost – Mean life cycle cost per socket. For example, if Monte Carlo analysis was on, and you simulated 1000 samples, then this is the average life cycle cost of a socket determined from 1000 sockets simulated.

Standard Deviation in Life Cycle Cost – Size of one standard deviation in the life cycle cost per socket. If Monte Carlo analysis is off or if there are no distributions defined for any of the input variables, this will be zero.

Mean Operational Availability (%) – The availability is computed as,

$$Availability\ (\%) = 100\left[1 - \frac{T_D}{T_T}\right] \tag{2}$$

where

T_D = Accumulated downtime when the system needs to be up. Total before mission and during mission time spent doing maintenance. Time for scheduled maintenance (which includes PHM precipitated maintenance) and after mission maintenance not included.

T_T = Total time the system needs to be up. Product of the operational time per year and the operation and support life.

Standard Deviation in Operational Availability – Size (in %) of one standard deviation in the operational availability.

Failures Avoided (%) – Failures avoided is calculated using,

$$Failures\ Avoided\ (\%) = 100\frac{M_s}{(M_s + M_{us})} \tag{3}$$

where

M_s = number of scheduled maintenance events

M_{us} = number of unscheduled maintenance events.

Cost Per Operational Hour – Mean cost per socket per operational hour.

Average number of LRUs per socket – Average number of LRUs that occupy a socket during the operation and support life of the socket.

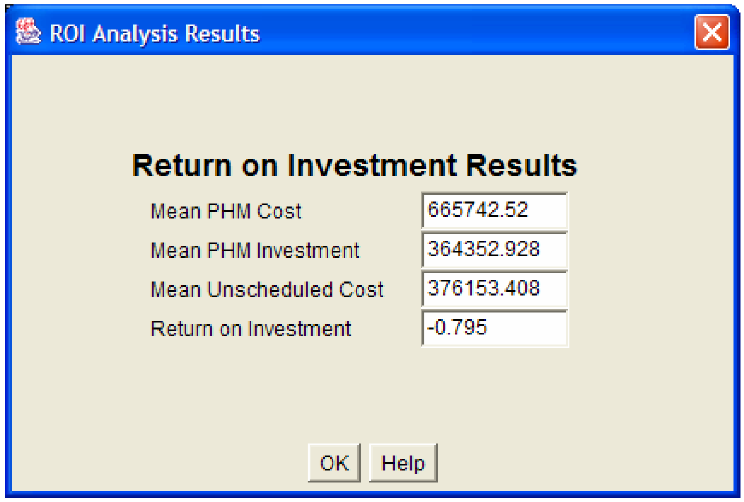


Figure 13 – ROI analysis results dialog box.

4.2 <ROI> Button Outputs

When the <ROI> button is pressed, a return on investment (ROI) of the selected PHM approach relative to unscheduled maintenance is determined. The follow relation is used to calculate the ROI,

$$ROI = \frac{C_{us} - (C_{PHM} - I)}{I} - 1 \quad (4)$$

where

C_{us} = cost per socket if unscheduled maintenance is used (“Mean Unscheduled Cost” in Figure 13)

C_{PHM} = cost per socket using the selected PHM approach (“Mean PHM Cost” in Figure 13)

I = total investment cost associated with the PHM approach (“Mean PHM Investment” in Figure 13)

An ROI value of 0 represents breakeven. ROI > 0 means that a financial case can be made for PHM and ROI < 0 means that there is not a direct financial return using PHM.

Note, if the selected sustainment approach is unscheduled maintenance, the ROI calculation will return an ROI of zero.

Acronyms

AMAD	Airframe Mounted Accessory Drive
APC	Armored Personnel Carriers
BEP	Break Even Point
CBA	Cost Benefit Analysis
cdf	Cumulative Density Function
CND	Can Not Duplicate
COCOMO	Constructive Cost Model
COTS	Commercial off the Shelf
DoD	Department of Defense
DRU	Depot Replaceable Unit
ECU	Engine Control Unit
EOL	End of Life
e-PHM	Electronics Prognostics and Health Management
FMECA	Failure Modes, Effects, and Criticality Analysis
HM	Health Monitoring
HMMWV	High Mobility Multipurpose Wheeled Vehicle
HUMS	Health and Usage Monitoring Systems
IDE	Integrated Data Environment
JSF	Joint Strike Fighter
LAV	Light Armored Vehicle

LCM	Life Consumption Monitoring
LCOM	Logistics Composite Model
LRU	Line Replaceable Unit
Mil-Spec	Military Specification
MRM	Maintenance Resource Management
MRO	Maintenance, Repair, and Overhaul
NASA	National Aeronautics and Space Administration
NFF	No Fault Found
NRE	Non Recurring Engineering
PBL	Performance Based Logistics
pdf	Probability Density Function
PHM	Prognostics and Health Management
PM	Program Manager
PoF	Physics of Failure
ROI	Return on Investment
RUL	Remaining Useful Life
SBCT	Stryker Brigade Combat Team
SLOC	Source Lines of Code
SRU	Shop Replaceable Unit
TTF	Time to Failure
UAV	Unmanned Aerial Vehicle

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