The Rise and Fall of CBM

Jacek S. Stecki
Plan of Presentation

→ Expectations

→ Technological progress (sensors, techniques, methods etc.)

→ Barriers to implementation

→ CBM/PHM

→ Risk assessment

→ Modelling failure

→ Taxonomy

→ Sensor fusion

→ Jet Engine lubrication system – example

→ Concluding remarks
Defence equipment and systems function in harsh environmental and operational conditions and must meet stringent requirements of reliability, safety, availability and maintainability – particularly with the introduction of performance based contracts (PBC).

To reduce the high cost of development for new products, OEMs use a vast array of computer aided techniques during the design and testing stages.

Maintainability requirements, long ignored by designers and OEMs, has assumed great importance and forced a rethinking of the way the design of new systems should be carried out.

Availability is a major constraint, and it has became important to develop techniques to monitor the health of a system, to diagnose system problems prior to its failure and to prognose the system's remaining life.

Efforts have been made to justify these new design approaches with a business case that reflects PBC requirements and the current US DoD system acquisition policies that focus on the cost of sustainment over the entire system life cycle.

Maintenance Technology has become recognized as an academic discipline.

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Expectations

- Enhanced system reliability and equipment safety
- Reduced maintenance manpower, spares and repair costs
- Eliminate or significantly reduce scheduled inspections
- Maximised lead time for maintenance and parts
- Procurement
- Automatically isolated faults
- Real time notification of an upcoming maintenance event for the logistics chain
- Catch potentially catastrophic failures before they occur
- Detect and monitor incipient faults until just prior to failure
The Rise of CBM

→ Rapid progress was made in the 1960s - 1980s in the development of new sensors, symptom monitoring techniques and performance monitoring in aircraft, marine, railways and mining machinery applications

→ During this period, monitoring techniques were seldom used together to provide comprehensive and reliable detection and diagnosis of failures

→ Likewise, research on detection and diagnostic techniques and methodology was usually directed towards a single technique; for example: vibration monitoring

→ The situation changed in the early eighties when the concept of On-Condition Maintenance was developed [over the years the name changed to Condition Based Maintenance (CBM)] and applied in high risk industries like aviation, mining and offshore oil production

→ Since the 1990s there has been significant progress in the development of new sensing techniques, diagnostic and prognostic methodologies and the application of computer analysis techniques
Technical Barriers to effective CBM

The Advanced Technology Program (ATP), of the National Institute of Standards and Technology (NIST), held a workshop on Condition-Based Maintenance (CBM) as part of its November 17-18, 1998 Fall Meeting in Atlanta.

Discussions with companies identified 3 technical barriers to CBM's widespread implementation:

→ The inability to accurately and reliably predict the remaining useful life of a machine (prognostics)
→ The inability to continually monitor a machine (sensing)
→ The inability of maintenance systems to learn and identify impending failures and recommend what action should be taken (reasoning).

These barriers could potentially be addressed through innovations in three technical areas:

→ Prognostication capabilities
→ Cost effective sensor and monitoring systems
→ Reasoning or expert systems
Systemic Barriers to effective CBM

→ In many military/industrial applications the metrics for evaluating successful implementation of CBM are not clearly defined (risk, economics, performance)
→ Lack of clear guidelines or business case for when and why CBM is preferred to other maintenance approaches (technical/economic)
→ CBM programs are initiated without full knowledge of how the system can fail
→ The effectiveness of a CBM program cannot be evaluated with current management tools.
→ Maintenance requirements/specifications are not defined at the concept formulation stage of the design process
→ Identification of an optimum level of diagnostic and prognostic requirements and specifications is not generated
→ Selection of an optimum monitoring mix (selection of sensors) should be system oriented but is often driven by the vendors of sensors
→ Maintenance management systems are inadequate
→ Historical data, postmortem results not available or accessible
→ Uncertainty of ROI (Plant Services Magazine (USA)”. In a survey of 500 companies, less than 3% of respondents were able to achieve a measurable return on their investment in Predictive Maintenance technologies”)
Knowledge Barriers to effective CBM

→ Limited or no knowledge retention about CBM within the OEM or customer
→ Skills issues are not addressed
→ Education of CBM managers/engineers not available at Universities (Monash University had undergraduate/postgraduate programs in CBM supported by multidisciplinary laboratory from 1980 to 1996)
→ Widespread research in CBM but it is invariably directed towards specific techniques (better mousetrap symptom)

Google “Condition based Maintenance” - 33,000,000 hits!
Google “Condition based Maintenance barriers” - 1,080,000 hits!
Google “Gearbox Condition monitoring” - 44,000 hits
Google “Bearings Condition monitoring” - 350,000 hits
Google “Vibration Condition monitoring” - 351,000 hits
Google “Contamination Condition monitoring” - 304,000 hits
CBM / PHM / RCM and other TLAs

→ The methodologies and approaches of CBM evolved from On-Condition Maintenance (OCM)
→ Reliability Centred Maintenance (RCM) is a variant of the CBM approach
→ PHM is a further evolution of the CBM concept, and is also sometimes referred to as Vehicle Health Management (VHM)
The PHM cycle

An effective PHM implementation for a system requires two main cycles of development: design and operation.

→ The Design Cycle is required in order to generate the knowledge base from which the PHM system can obtain its decisions.

→ The Operation Cycle describes the steps taken within the PHM system from detection of faults through to conveying instructions or actions.
CBM/PHM - what are we dealing with?

Fault Tree

- Training
- Diagnosis
- Sensors
- Reliability
- FMECA

Failure modes

- Production Losses
- Detection
- Prognostics
- BIT
- Simulation

Condition monitoring

- Maintenance
- Testing
- Hazards
- Safety

Fall-back Analysis

- ROI

Risk Minimization

- Detection
- BIT
- Simulation
- Downtime
- Safety

Education

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Interaction of MAD and CBM/PHM Layers at Design Stage

System Concept

System specification

Constraints

Functional diagram

FAST

PHM Layer

Optimization

Life cycle

PHM Layer

Techniques

Diagnostics

Prognostics

Sensors

Sensor set

FMECA/HAZOP

Risk Layer

Techniques

Faults

Functions

MAD Layer

Implementation

Manufacturing

Design process

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Case Study - Mining

- 12 mine sites – mining trucks, conveyors, shovels etc.
- Data from mines' maintenance management systems
- Approx 500 MB of data collected over period of up to 5 years
- Limited number of detection/diagnostic/techniques
- External contractors – no in-house knowledge
- Only 4 sites had useful information – although incomplete

Conclusions (from the report):
- Sampling/detection and diagnosis do not follow the best practice to achieve meaningful indication of machine state
- Any reporting should have have deliverables, or information will not be useful.
- Unspecified conditions before failure occurred
- Lack of information of how the system, component, part failed ie. postmortem
- Outline the reactive and pro-active activities.
- Unknown or missing – grade and quality of roads, drivers, trained, gender, mechanics, conditions, weather, material being hauled, oil used, petrol used, original parts used, shift work, 7 day week, support, underground, humidity, walk around each day, same route etc.
- Effective FMEA/FMECA Analysis should be conducted prior to monitoring
- No visible CBM design/plan
- No possibility to assess ROI
Subsea / Aerospace

Risks
→ Severe operating environment
→ Stringent statutory safety standards
→ Safety critical systems
→ Expensive maintenance
→ Long innovation lead time
→ High technology
→ Conservative attitudes
→ High reliability requirements
→ Single shot operations
→ Very high cost of failure

Tools to deal with risks
→ Computer based design methods
→ Reliability and Hazard Analysis
→ Failure analysis (FMECA/FTA)
→ PHM (Prognostics and Health Management)
→ Condition Monitoring - CBM
→ Testing
What is it?

→ Risk assessment using techniques like FMECA, HAZOP, RCM etc.
→ Diagnostics – is the process of determining the state of a component to perform its function(s)
→ Prognostics – is predictive diagnostics which includes determining the remaining life or time span of proper operation of a component
→ Health Management – is the capability to make appropriate decisions about maintenance actions based on diagnostics/prognostics information, available resources and operational demand.
Criteria for RCM Processes

SAE JA1011 “Evaluation Criteria for RCM Processes” defines seven questions for RCM:

- What are the functions...of the asset...(functions)?
- In what ways can it fail...(functional failures)?
- What causes each functional failure (failure modes)?
- What happens when each failure occurs (failure effects)?
- In what way does each failure matter (failure consequences)?
- What should be done...(proactive tasks and intervals)?
- What should be done if a suitable proactive task cannot be found?
Risk Assessment - FMECA

Failure Modes
- Possible Failures

Effects
- What effect does the failure have?

Criticality Analysis
- Criticality Analysis of each failure
Risk Assessment – e.g. FMECA

Why FMECA is carried out

→ Statutory requirement – must be done
→ We need to have audit trail in case of problems
→ A need to know of how to improve system safety
→ The integrator insisted on it
→ Reliability people need it

Why FMECA should be carried out

→ We need to know what to monitor and what sensors to use
→ We need to have capability to detect, diagnose and prognose the state of the system
→ To design-out failures
→ We need to know how the system can fail so we are prepared to deal with it
→ To enhance diagnostic capabilities
Reasons for failure of Risk Assessment

→ Dependencies of failures not identified – spreadsheet vs model based
→ Inadequate Identification of Risks - functional failures (failure modes) vs physical failures
→ Incomplete database of failures (deficient FMECA)
→ Taxonomy – confusion what is the cause, mechanism of failure, fault, symptom and/or failure mode
→ Symptom vs Syndrome approach
→ Sensor fusion not based on failures dependencies (fall-back – testability)
→ Diagnostic rules not based on dependencies
→ Reliability of Hardware not the same as Functional Reliability
→ Different models for Criticality and Reliability Assessment
Risk reduction or is it?

- Risk is still there if failures are missed
- We cannot design a diagnostic system without knowledge of failures
- We do not really know what we should monitor
- Sensors cover only identified failures

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Dependencies Modelling

- **Component**
- **Connector**

**Fault**

**Pressure P down**
- Q down (e.g., pipe leakage)
- Q down (e.g., pump leakage)
- Q up (e.g., check valve leakage)
- Q up (e.g., relief valve open)

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Fault propagation - dependability

→ All faults are enumerated.
→ Transient and steady-state responses to faults are identified.
Model of a Pump

- Vibrations
- Noise
- Heat
- Wear debris
- Symptoms

- RPM
- Suction conditions
- Pump size

- Produce flow

- Disturbances
- Temperature
- Contamination
- Aeration

- Response

- Flow rate OK
- Too high

- Too low
- No flow

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Modelling of failure

The external and environmental disturbance (e.g. ambient temperature) → Disturbances → Root causes

Load → Time → Temperature → Environment

Failure agents → Failure cause

Physical/chemical processes → Misapplication → Design defects → Disturbance

Environmental factors → Parameters changes

Sensors → Symptoms → Losses

Material → Energy → Signal → Environment

Component: Pump
Function: Deliver Flowrate

Fault (State) → Failure Mechanism

The physical process that results in a failure to a system, device or process.

Failure Mode of subassembly

An operating condition or device state which is abnormal or unexpected.

e.g. broken shaft

Failure Mode

The manner in which the failure is observed

e.g. no torque

e.g. pump flowrate null

e.g. no pump pressure

Failure Effect

The consequence of failure mode

Fault (State)
## Taxonomy problems

<table>
<thead>
<tr>
<th>Source - Item</th>
<th>Failure term</th>
<th>Cause</th>
<th>Mechanism</th>
<th>Fault</th>
<th>L/S</th>
<th>FF</th>
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L/S = Loss/Sympton  
FF = Functional Failure  
LIF = Lower Indenture Level Failure
## Taxonomy problems

<table>
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<tr>
<th>Function</th>
<th>Failure Modes</th>
<th>Effects</th>
<th>S</th>
<th>C</th>
<th>Causes</th>
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<th>Detection Action</th>
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Failures - Symptoms/Syndromes

Symptom

Symptom

Symptom

Symptom

Symptom

Syndrome of failure
RR250 Engine Lubrication System
Engine Lubrication System Model
Define Component Structure
Define Component Functions
Define Physical Failures
Propagate Functional Failures >> Dependency

[Diagram of lubrication system for RR250-20C Engine]

<table>
<thead>
<tr>
<th>Component</th>
<th>Flow Property</th>
<th>Failure</th>
<th>3 Scavenge Pump</th>
<th>3 Scavenge Pump</th>
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<th>Check Valve</th>
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<th>Check Valve B7</th>
<th>Cooler Bypass Valve</th>
<th>Flex Shaft Coupling</th>
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</table>
Assess Criticality

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Produce FMEA/FMECA Report

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Assess hardware Reliability
Define Sensors Locations

---

### Lubrication system for RR250-20C Engine

<table>
<thead>
<tr>
<th>Name</th>
<th>Location</th>
<th>Type</th>
<th># of Sensors</th>
<th>Coverage</th>
<th>Possible Cov.</th>
<th>Cost</th>
<th>Weight (kg)</th>
<th>Description</th>
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<tr>
<td>Dynamic Sensor Set</td>
<td>Lubrication system for RR250-20C Engine</td>
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NATO RTO Workshop – “Implementation of Condition Based Maintenance”
Bucharest, Romania
4-6 October 2010
Select sensors and generate diagnostic rules
PHM Design Cycle Deliverables

At the end of the risk assessment process, the user has knowledge of:

→ How the system can fail (failure modes)
→ How critical each failure is
→ What are the causes of functional failures
→ What are the interactions between functional failures
→ What physical failures are linked to functional failure
→ Where to place sensors – i.e sensor fusing
→ How to monitor physical failures
→ How to diagnose functional failure
→ What is the expected reliability of the sensing system
→ What is the expected functional and hardware reliability of the system
Concluding Remarks

Despite expectations the acceptance and effectiveness CBM is in question. To be effective:

- CBM/PHM programs must be designed and executed with the knowledge of the risks to which a system is exposed, i.e. the knowledge of how the system fails.
- Model-based failure analysis, defining failures dependencies and improving the completeness of risk identifications, should be adopted in preference to checklists and “spreadsheet” based FMECA methodology or tools.
- Model-based failure analysis should be adopted to enhance knowledge retention, knowledge transfer and to facilitate integration of risk assessment through supply chains.
- Standardised taxonomies of functions, failure concepts and components should be adopted to improve readability/portability of risk assessment results.
- Diagnostic rules and Sensors sets should be selected on the basis of the identified dependencies between failure modes (symptoms >> syndrome).
- Clear hierarchy of failure concepts should be enforced in the risk assessment process (cause > failure mechanism > fault > failure mode).
- Physical failures (cause/failure mechanism/fault) and their symptoms should form the basis for BIT design.