Tutorial Session 4: Return on Investment
(Determining the Cost and Value of PHM)

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Cost and Return on Investment (ROI) Analysis

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The Fundamental Maintenance/Value Tradeoff

Goal (depending on application) is either to:

Perform maintenance so that the remaining useful life (RUL) and the remaining useful performance (RUP) are minimized (use up as much of the life as possible), while simultaneously avoiding failures (unscheduled maintenance)

or

Find the optimum mix of scheduled and unscheduled maintenance that minimizes the life-cycle cost

Note, we are not advocating the avoidance of all failures here, this is NOT a “safety” argument, it is an economic argument.
Deriving Value from PHM at the System and Enterprise Levels

– System-level PHM value means taking action based on prognostics to manage one specific instance of a system, e.g., one truck or one turbine. The actions tend to be “real-time” and consist of:
  • Modify how you sustain the system (e.g., call ahead to arrange for a maintenance action)
  • Modify the mission (e.g., reduce speed, take a different route)
  • Modify the system (e.g., adaptive re-configuration)

– Enterprise-level PHM value means using prognostics to manage an enterprise, e.g., a whole fleet of trucks or a farm of turbines. The actions are longer-term strategic planning things (usually not real-time):
  • Optimizing the logistics
  • Management via availability and other outcome-based contracts

The optimum for an individual system instance ≠ the optimum for the system instance within a population if the population is managed via an outcome-based contract

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)
    - Lead time reduction
    - Better use of (control over) inventory
  - Minimization of investment in external test equip
  - Optimization of resource usage
- Repair
  - Better diagnosis and fault isolation (decreased inspection time, decreased trouble shooting time)
  - Reduction in collateral damage during repair
  - Reduction in post-repair testing
- Reduction in redundancy (long term)
  - Can redundancy be decreased for selected sub-systems?
- Reduced waste stream
  - Less to end-of-life (dispose of) – disposal avoidance
  - Reduction in take-back cost

Problem: Future cost avoidance is a hard sell

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.
Discrete Event Simulation (DES)

- Dynamic simulation (models changes over time)
- State variables change only at a discrete set of points in time (i.e., at “events”)
- Event = something that happens to the system at an instant in time that may change the state of the system (by definition, nothing relevant to the model changes between events)
- Discrete (successive changes are separated by finite amounts of time)
- Timeline = the sequence of events and their calendar times
- Path = a particular sequence of events

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 to the socket after repair

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 PHM

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

2) Predict failure date of LRU in the socket

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

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

6) Compute/accumulate:
   - Life-cycle 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

Discrete Event Simulation – Data-Driven

- 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)
Very Simple Baseline Data
Assumptions for the Example Cases

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

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

PHM Approaches

- Reliability-Based – Historical reliability predictions used to produce failure distributions
  - Average part, average environmental stress
- Model-Based (Physics of Failure) – Observing the environmental stress history that a system has been subjected to and deciding based on an understanding of a nominal system, that the system may be unhealthy (indirect method) – degradation inferred from environmental stress
  - Average part, actual environmental stress
- Data-Driven – Directly observing the system and deciding that it looks unhealthy (e.g., precursor to failure, LRU-dependent canaries, anomaly detection) – measured properties are correlated to actual failure
  - Actual part, actual environmental stress
- Fusion – Combines data-driven and physics of failure approaches together to enable calculation of remaining useful life (RUL)
Background – Time to Failure (TTF) Distributions

- Doesn’t have to be “time”, could be thermal cycles, miles, takeoffs and landings, etc.
- Triangular distributions shown for simplicity

If the test was run until all instances of the product failed, then the area under the curve is 1 and we have a PDF of failures.

The LRU’s TTF distribution represents variations in manufacturing and materials.

Fixed Interval Scheduled Maintenance

The TTF distribution is wide when the width of the time to failure distribution is large.

The TTF distribution is narrow when the width of the time to failure distribution is small.

Effective Life Cycle Cost (per socket)
Data-Driven Methodologies
(Precursor to Failure, Health Monitoring, LRU Dependent Canary)

- Example: A canary 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

Model-Based Methodologies
(LRU Independent, Life Consumption Monitoring (LCM), LRU Independent Canary)

- 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.
Comments

The fundamental difference between the two models:

- Data-Driven = the TTF distribution associated with the PHM structure (or sensor/canary) is unique to each LRU instance
- Model-Based = the TTF distribution associated with the PHM structure (or sensor/canary) 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
### Data-Driven vs. Model-Based Methods

(Varying PHM Distribution Width)

#### Model-Based

- 2000 hr TTF width, 1000 hr MB width
- 2000 hr TTF width, 2000 hr MB width
- 2000 hr TTF width, 4000 hr MB width

#### Data-Driven

- 2000 hr TTF width, 1000 hr DD width
- 2000 hr TTF width, 2000 hr DD width
- 2000 hr TTF width, 4000 hr DD width

(10,000 sockets followed)

### 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

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### Single Socket

**Variations in PHM distribution width**

**PHM Width**

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**PHM Approach Time-to-Failure**
Multiple Socket Systems

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

If \[ |\text{Time}_{\text{current maintenance action}} - \text{Time}_{\text{required maintenance action on LRU } i}| < \text{Time}_{\text{coincident}} \]

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

Two different LRUs that are part of the same system.

LRU1 Timeline

LRU2 Timeline

Cumulative Timeline

- \( \text{LRU1 and LRU2 Replaced} \)
- \( \text{LRU1 and LRU2 Replaced} \)

\( \text{LRU instance-specific TTF samples} \)
Evaluating the Return on Investment (ROI) Associated with PHM

What is ROI?

\[
ROI = \frac{\text{Return - Investment}}{\text{Investment}} = \frac{\text{Cost Avoidance - Investment}}{\text{Investment}}
\]

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
Formulating an ROI for PHM

- ROI relative to unscheduled maintenance gives

\[
ROI = \frac{C_{us} - C_{PHM}}{I_{PHM}}
\]

- Investment cost

\[
I_{PHM} = C_{NRE} + C_{REC} + C_{INF}
\]

ROI for PHM (continued)

- 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?

This cost is a result of the investment, not part of the investment

- 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 LRUs at differently timed maintenance events
Example: PHM Return on Investment

Sandel ST3400 TAWS/RMI
Electronic Display Unit

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


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

\[ \text{Life Cycle Cost per Socket} \]

\[ \text{Prognostic Distance (hours)} \]

\[ $76,000 \to $78,000 \to $80,000 \to $82,000 \to $84,000 \to $86,000 \to $88,000 \]

\[ 0 \to 200 \to 400 \to 600 \to 800 \to 1000 \to 1200 \]
Cumulative Life-Cycle Costs

ROI Analysis: Data-Driven

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

> 0, Cost benefit

< 0, No cost benefit
ROI as a Function of Time

ROI of data-driven PHM relative to unscheduled maintenance

ROI for the Application of PHM to Wind Turbines (EADS)

TRIADE includes temperature, pressure, vibration, strain and acoustic sensors that can be used to monitor the health of turbine blades in a wind turbine

Time history of 1000 wind turbines:

Other Things to Consider …

- Redundancy
- Not “as good as new” repair
- Socket failures
- Multiple failure mechanisms
- Simple canaries are 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

Making Business Cases

- Cost avoidance is a hard sell
- Program/project management hears that the “sky is falling” every day from engineers
- Resource allocation is based on:
  1) The occurrence of serious events
  2) Projected future impact (cost, availability)
Resources

General Cost/Maintenance Model Description:


Return on Investment Modeling:


http://www.enme.umd.edu/ESCML/Papers/Feldman_et_al_IEEE_Trans_Rel.pdf

PHM Applied to Electronics: