PHM Enabled Logistics
(Return on Investment and Availability Management)

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Definition of Logistics

Logistics is the management of the flow of goods, information and other resources, including energy and people, between the point of origin and the point of consumption in order to meet the requirements of customers.

Business View:
- Supply chain management
- Distribution planning
- Transportation management
- Inventory management
- Purchasing
- Customer service

Manufacturing Support

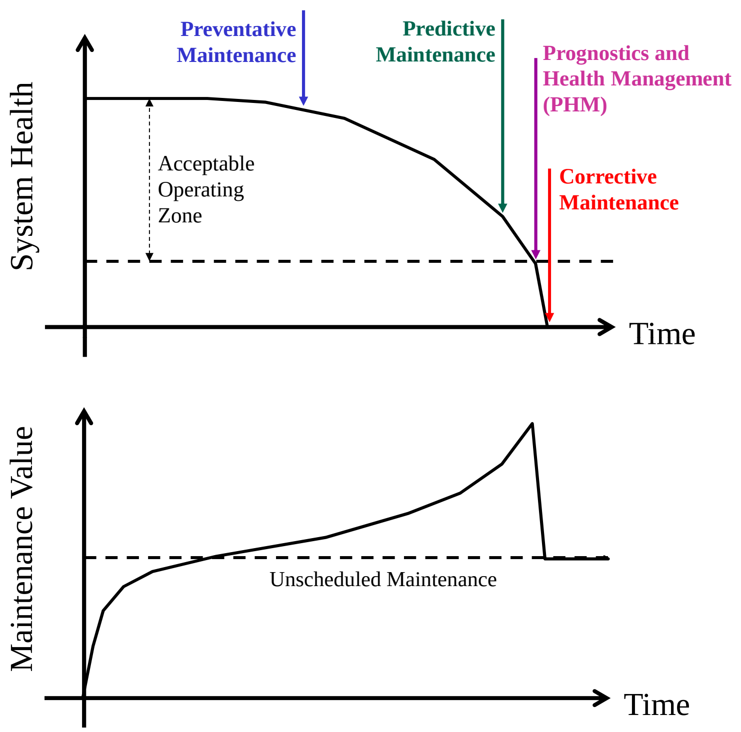
Sustainment View:
- Sparing
- Maintainability
- Affordability
- Availability
- Readiness
- Obsolescence management

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. The actions tend to be “real-time” and fall into the following categories:
  - Modify the sustainment (e.g., call ahead to arrange for a maintenance action)
  - Modify the system (e.g., adaptive re-configuration)
  - Modify the mission (e.g., reduce speed, take a different route)

– Enterprise-level PHM value means taking action based on prognostics to manage an enterprise, e.g., a whole fleet of trucks. The actions are longer-term strategic planning things (usually not real-time):
  - Optimizing the logistics
  - Adapting the business models

The Fundamental Maintenance/Value Tradeoff

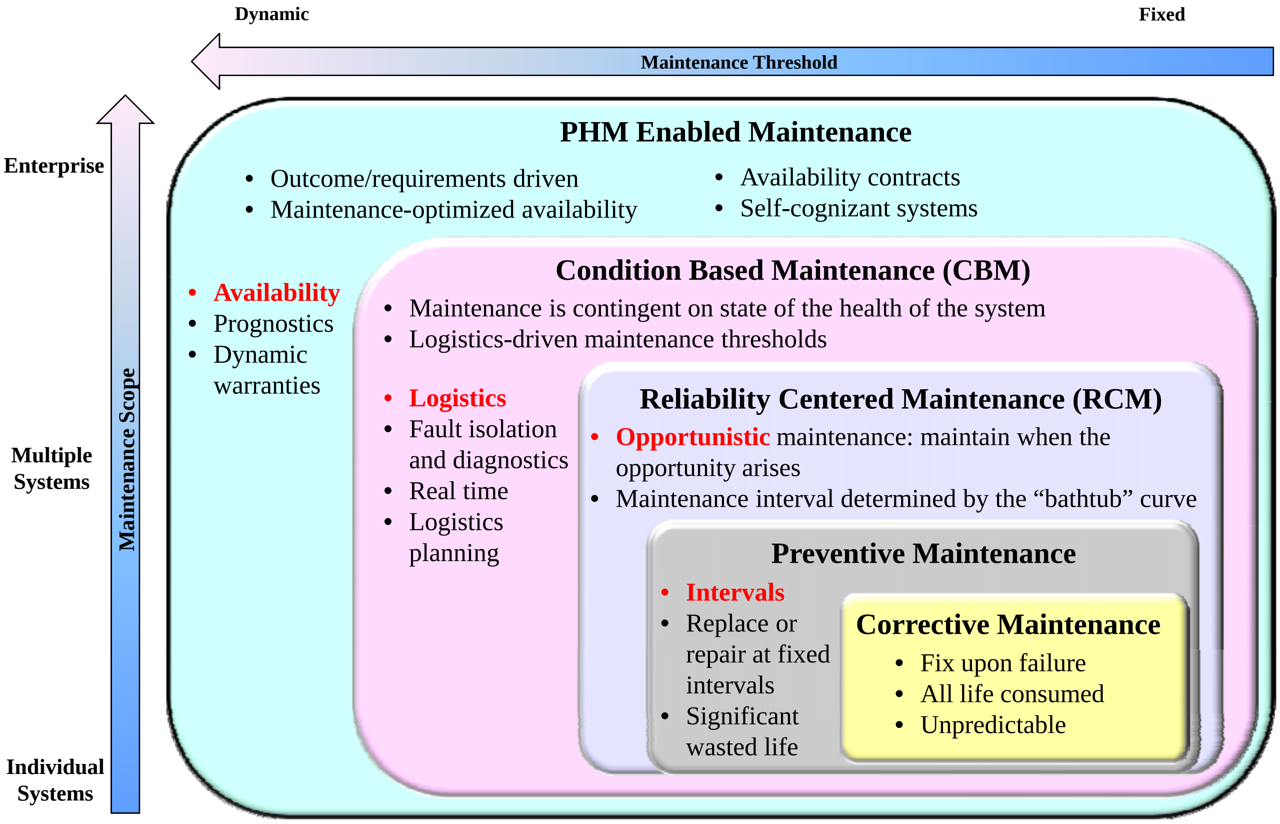


<u>Goal (depending on application):</u> Perform maintenance such that the remaining useful life (RUL) and the remaining useful performance (RUP) are minimized, while avoiding unscheduled maintenance

<u>or</u>

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

Evolution of Maintenance Paradigms



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
- Reduction in no-fault-founds
- Eases design and qualification of future systems
- Reduced liability
- Warranty claim verification (resulting in warranty reserve fund reduction)

Estimated Costs of Wind Turbine Condition Monitoring

- Condition monitoring system lifetime cost
  - $11,000
- Repair cost for the gearbox
  - 40% of the cost of a new gearbox if detected with condition monitoring
  - 70% of the cost of a new gearbox if detected during routine inspection
  - 100% of the cost of a new gearbox if run to failure (not repairable if run to failure)
- Up-tower repair costs (cost of the maintenance crew and resources)
  - $80,000 per event if predicted or planned
  - $140,000 per event if unscheduled

(EPRI, 2011)

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

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

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

- Investment cost

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

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

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

Feldman, Jazouli, and Sandborn, "A Methodology for Determining the Return on Investment Associated with Prognostics and Health Management," *IEEE Trans. On Reliability, June 2009.*

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

Time

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)

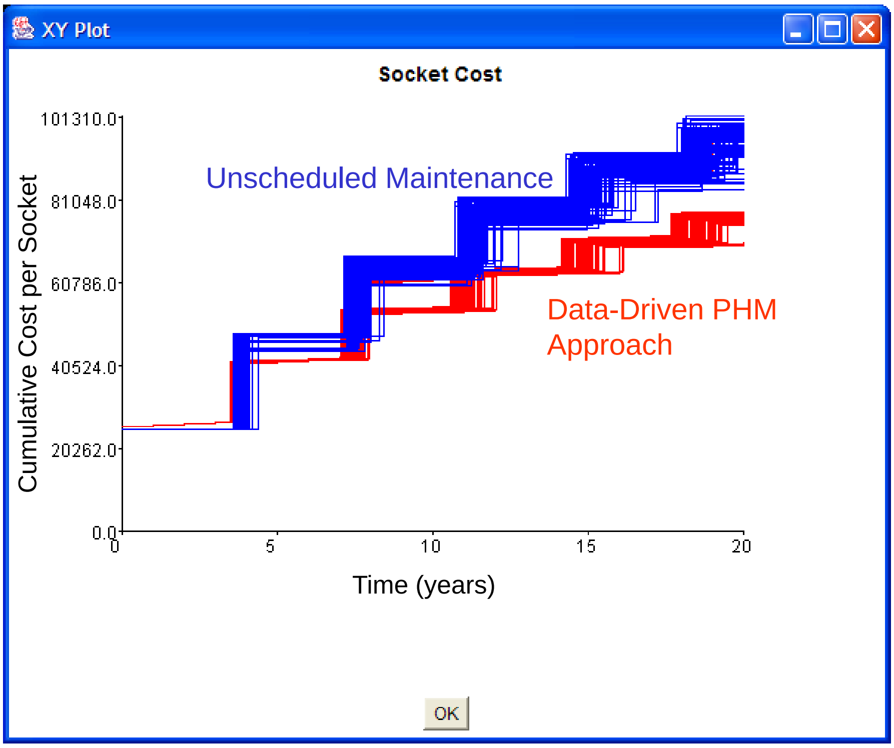
6) Compute/accumulate:
- Lifecycle cost/socket
- Cost/operating hour
- Availability
- Failures avoided
- Number of LRUs/socket

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

*Socket = A socket is a location in a system where a single instance of the item being maintained is installed. The socket may be occupied by one or more items during the lifetime of the system.

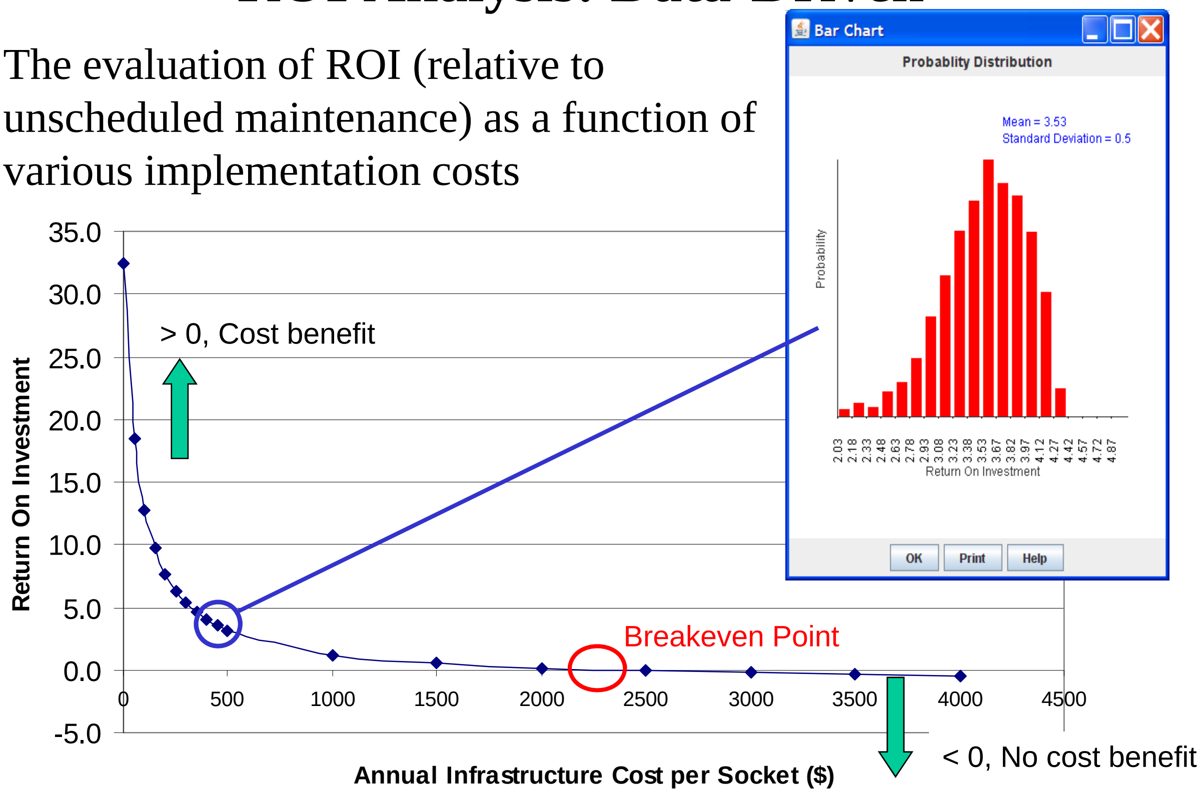
Cumulative Life Cycle Costs



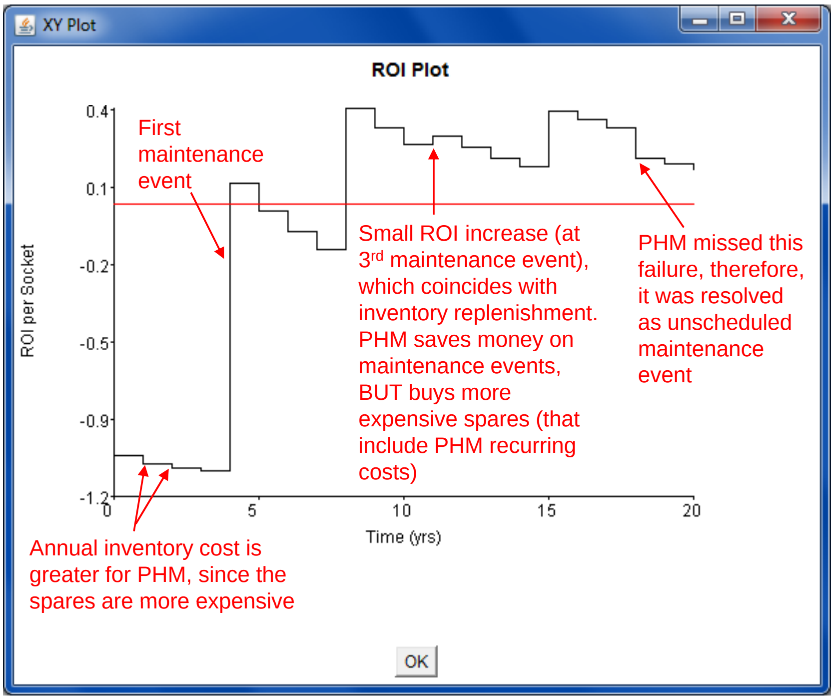
(without spares inventory)

ROI Analysis: Data-Driven

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



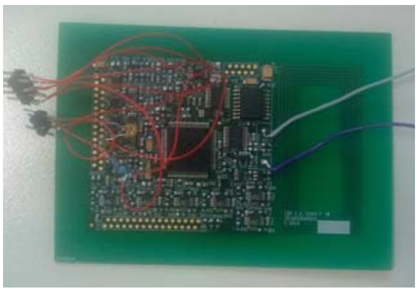
ROI as a Function of Time



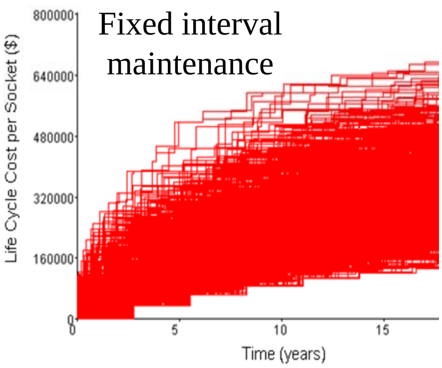
ROI of data-driven PHM relative to unscheduled maintenance

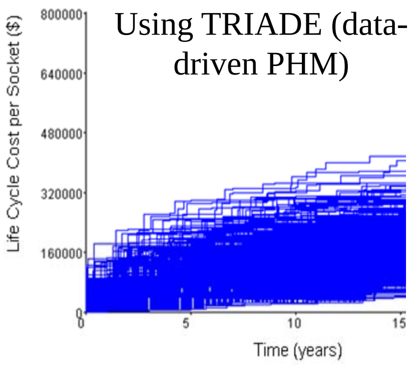
ROI for the Application of PHM to Wind Turbines (EADS)

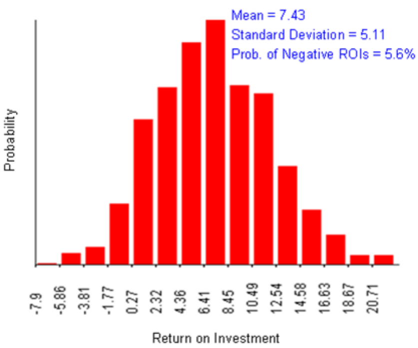
TRIADE includes temperature, pressure, vibration, strain and acoustic sensors that can be used to monitor the health of turbine blades in a wind turbine



Time history of 1000 wind turbines:







Haddad, Sandborn, Jazouli, Foucher, and Rouet, “Guaranteeing High Availability of Wind Turbines,” *Proc. ESREL*, 2011.