PHM Return on Investment (ROI)
(Use of PHM in Maintenance Planning)

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Objective:

Development of lifecycle cost models and business cases that evaluate the incorporation of prognostics into systems

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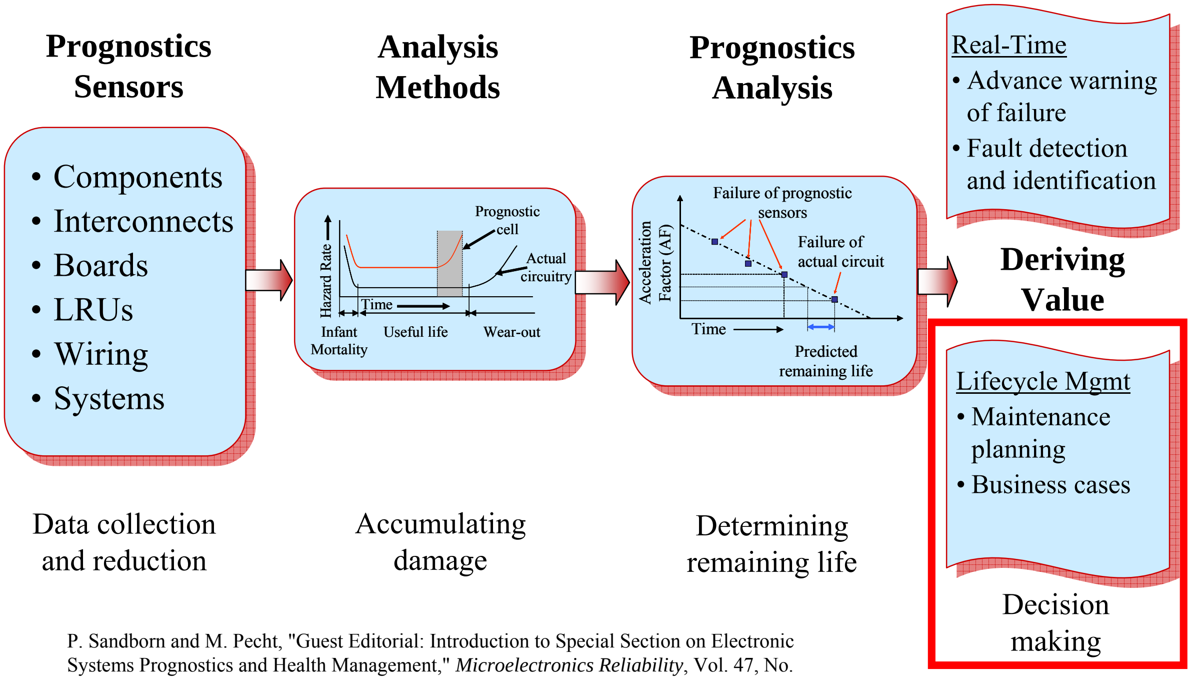
Prognostics and Health Management



Prognostics Sensors

- Components
- Interconnects
- Boards
- LRUs
- Wiring
- Systems

Data collection and reduction

Analysis Methods

Accumulating damage

Prognostics Analysis

Determining remaining life

Real-Time
- Advance warning of failure
- Fault detection and identification

Deriving Value

Lifecycle Mgmt
- Maintenance planning
- Business cases

Decision making

P. Sandborn and M. Pecht, "Guest Editorial: Introduction to Special Section on Electronic Systems Prognostics and Health Management," *Microelectronics Reliability*, Vol. 47, No. 12, pp. 1847-1848, December 2007.

Evaluating the ROI Associated with Electronics PHM

What is ROI?

$$\text{ROI} = \frac{\text{Return - Investment}}{\text{Investment}}$$

(Arithmetic Formulation)

Why evaluate the ROI?

- To build a business case for implementation
- To perform cost/benefit analysis on different prognostic approaches
- Evaluate when PHM may not be warranted

Interpreting ROI:

0 = breakeven (no cost impact)

> 0 there is a direct cost benefit

< 0 there is no direct cost benefit

Cost of PHM Implementation

- Development cost
  - Hardware and software design, development, testing and qualification
  - Integration costs
- Additional costs associated with product manufacturing
  - Recurring cost per product for additional hardware, additional processing, additional recurring functional testing
  - Installation costs
- Cost of creating and maintaining the infrastructure to make effective use of the PHM data
  - Cost of data archiving
  - Cost of maintaining the PHM structures (logistics footprint)
  - Cost of training personnel
  - Cost of creating and maintaining documentation
  - Cost of changing the logistics/maintenance culture
- Cost of performing the necessary analysis to make it work
  - Cost of data collection
  - Cost of data analysis
  - Cost of false positives
- Financial costs (cost of money)
  - $1 today (to implement PHM) costs more than $1 to repair tomorrow

Potential Cost Avoidance (Return) Associated with PHM

- Failures avoided
  - Minimizing the cost of unscheduled maintenance
  - Increasing availability
  - Reducing risk of loss of system
  - Increased human safety
- Minimizing loss of remaining life
  - Minimizing the amount of remaining life thrown away by scheduled maintenance actions
- Logistics (reduction in logistics footprint)
  - Better spares management (quantity, refreshment, locations)
  - Better use of (control over) inventory
  - Minimization of investment in external test equip
- Repair
  - Better diagnosis and fault isolation (decreased inspection time, decreased trouble shooting time)
  - Reduction in collateral damage during repair
- Reduction in redundancy (long term)
  - Can redundancy be decreased for selected sub-systems?
- Reduction in no-fault-founds
- Reduced waste stream
  - Less to end-of-life (dispose of) – disposal avoidance
  - Reduction in take-back cost

- Eases design and qualification of future systems
- Reduced liability
- Warranty claim verification

Predicting the Cost Avoidance Enabled by PHM

ROI calculation must be performed stochastically, i.e., you either:

- Get a probability distribution of ROIs as an output
- Specify a confidence level and you get a minimum ROI as an output

Cost avoidance cannot be predicted without constructing some kind of maintenance model:

- While the majority of simple PHM cost models contain factors associated with the maintenance, they do not actually model the maintenance process
- The most accurate models of the PHM ramifications on cost and availability come from maintenance models

PHM Cost Model

Discrete-event simulation that follows a population of sockets through their lifetime from first LRU installation to retirement of the socket.

- “Discrete-event simulator” refers to the simulation of a timeline, where specific events are added to the timeline and the resulting event order and timing can be used to analyze throughput, cost, availability, etc.
- “Socket” refers to one instance of an installation location for an LRU.
- “Population” means that the simulator is stochastic (governed by the laws of probability) so that a statistically significant number of non-identical fielded systems can be assessed and the results are distributions rather than single values.

Following Sockets vs. LRUs

The discrete-event simulation follows a population of sockets through their lifetime (socket = the installation location of an LRU); issues with modeling sockets:

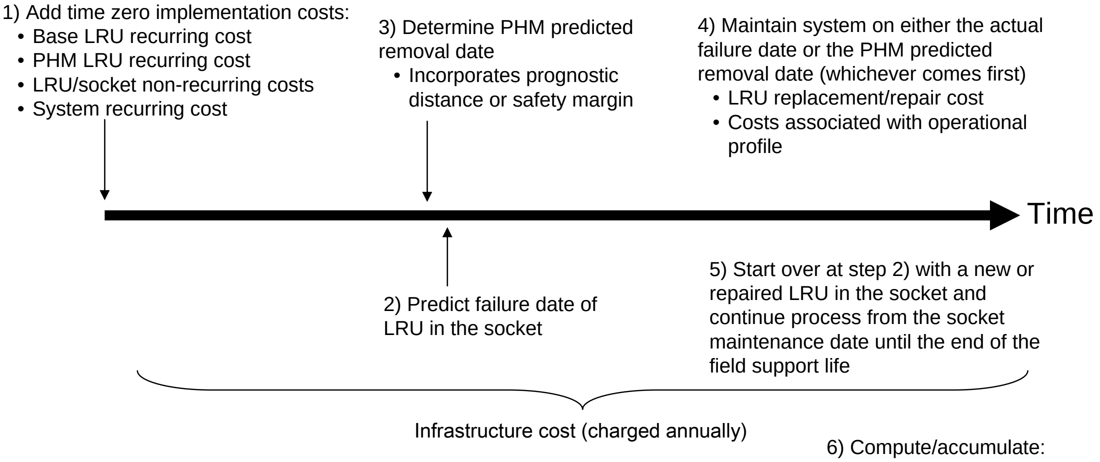
- Easy to calculate socket cost and availability
- Implicit assumption of a stable population of LRUs
- Not-good-as-new repair – easy to model if you assume the same LRU comes back after repair, but what if a different one comes back?

Alternatively, a simulation could follow LRUs; issues with following LRUs:

- Repaired LRUs don’t necessarily go back into the same socket, so you must model the LRU supply chain
- How are socket failures accounted for?
- Difficult to calculate socket cost and availability

Discrete Event Simulation

For one socket:



1) Add time zero implementation costs:
- Base LRU recurring cost
- PHM LRU recurring cost
- LRU/socket non-recurring costs
- System recurring cost

3) Determine PHM predicted removal date
- Incorporates prognostic distance or safety margin

4) Maintain system on either the actual failure date or the PHM predicted removal date (whichever comes first)
- LRU replacement/repair cost
- Costs associated with operational profile

2) Predict failure date of LRU in the socket

5) Start over at step 2) with a new or repaired LRU in the socket and continue process from the socket maintenance date until the end of the field support life

Infrastructure cost (charged annually)

6) Compute/accumulate:
- Lifecycle cost/socket
- Cost/operating hour
- Availability
- Failures avoided
- Number of LRUs/socket

Every value used is “sampled” from a probability distribution that represents the input parameter

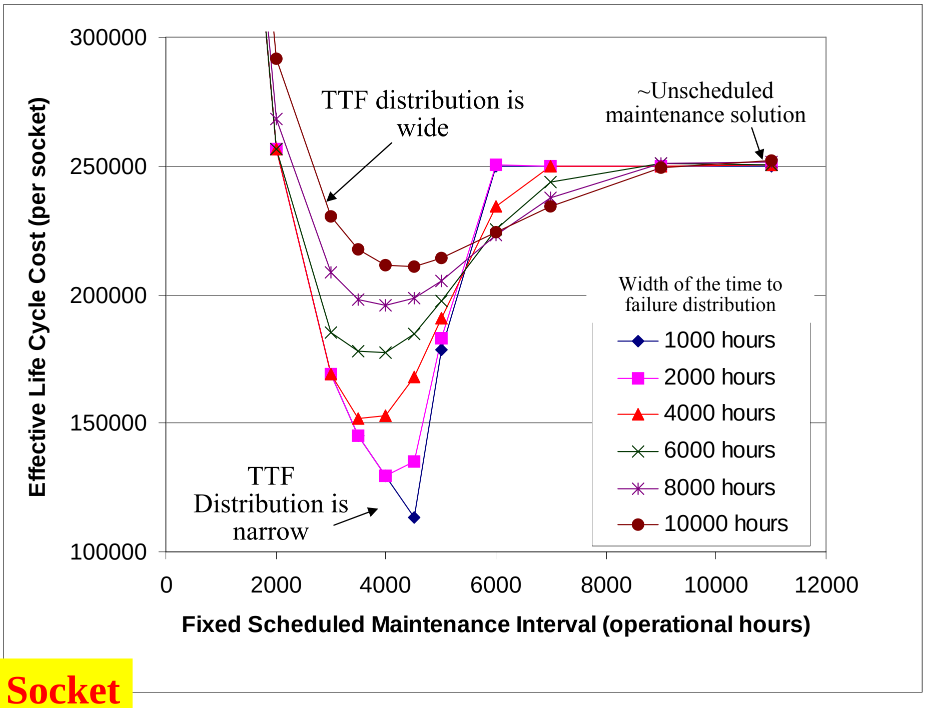
Repeat the process for many sockets
Generate a histogram of the computed quantities

Very Simple Baseline Data Assumptions for the Example Cases

Variable in the model	Value used for example analysis	
Production cost (per unit)	$10,000	
Time to failure (TTF)	Various values and distributions	
Operational hours per year	2500	
Sustainment life	25 years	
	Unscheduled	Scheduled
Value of each hour out of service	$10,000	$500
Time to repair	6 hours	4 hours
Time to replace	1 hour	0.7 hours
Cost of repair (materials cost)	$500	$350
Fraction of repairs requiring replacement of the LRU (as opposed to repair of the LRU)	1.0	0.7

- 0 investment cost
- 0 infrastructure cost
- Spares assumed to be available and purchased as needed

Fixed Interval Scheduled Maintenance



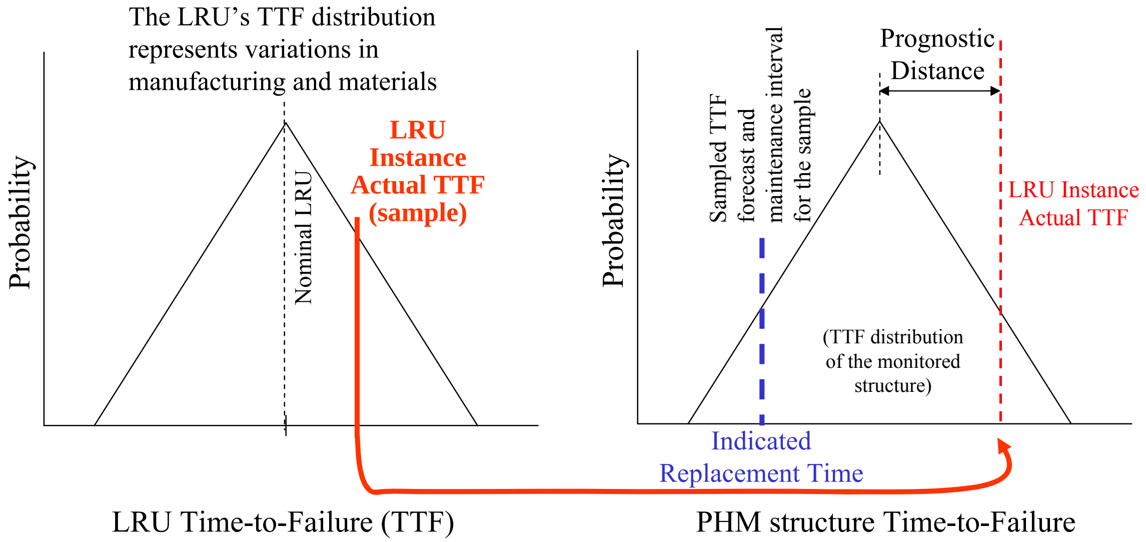
Single Socket

(10,000 sockets followed)

Data-Driven Methodologies

(Precursor to Failure, Health Monitoring, LRU Dependent Fuse)

- Example: A fuse or other monitored structure is manufactured with the LRUs, i.e., it is coupled to a particular LRU's manufacturing or material variations
- Prognostic Distance = length of time (in operational hours) before system failure that the prognostic structures are designed to indicate failure



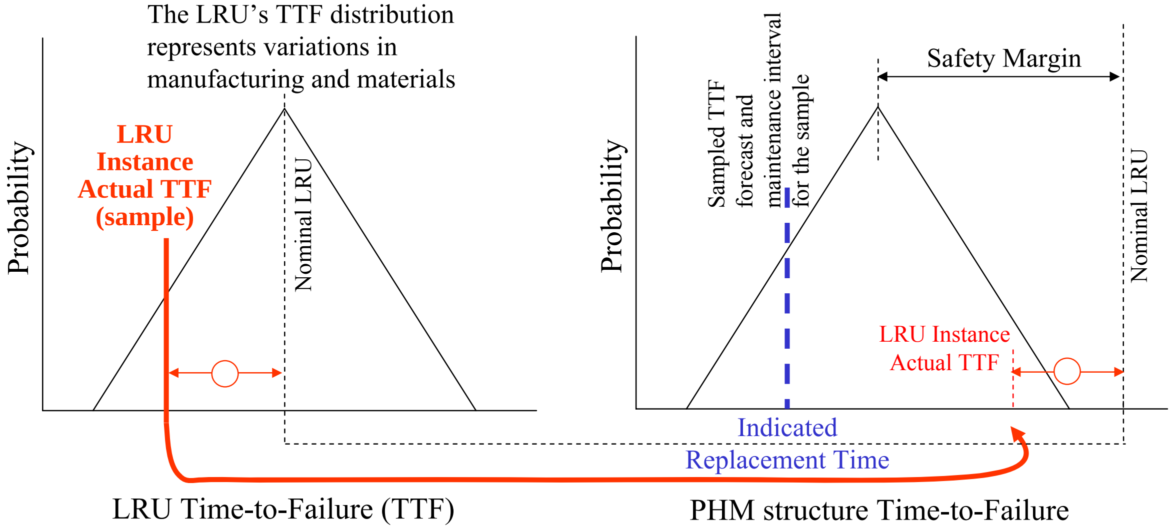
LRU Time-to-Failure (TTF)

PHM structure Time-to-Failure

Model-Based Methodologies

(LRU Independent, Life Consumption Monitoring (LCM), LRU Independent Fuse)

- The PHM structure (or sensors) are manufactured independent of the LRUs, i.e., it is not coupled to a particular LRU's manufacturing or material variations
- Safety Margin (Designed Prognostic Distance) = length of time (in operational hours) before failure of the nominal LRU that the PHM approach/structure is design to indicate failure.



The LRU's TTF distribution represents variations in manufacturing and materials

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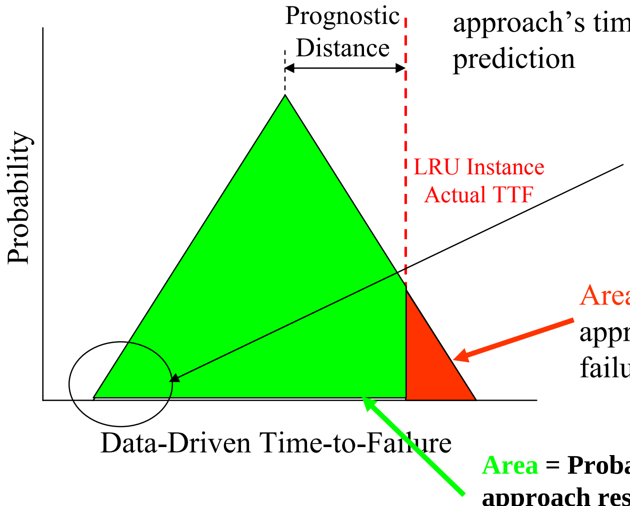
Maintenance Emulation: Modeling False Alarms

False alarms = predictions of failure by the PHM approach that are erroneous or too early.



Distribution of the PHM approach's time to failure prediction

False alarms are represented by the left tail of these distributions

Area = Probability that the PHM approach results in a prediction of failure that is too late.

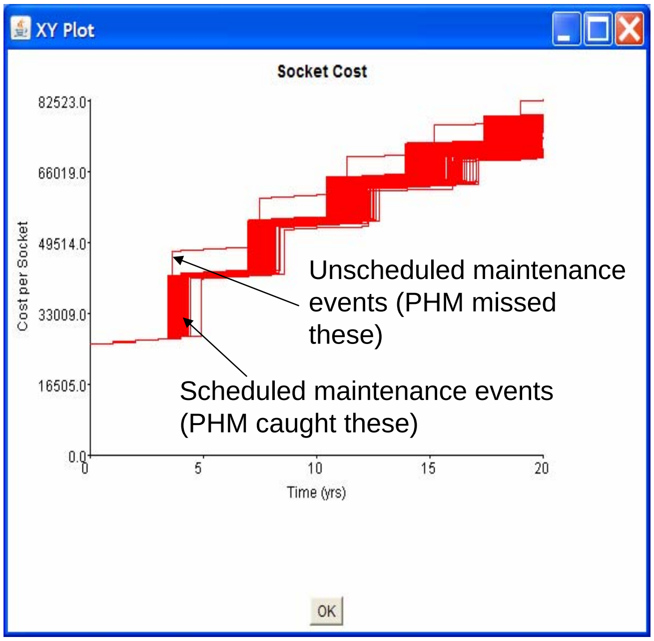
Area = Probability that the PHM approach results in a prediction of failure that is too early.

Triangular distribution used for illustration purposes only.

Comments

- ☆The fundamental difference between the two models:
  - Data-Driven = the TTF distribution associated with the PHM structure (or sensor) is unique to each LRU instance
  - Model-Based = the TTF distribution associated with the PHM structure (or sensor) is tied to the nominal LRU and knows nothing about manufacturing/material variations between LRU instances
- Notes:
  - Failure does not have to be characterized by time – it could be cycles, etc.
  - Triangular distributions are only used for simplicity

Discrete Event Simulation – Data-Driven



Unscheduled maintenance events (PHM missed these)

Scheduled maintenance events (PHM caught these)

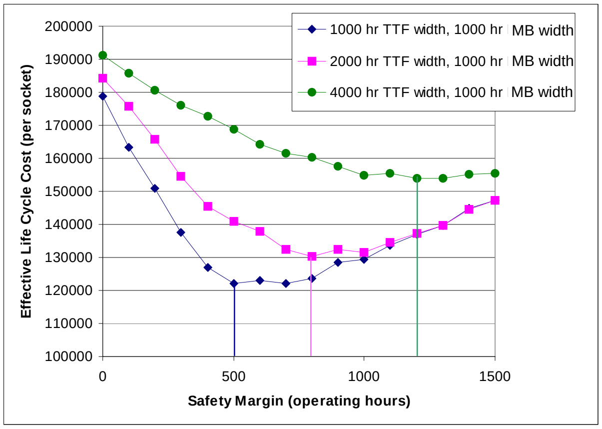
(without spares inventory)

- 1,000 sockets simulated
- Small steps in the graph correspond to annual accumulation of infrastructure costs
- Big jumps in cost correspond to replacement of the LRU (average of 5 LRUs used per socket over the support life)

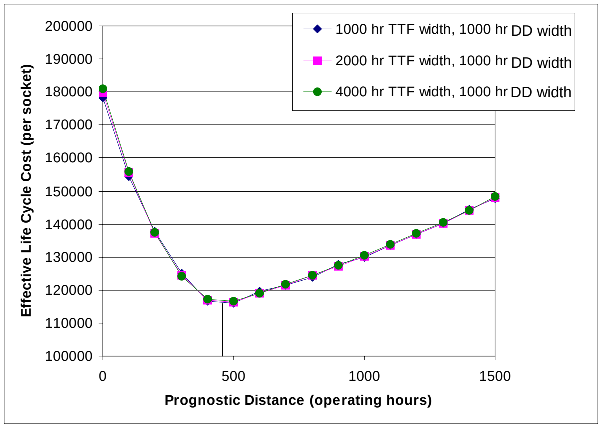
Data-Driven vs. Model-Based Methods

(Varying TTF Distribution Width)

Model-Based

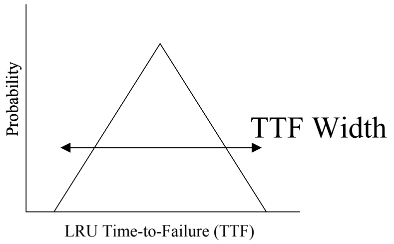


Data-Driven



(10,000 sockets followed)

Variations in TTF distribution width

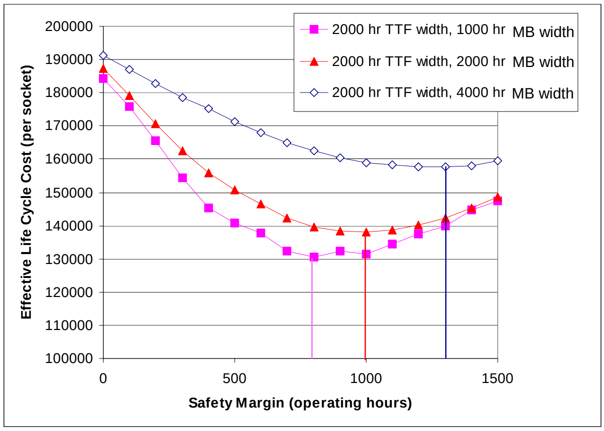


Single Socket

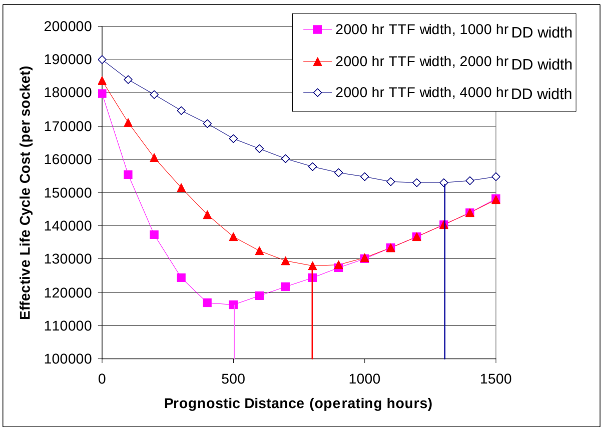
Data-Driven vs. Model-Based Methods

(Varying PHM Distribution Width)

Model-Based

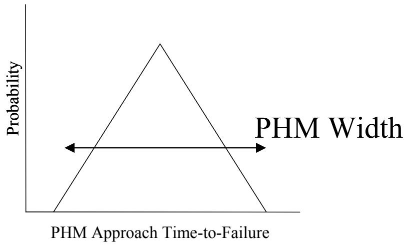


Data-Driven



(10,000 sockets followed)

Variations in PHM distribution width



Single Socket

Data-Driven vs. Model-Based Method Observations

1) The model-based approach is highly dependent on the LRU’s TTF distribution
2) Data-driven methods are approximately independent of the LRU’s TTF distribution
3) All things equal,* optimum prognostic distances for data-driven methods are always smaller than optimum safety margins for model-based methods,** and therefore,
4) All things equal,* data-driven PHM methods will always result in lower life cycle cost solutions that model-based methods**

*All things equal = same LRUs, same shape and size distribution associated with the PHM approach

**Assumes that you have a choice, i.e., that there is a data-driven method that is applicable – there may not be

Single Socket

Multiple Socket Systems

Coincident time = time interval within which different sockets should be treated by the same maintenance action.

If $\left| \text{Time}_{\text{current maintenance action}} - \text{Time}_{\text{required maintenance action on LRU i}} \right| < \text{Time}_{\text{coincident}}$

Current maintenance action for the system

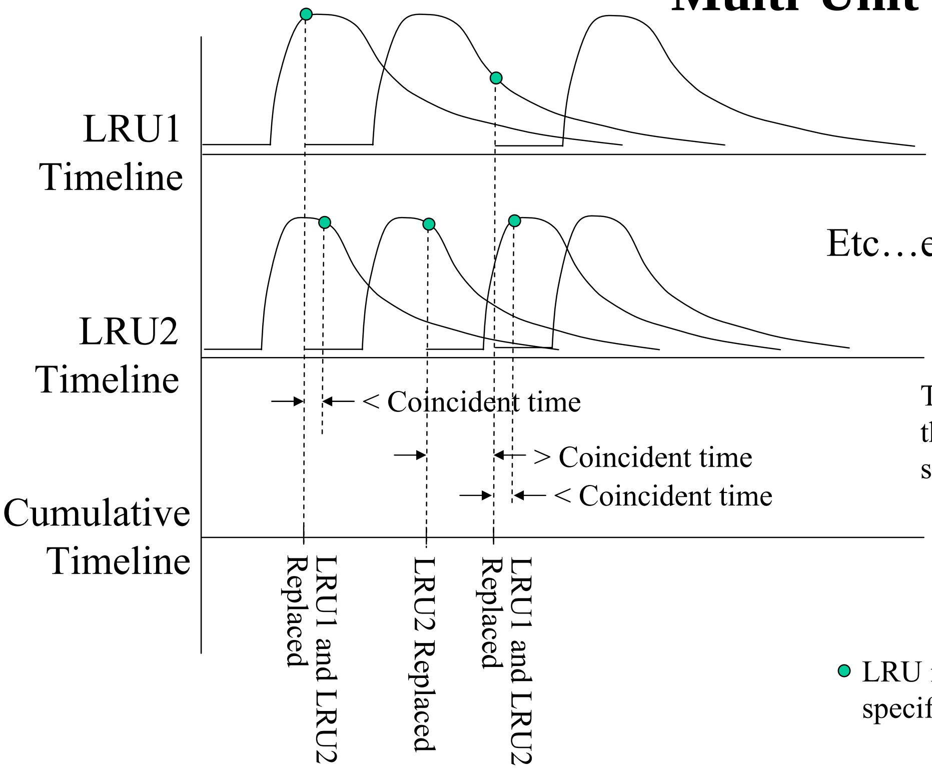
Next predicted maintenance action for socket i (from PHM approach)

then LRU i is addressed at the current maintenance action

Coincident time = 0 means that each socket is treated independently

Coincident time = infinite means that any time any LRU in the system demands to be fixed, all sockets are fixed no matter what life expectancy they have

Multi-Unit Timelines

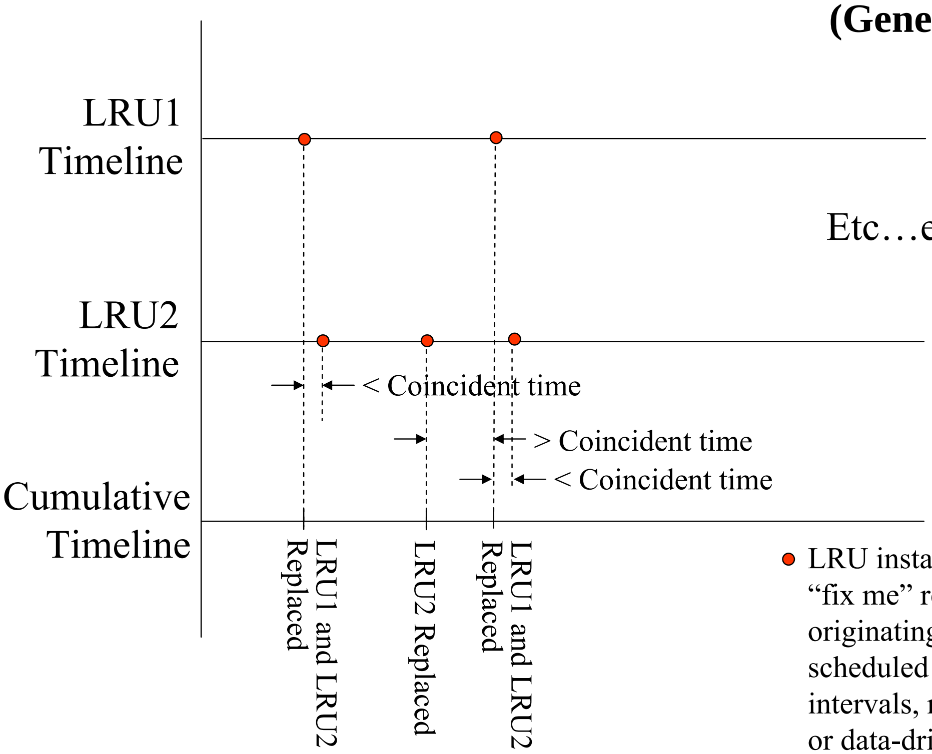


Etc…end of support

Two different LRUs that are part of the same system

● LRU instance-specific TTF samples

Multi-Unit Timelines
(General)



Etc…end of support

● LRU instance-specific "fix me" requests originating from either scheduled maintenance intervals, model-based or data-driven decisions

Three Types of Multiple-Socket System Responses

- Dissimilar LRUs
  - LRUs with substantially different reliabilities
  - LRUs with different PHM approaches (or no PHM approach at all)
- Similar LRUs
  - LRUs with similar reliabilities
  - LRUs using similar PHM approaches
- Optimizable Mixed Systems of LRUs
  - Systems that have specific non-trivial coincident time optimums

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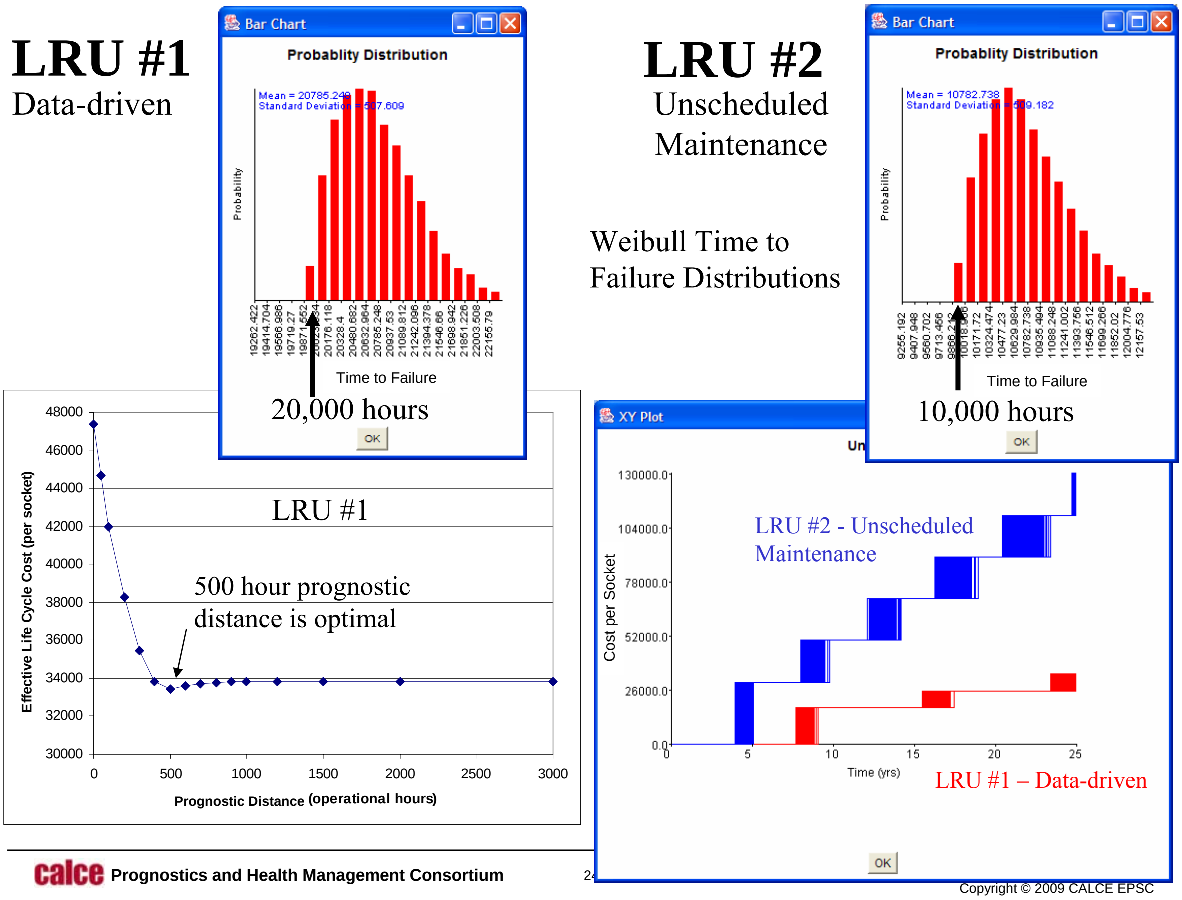
LRU #1

Data-driven

LRU #2

Unscheduled Maintenance

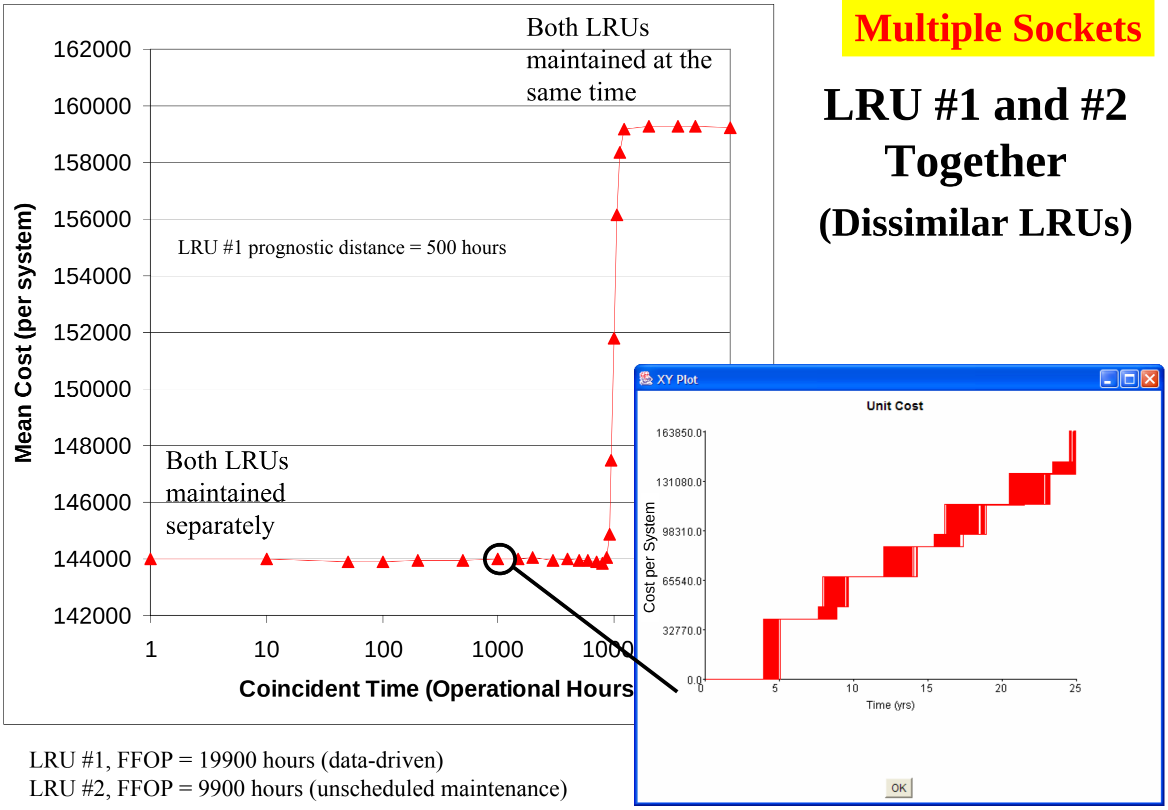
Weibull Time to Failure Distributions



Multiple Sockets

LRU #1 and #2 Together

(Dissimilar LRUs)

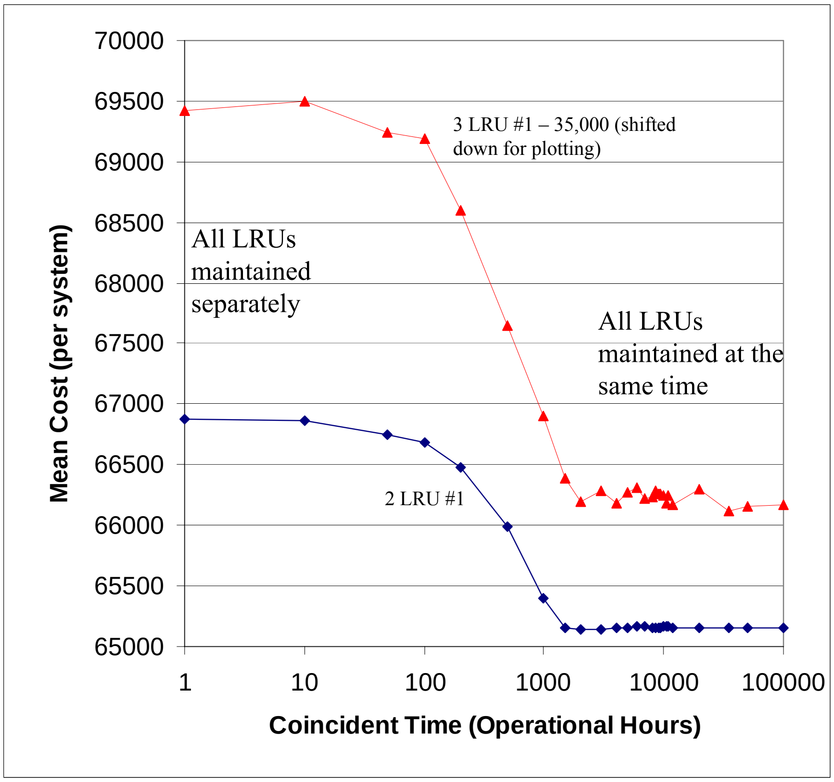


LRU #1, FFOP = 19900 hours (data-driven)
LRU #2, FFOP = 9900 hours (unscheduled maintenance)

Multiple Sockets

Multiple LRU #1 in a System

(Similar LRUs)



All LRUs using HM

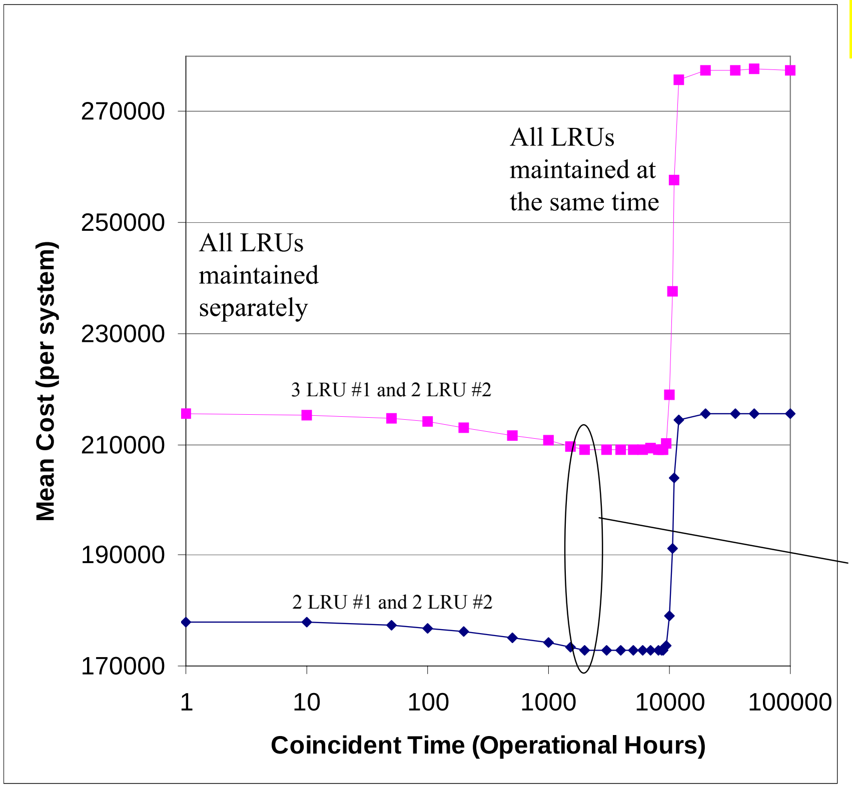
Prognostic distance = 500 hours in all cases

Height of step depends on number of hours to perform scheduled maintenance and the cost of those hours

Multiple Sockets

Multiple LRU #1 and #2 in a System

(Mixed LRUs)



Minimum life cycle costs are for coincident times = 2000 operational hours

All LRUs using data-driven

Prognostic distance = 500 hours in all cases

ROI for PHM

So, how do we formulate an ROI for PHM?

Problem #1 – The "return" in this case is not a return at all, it is a "cost avoidance," i.e., a reduction in costs that have to be paid in the future to maintain the system:

$$\mathrm{ROI} = \frac{\mathrm{Return} - \mathrm{Investment}}{\mathrm{Investment}} = \frac{\mathrm{Cost\ Avoidance}}{\mathrm{Investment}} - 1$$

Problem #2 - ROI compared to what? Some types of systems (e.g., electronics, consumer) are managed using unscheduled maintenance, i.e., operate the system until failure and perform the appropriate maintenance actions (repair or replace) to restore the system to operation. In other cases, it may be most applicable to compare to fixed interval maintenance.

Problem #3 – Separating PHM life cycle costs from non-PHM life cycle costs may be impossible to do.

ROI for PHM (continued)

- ROI relative to unscheduled maintenance gives

$$ROI = \frac{(C_{us} - I_{us}) - (C_{PHM} - I_{PHM})}{(I_{PHM} - I_{us})} - 1$$

where,

C_{us} = total life cycle cost using unscheduled maintenance
C_{PHM} = total life cycle cost using the selected PHM approach
I_{us} = unscheduled maintenance investment cost
I_{PHM} = PHM investment cost

- By definition, $I_{us} = 0$ (contains no investment in PHM)
- ROI becomes,

$$ROI = \frac{C_{us} - (C_{PHM} - I_{PHM})}{I_{PHM}} - 1$$

ROI for PHM (continued)

- Investment cost

$$I_{PHM} = C_{NRE} + C_{REC} + C_{INF}$$

where,

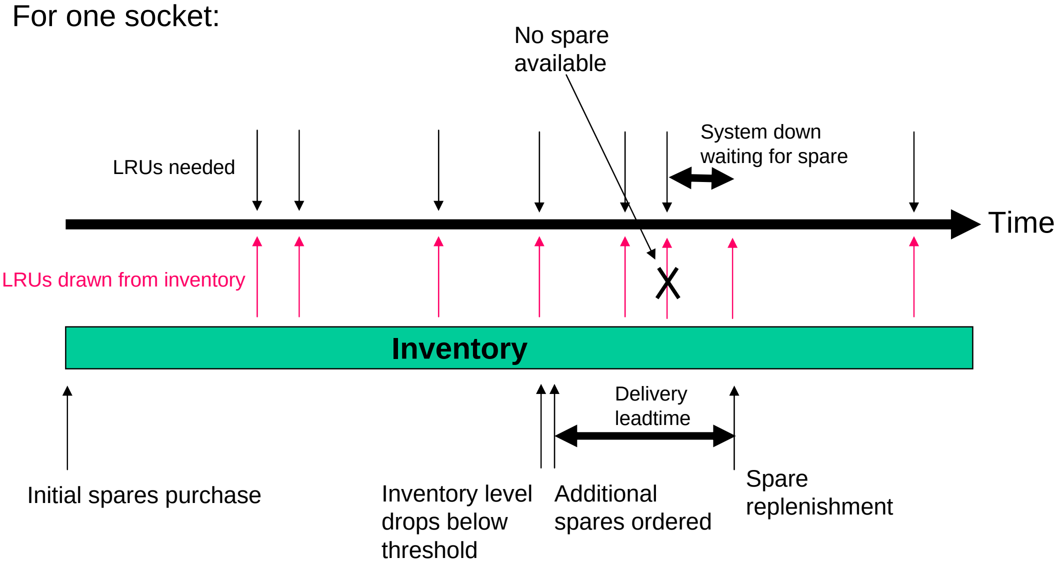
C_{NRE} = PHM non-recurring costs
C_{REC} = PHM recurring costs
C_{INF} = PHM infrastructure costs

- Not so fast! Is I_{PHM} complete? Are there other investment costs too?
- Example: Employing PHM will result in as many or maybe more maintenance events as unscheduled maintenance. If PHM results in the need for more spare replacement units, is the cost of these units an investment cost?

- The costs of: false alarm resolution, procurement of a different quantities of LRUs, and variations in maintenance costs are not included in the investment cost because they are the result of the investment and are reflected in C_{PHM}
- C_{PHM} must also include the cost of money differences associated with purchasing LRU at differently timed maintenance events

Spares Inventory
(in discrete event simulation)

For one socket:



No spare available

LRUs needed

System down waiting for spare

Time

LRUs drawn from inventory

X

Inventory

Delivery leadtime

Initial spares purchase

Inventory level drops below threshold

Additional spares ordered

Spare replenishment

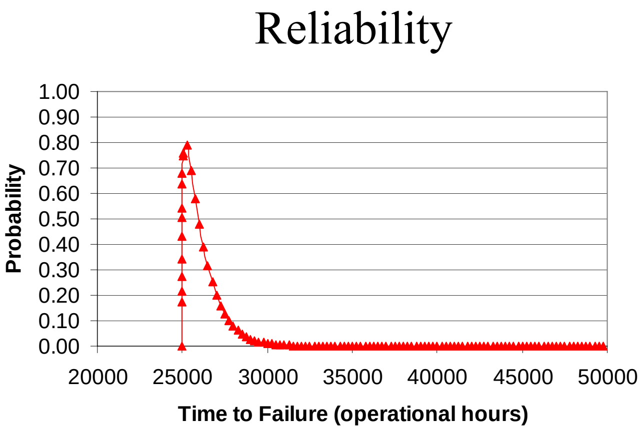
Costs:
- Initial spare purchase
- Replenishment spares purchase
- System downtime waiting for a spare
- Inventory
- Extra unused spares
- Cost of money

Example LRU

Base LRU: Sandel ST3400
TAWS/RMI Display Unit

LRU installed in a Boeing 737 Base cost: $25,000.

- 502 Aircraft in fleet
- 2 sockets per aircraft
- Support life: 20 years
- Negligible false alarms assumed
- 7% discount rate



Reliability

Model Inputs

Implementation Costs:

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

Unscheduled Maintenance Costs:

Maintenance Event	Probability	Value
Before mission (during preparation)	0.19	$2,880
Maintenance event during mission	0.61	$5,092
Maintenance event after mission (during downtime)	0.20	$500/hour

Operational Profile:

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

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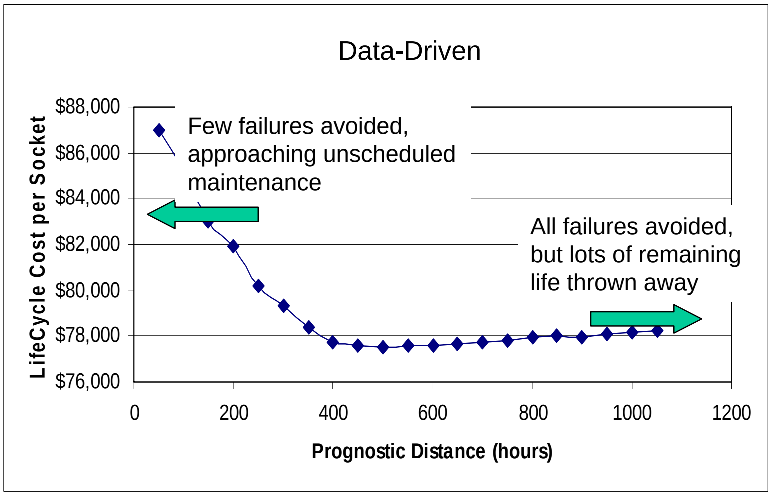
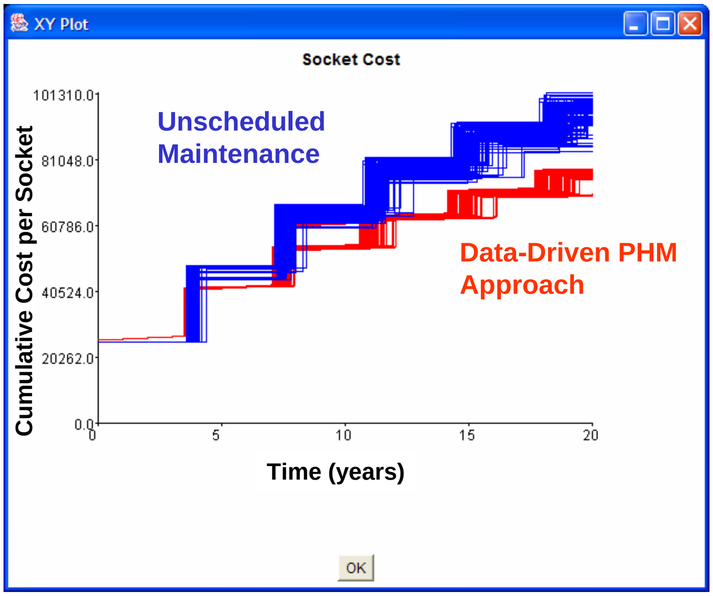
Prognostic Distance

- For a data-driven PHM approach, an analysis is performed to find the prognostic distance that yields the lowest cost



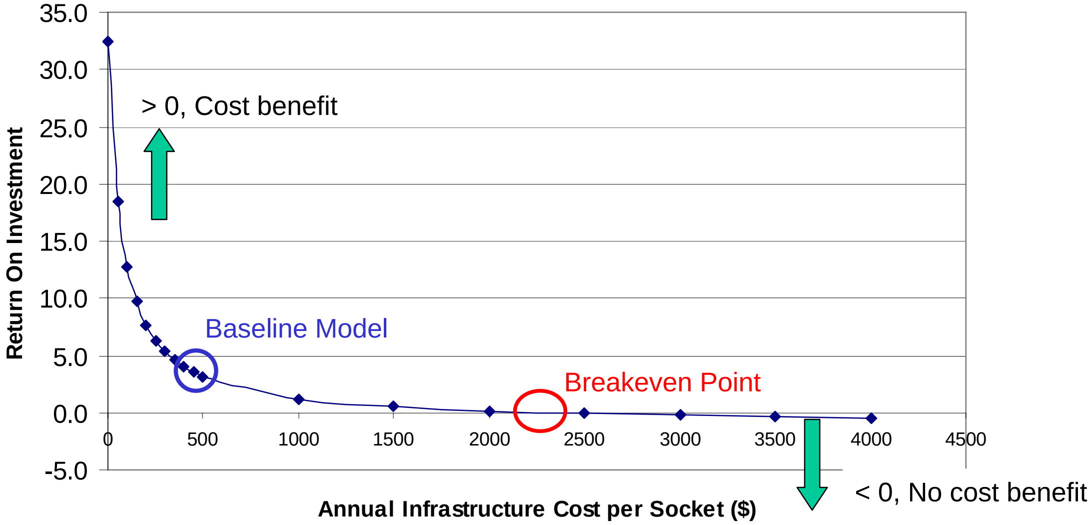
- The prognostic distance that produces the lowest costs is a function of the inputs and is application-specific
- For the data-driven approach, used here, the prognostic distance was chosen as 475 hours



(without spares inventory)

ROI Analysis: Data-Driven

The evaluation of ROI (relative to unscheduled maintenance) as a function of various implementation costs



ROI for PHM (continued)

More problems:

Problem #4 – The formulation we have measures the ROI of a PHM approach relative to unscheduled maintenance. How do we measure the ROI of one PHM approach relative to another?

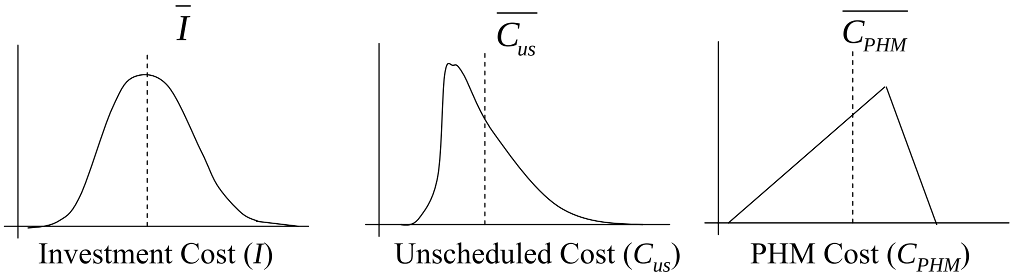
It is not valid to calculate the ROIs of each of the PHM approaches relative to unscheduled and subtract them. ROI of PHM_2 relative to PHM_1:

$$ROI = \frac{\left(C_{PHM_1} - I_{PHM_1}\right) - \left(C_{PHM_2} - I_{PHM_2}\right)}{\left(I_{PHM_2} - I_{PHM_1}\right)} - 1$$

Problem #5 – How can uncertainties be taken into account?

Non-Stochastic ROI

Non-Stochastic ROI Calculation:

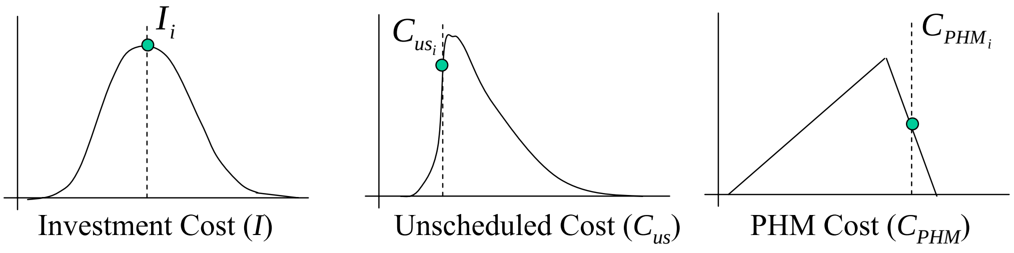


$$ROI_{PHM} = \frac{\overline{C_{us}} - \left(\overline{C_{PHM}} - \overline{I}\right)}{\overline{I}} - 1$$

This calculation is static, <u>not</u> stochastic. It uses values that are averaged over the whole population of sockets.

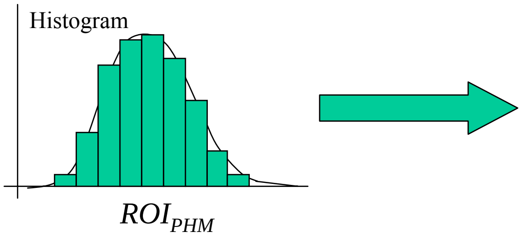
Stochastic ROI

Problem – a particular socket instance (socket *i*) may be represented by this set of values:



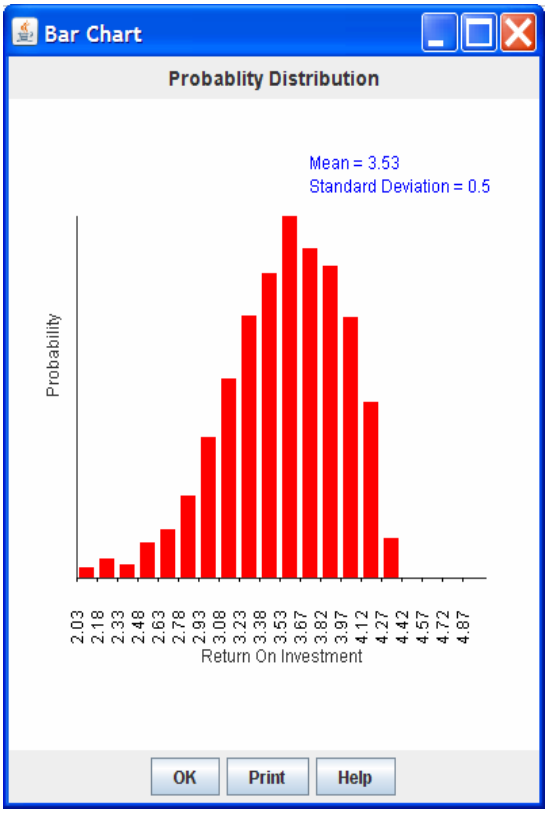
$$ROI_{PHM_i} = \frac{C_{us_i} - \left(C_{PHM_i} - I_i\right)}{I_i} - 1$$

ROI for each socket instance



Value:

- Mean ROI
- ROI uncertainty
- ROI confidence



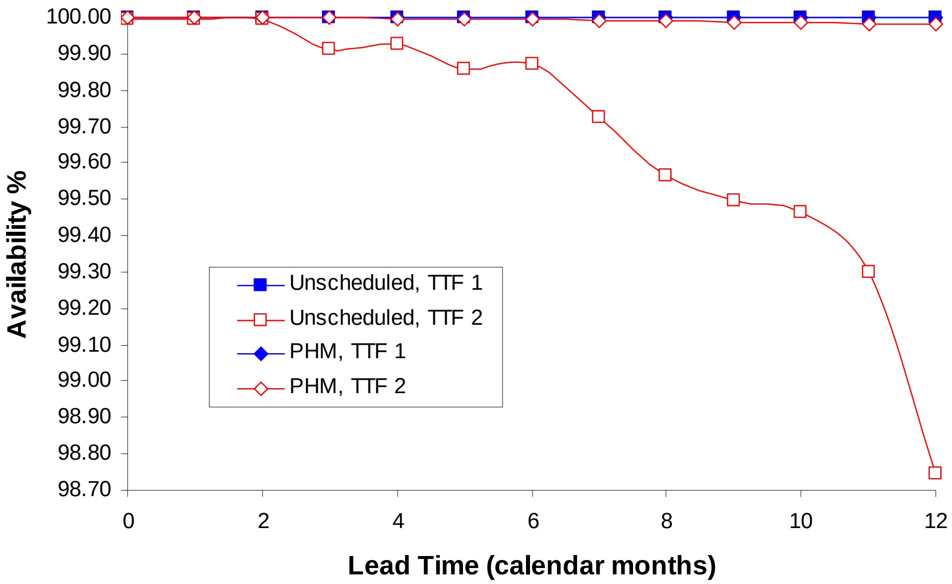
Histogram of ROIs

(Data-Driven)

Using this histogram (distribution), valuable business case parameters can be extracted, such as: assuming we have estimated the uncertainties in the input parameters appropriately, this case study indicates that we can have an 80% confidence that the ROI is greater than 2.8.

3000 sockets tracked

Availability Analysis



The Time to Failure distribution of the LRU were modeled as 3-parameter Weibulls:
TTF 1 = shape parameter 1.1, scale parameter of 1200, and a location parameter of 25,000 hours
TTF 2 = shape parameter 3.0, scale parameter of 25,000, and a location parameter of 0 hours

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Other Things to Consider …

- Redundancy
- Not “as good as new” repair
- Socket failures
- Multiple failure mechanisms
- Simple canaries modeled as LRU independent fuses, but may actually be mixtures of fuses and LRU-independent methods
- Second order uncertainty (uncertainty about uncertainty) may be a very real thing for this analysis
- Determining the right shape and size of distributions associated with various PHM approaches

Resources

General Cost/Maintenance Model Description:

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