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A Study of Condition Based Maintenance for Land Force Vehicles

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ABSTRACT

Condition Based Maintenance (CBM) is a method of both diagnostic and prognostic maintenance that has been used extensively in the air environment. This report describes a literature review of CBM where it relates to the land-based platform maintenance in particular. The review outlines the current state of CBM analysis, and in particular in terms of prognostic fleet management. Emphasis is further placed on an enquiry into the costs and benefits of CBM for land force equipment maintenance. A number of CBM cost-benefit studies are used as case studies to provide a framework for future analysis, including the potential challenges and the issues that CBM could bring to Army if implemented. The insights gained from this review give an understanding of the introduction and implementation of CBM to legacy fleets, but in particular the adoption of CBM into new equipment fleets such as LAND 400.

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Executive Summary

There has been a drive over recent years to incorporate the concepts of condition monitoring which have been developed in the air environment into the domain of land-based platform maintenance. Under this paradigm maintenance transition from a time-based construct to one based on the need, or condition, of the platform itself. This Condition Based Maintenance (CBM) remains relatively new within the context of legacy military land vehicles within the Australian Army, yet it is likely to become more prevalent with future platform acquisitions, such as LAND 121 and LAND 400 in particular.

This report presents a literature review of CBM, with emphasis placed on the issues relating to land platforms. An important component of this review is an attempt to articulate what is understood in terms of a CBM system, and to provide a working definition for discussion. Another central theme of this review is to inform debate on developing a value proposition for CBM being introduced into Army, and in new fleets in particular. An important component of this is to understand the cost-benefit analysis that has been done to date and identify relevant factors for any future work conducted by Land Operations Division.

Whilst the literature review found technical papers focusing on the capacity to sense equipment condition, there were fewer dealing directly with the health prediction of specific sub-systems. There is less published on the success or otherwise of actual systems applied to land vehicles. Indeed, the predominant focus has been the technology aspects of the sensors themselves. There has been less analysis on the broader requirements of CBM beyond the platform, or indeed how CBM might inform decisions at different levels within Defence, or how it might be used to prime the spares supply chain. The report outlines at least some of the likely costs and benefits and furthermore discusses some of the potential challenges to be faced during the introduction of any CBM system into Army land-based platforms.

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Glossary

AAAV – Advanced Amphibious Assault Vehicle

AAV – Amphibious Assault Vehicle

ADF – Australian Defence Force

AI – Artificial Intelligence

ANN – Artificial Neural Networks

Ao – Operational Availability

CBM – Cost Benefit Analysis

CBM – Condition Based Maintenance

CLOE – Common Logistic Operating Environment

CM – Corrective Maintenance

DoD – Department of Defense

EA – Evolutionary Algorithms

FIC – Fundamental Inputs to Capability

FNN – Fuzzy Neural Networks

HMM – Hidden Markov Model

HUMS – Health and Usage Monitoring System

LCVS – Land Combat Vehicle System

LRU – Line Replaceable Unit

MILIS – Military Integrated Logistic Information System

MLDT – Mean Logistic Delay Time

MTBF – Mean Time Between Failure

NCW – Network Centric Warfare

OEM – Original Equipment Manufacturers

PHM – Proportional Hazard Model

PIM – Proportional Intensity Model

PM – Preventative Maintenance

RCM – Reliability Centered Maintenance

R & O – Repair and Overhaul

ROI – Return On Investment

RUL – Remaining Useful Life

SBCT – Stryker Brigade Combat Team

SPC – Statistical Process Control

SVM – Support Vector Machine

TWV – Tactical Wheeled Vehicle

USD – US Dollars

1 Introduction

The sustainment of land equipment fleets is a critical capability determinant of the Australian Army. Higher operational tempo, ageing fleets, and the requirement to transition to newer more advanced fleets has correspondingly heightened the degree of attention being focussed on land fleets. The Strategic Reform Program has further highlighted the need to reduce the cost of ownership through such measures as 'smart sustainment'. The Land Combat Vehicle System (LCVS), i.e. Land 400, is an example of a new sophisticated vehicle fleet that Defence will commence acquiring within the next decade. These vehicles represent significant changes in technology in terms of both the war-fighting capability and the capability of platforms themselves. Such is the increase in complexity that these vehicles will almost certainly require changes in the way they are supported both in-barracks and on deployment.

One area which is being actively investigated by Army is that of CBM, where maintenance is driven by actual equipment needs rather than a fixed time or usage-based preventative maintenance schedule. Whilst this maintenance paradigm has been prevalent within the air environment for many decades, and within the commercial land fleets, it is relatively new in terms of Army land-based platform maintenance. Whilst the argument in the air environment is based largely upon safety, the same argument does not apply as strongly within the land environment. Thus a new value proposition is required to be developed to justify the investment in CBM for Army, and Land 400 specifically. This report represents a literature review of the current state of publically available knowledge of CBM primarily within the Land environment. The report does not however consider in detail the specific sensor technologies that have or may be used on land platforms.

This report is organised as follows. Section 2 provides an introduction into the area of reliability and maintenance, with a history of where CBM has evolved from. Section 3 describes the study team's view of what constitutes a generic CBM system and its defining characteristics. Section 4 describes some CBM case studies. Section 5 provides an overview of cost-benefit examples that have been provided in both the commercial and specifically land-based platform maintenance, and how these might be broadly related to Defences business model of the fundamental inputs to capability. Finally Section 6 highlights perceived outstanding issues that will likely need to be addressed in any detailed value proposition for introduction of CBM within the LAND 400.

2 Background

2.1 Reliability/Maintenance

Reliability is defined as the ability of a system to perform as designed in an operational environment over a prescribed period without failure. Reliability Centered Maintenance (RCM) is a method for developing and selecting maintenance strategies and design alternatives, based on operational, economic and safety/ environmental criteria [1]. RCM was founded in the 1960s and initially oriented towards aircraft maintenance. Over the past decade this concept has started migrating to other industries [2]. The goal of an

RCM approach is to determine the most applicable cost-effective maintenance technique to minimise the risk of impact and failure and to create a hazard-free working environment while protecting and preserving capital investments and their capability. This goal is accomplished through an identification of failure modes and their consequences for each system. This allows system and equipment functionality to be maintained in the most economical manner [3]. The United States Department of Defense's (DoD) system reliability objective is to minimise the risk of failure within the defined availability, cost, schedule, weight, power, and volume constraints [4].

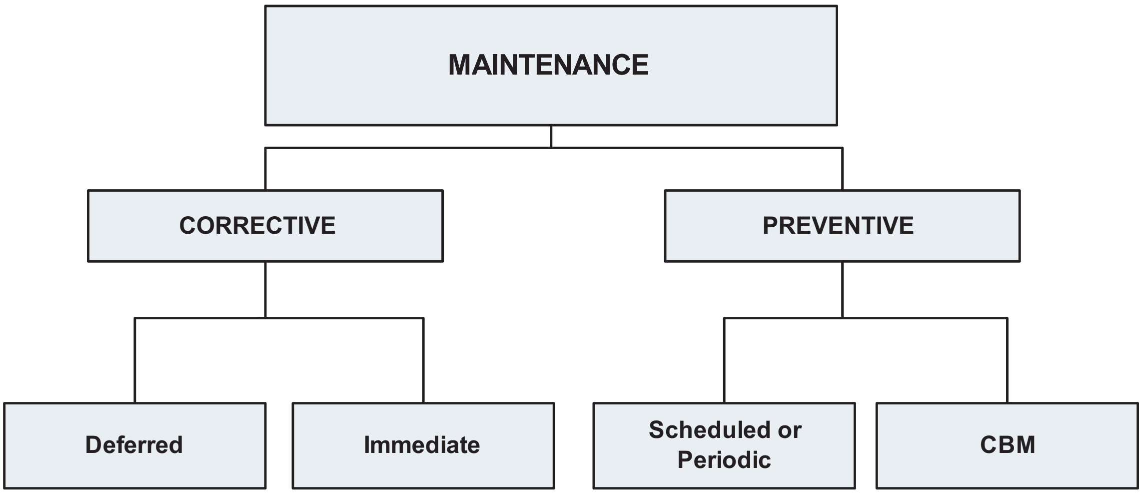

Figure 2.1: *Types of Maintenance*

Maintenance encompasses a wide variety of activities. Two main categories of maintenance shown in *Figure 2.1* namely Corrective Maintenance (CM) and Preventive Maintenance (PM)cover the full range of maintenance actions available. Corrective maintenance is conducted after failure or fault recognition and is intended to restore equipment to a state in which it can perform a required function. Battle damage repair can be considered as a special form of corrective maintenance, and is utilised to return materiel to a condition that enables it to complete a task or to enable rapid recovery for its continued operational use [5].

Preventive maintenance is the systematic and/or prescribed maintenance intended to reduce the probability of failure. Preventive maintenance requires the assessment, determination and description of tasks required to preserve the condition of an asset prior to failure. Preventive maintenance requirements are initially determined during the design of a system and further refined through use [5]. Preventive maintenance performed can encompass an inspection, test, servicing, even an overhaul or complete replacement [4].

The objective of any PM programme is the minimisation of inspection, repair and equipment downtime (measured in terms of lost production capacity or availability or reduced product quality). Two approaches have evolved for performing PM. The traditional approach is based on the use of statistical and reliability analysis of equipment failure. Under statistical-reliability-based PM, the minimum total cost objective is pursued by establishing fixed statistically "optimal" PM intervals at which to replace or overhaul equipment or components, termed scheduled maintenance. This is usually time-based or usage-based. The second approach involves the use of sensor-based monitoring of equipment condition in order to predict when machine failure will occur. Under CBM, intervals between PM actions are no longer according to a fixed schedule, but are performed only "when needed" [6]. It should be noted that scheduled maintenance and CBM can be done together and are not mutually exclusive, as suggested in *Figure 2.1.* Thus unplanned maintenance, and associated downtime, can be replaced by maintenance planned to interfere less with operational requirements and thus mission reliability can be improved [5].

For the purpose of this paper, CBM is defined as: An established and accepted maintenance practice that derives maintenance requirements, in large part, from timely assessment of system condition obtained from embedded sensors and/or external tests and measurements using built-in or portable diagnostic equipment [7]. The goal of CBM is to perform maintenance based only upon the evidence of a need rather than any predetermined time cycle, equipment activity count, or other engineered basis [7, 8, 9, 10, 11, 12, 13, 14].

2.2 History of Condition Based Maintenance

CBM is a traditional concept, if you consider human operators and maintainers as condition sensors. Automation of monitoring condition first appeared in the late 1940's in the Rio Grande Railway Company, to detect coolant and fuel leaks in a diesel engine by testing for traces in the lubricating oil [15]. They achieved outstanding economic success in reducing engine failure by performing maintenance whenever "any" glycol or fuel was detected in the engine oil. The U.S. army, impressed by the relative ease with which physical asset availability could be improved, adopted those techniques and developed others. During the 1950's, through to the 70s [16], CBM grew in popularity and a vibrant CBM technology industry emerged providing training, products, and services which came to be known as "predictive maintenance" [15]

CBM involves the use of various process parameters (e.g. pressure, temperature,vibration, flow) and material samples (e.g. oil and air) to monitor conditions. The data is collected, analysed, trended, and used to predict equipment failures. Once the timing of equipment failure is forecast, actions can be scheduled to prevent or delay failure. In this way, the reliability of the equipment can remain high [17, 14, 6].

There are two types of condition monitoring: continuous and periodic [11]. By continuous monitoring, the system continuously monitors (usually by mounted sensors) and triggers a warning alarm whenever a threshold is exceeded. Two limitations of continuous monitoring are: (1) it is often expensive; (2) to continuously monitor raw signals with noise can produce inaccurate diagnostic information [11]. Periodic monitoring is preferred as it is often more cost effective and provides more accurate diagnosis using filtered and/or processed data. The risk associated with using periodic monitoring relates to the possibility of missing failure events occurring between successive inspections [18, 19]. The main issue relevant to periodic monitoring is the determination of the appropriate condition monitoring, i.e. polling, interval [11].

The US Army has recognised the benefits of CBM and broadened these benefits in its "CBM+" plan, which includes not only the use of sensors but all practices, techniques, and technologies that improve maintenance plans and execution [20]. "CBM+" was a concept originally developed in 2002 as a DoD initiative to provide a focus for a broad variety of maintenance improvements that would benefit both the maintainer and the warfighter [21]. "CBM+" is considered condition based maintenance enhanced by reliability analysis [4]. It is believed to lead to more efficient maintenance, better readiness, and cost savings associated with smaller logistics footprints [4].

"CBM+" builds squarely on the foundation of CBM and is focussed on inserting state-of-the-art maintenance applications, technologies, and techniques to improve the maintainability and availability of both new and legacy weapon systems. It involves re-engineering of maintenance business processes to improve logistics system responsiveness.

Capabilities within the "CBM+" initiative require [22]:

- enhanced prognosis and diagnosis techniques
- failure trend analysis and electronic portable maintenance aids
- automatic identification technology and data-driven interactive maintenance training.

The synergy between RCM and "CBM+" relates to the use of applicable "CBM+" technologies and methods to support management decisions for selecting and executing maintenance tasks. By linking RCM and "CBM+" as complementary management tools, maintainers might strengthen the rationale for choosing the most technically appropriate and effective maintenance task for a component or end item. In particular, the availability of timely and accurate condition assessment data made available through "CBM+" capabilities should improve the RCM analytical determination of failure management strategies. RCM and "CBM+" have a mutually beneficial relationship. Health management without RCM analysis becomes technology insertion without a justified functionality. Conversely, collection of aggregated or platform-centric health data without an understanding of which failure modes are consequential, and the most effective course-of-action, can lead to wasted effort and unnecessary expenditure of resources [4].

3 Condition Based Maintenance

3.1 Potential Advantages

To get a sense of how a CBM system is employed, we look at both "on-board" and "off-board" computing capabilities. By "on-board", we mean embedded into the operating equipment to be monitored. This way of characterizing CBM capability enables an analysis of how information is collected, analyzed, and acted upon in real time. The more embedded the technology, ideally the more real-time it can be.

The spectrum of CBM capability ranges from quite limited to potentially a more networked and sophisticated capability. Basic CBM capability could be monitoring a small number of systems or subsystems, collecting a history of monitored parameters and analyzing the data for trends. The vision for a sophisticated completely networked automated CBM system, for all primary platforms (ground, air and support) is to have embedded health monitoring systems covering the majority of mission-critical components [23, 24, 25, 26].

The potential advantages of a CBM system are:

- **Real-time assessment of equipment health -** With the capability to provide useful reliability information, to the vehicle operator, CBM might be readily integrated into command and control systems. The value of CBM to the battlefield commander lies primarily in decision-making in order to increase mission effectiveness through reducing equipment downtime.
- **Improved operational availability -** CBM methodology may increase the operational availability of military platforms by eliminating unnecessary inspection or maintenance as well as improve system performance [12]. Diagnostic and prognostic technology can reduce the trouble shooting time and prognostics can reduce the time to acquire a replacement part based on the ability to order spares, while the platform is still functional.
- **More predictive/decision making -** In a dynamically changing training or contingency scenario, time and information are crucial elements needed by commanders to make key decisions. Since CBM can provide useful predictions on the health of equipment, the commander has the potential to make better decisions on operational employment of equipment in support of missions. More importantly, a prognostic capability can provide an indication of the existence of a fault during preparation for a mission. This facilitates better planning, as it can allow the maintainers to replace the potentially (or anticipated) defective component before the mission. This contributes to maintaining the operational availability of the specific platform over the duration of the mission as well as maintaining the reliability of the equipment due to avoiding an operational failure [27].
- **Reduction in maintenance induced errors -** A portion of general troubleshooting may be automatically performed by the CBM system, which saves labour and helps reduce misdiagnosis. Repair technicians will perform fewer preventive maintenance actions such as inspections, adjustments and part replacements because a CBM system localises faults [12]. There is also a reduced requirement for data entry by both maintainers and operators.
- **Anticipatory supply chain -** With advance notice from the CBM system, supply clerks can order parts and have them on hand in maintenance bays once the vehicle arrives for maintenance [12]. Here, prognostics and CBM may enhance the effectiveness and responsiveness of logistics by improving visibility to expected demand throughout the supply chain [28].
- **A leaner supply chain/inventory -** A CBM system also provides important advantages to the supply chain. The proposed advantages are a reduction in reliance on expensive modes of transportation to meet urgent demands, as well as a reduction in the quantity of spares in inventory. One of the potentially important impacts upon military operations is the ability to provide advanced warning of an impending equipment failure through prognostics. Prognostics could also allow for decreased

inventory throughout all stages of the supply chain because of earlier warning of parts failure. Parts can be ordered and received before repairs are necessary and there could be potential substantial savings in inventory investment [12, 29].

- **Estimation of Remaining Fleet Life -** One of the applications of the captured usage is the impact on the remaining usable life of the system, and hence the expected life of type of the fleet as a whole. In a recent US study, data deficiencies and access constraints in enterprise-wide systems were identified as making such analysis difficult though possible [30]. Experience from recent US operations saw equipment with usage rates up to nine times the peacetime rate in harsh desert environments that were likely to generate even more accelerated degradation further emphasising the need to understand the usage history of equipment [31]. Also, with on-board systems it allows detailed understanding of how usage and degradation is spread throughout the fleet.

The condition monitoring and analysis part of CBM can be broken down into two types,

- Diagonostics
- Prognostics

These will be discussed in detail in the following sections.

3.2 Diagnostics

Diagnostics deals with post event analysis and includes fault detection, isolation and identification when it occurs.

Fault detection is a task to indicate whether something is going wrong in the monitored system; fault isolation is a task to locate the component that is faulty; and fault identification is a task to determine the nature of the fault when it is detected [11].

To better ensure readiness and decrease downtime costs, health monitoring technologies are developed for CBM of individual equipment items within a fleet. A common way of detecting faults in mechanical equipment, such as a ground-vehicles suspension and chassis, is to compare measured operational vibrations to a healthy reference signature in order to detect anomalies. The main challenge to this approach is that many legacy vehicles are not equipped with the sensors or acquisition systems to acquire, process and store mechanical data. Therefore, to implement health monitoring, one must overcome the economic and technical barriers associated with equipping ground vehicles to continuously monitor responses or to poll responses from the sensors. If a vehicle cannot be equipped with sensors, an instrumented diagnostic cleat could alternatively be used to measure the vehicles dynamic response as it traverses the cleat at a fixed speed [32]. This approach potentially eliminates the need for on-vehicle sensors but provides measurements that indicate the condition of wheels and suspension systems. This approach can potentially improve total vehicle performance, reduce costly maintenance repairs and labor hours, and increase time efficiency so vehicles spend more time in the field and less time in a maintenance bay [32].

There are various machine fault diagnostic approaches which include statistical approaches, artificial intelligence approaches and model based approaches. Research into diagnostics includes statistical processes: like cluster analysis; Hidden Markov Models (HMM); signal grouping based on certain distance measures or a similarity measure between two signals; using Bayesian networks; support vector machine (SVM) techniques; and statistical process control (SPC) techniques etc.

Examples for artificial intelligent (AI) techniques include: artificial neural networks (ANNs); fuzzy logic systems; fuzzy neural networks (FNNs); neural fuzzy systems and evolutionary algorithms (EAs) [33, 34, 35, 36, 37, 38]. Work on model based techniques use residual generation methods such as the kalman filter, parameter estimation (or system identification); and parity relations that are used to obtain signals, called residuals, which are indicative of fault presence in the machine [11].

Since there are so many diagnostic methods, one of the difficulties is to understand and choose the right method. Another issue is to assess the success and cost of these methods. A major challenge of diagonostics in CBM is to identify correctly what conditions of the vehicle are to be monitored. Once identified, appropriate sensors combined with vehicle-level automated computational capability are needed to trigger warnings accurately. Sensor integration, component traceability regardless of platform and configuration management are also issues that should be addressed to have an effective CBM capability.

3.3 Prognostics

Prognostics deals with fault prediction; identifying whether a fault is impending and estimating how soon and how likely a fault is to occur. Prognostics achieves zero-downtime performance more efficiently than diagonostics. Diagnostics, however, is required when fault prediction fails and a fault occurs [11].

Compared to diagnostics, the literature on prognostics is less abundant. There are two main prediction types in machine prognostics. The most obvious and widely used prognostics is used to predict how much time is left before a failure occurs given the current machine condition and past operation profile. This is called Remaining Useful Life (RUL) of the system or subsystem. Similar to diagnosis, prognosis also falls into three categories. Statistical, artificial intelligence and model based approaches [11]. Some of the statistical methods used are Proportional Hazard Model (PHM), Proportional Intensity Model (PIM), Hidden Markov Model (HMM), continuous-discrete stochastic process, gamma process etc [39, 40, 41, 33, 42]. Some of the AI techniques applied to RUL estimation are neural networks and neural fuzzy approaches [43, 44]. Another class of machine fault diagnostic is the model-based approach, including the hierarchical modelling approach and non-stochastic model [45, 46, 47].

Accurate identification of RUL is a challenge that needs to be addressed in the prognostic area. Another difficulty would be prognostic algorithm development and sensor integration and overall system integration. Also another challenge is to evaluate, understand and test the level of maturity of the diagnostics and prognostics techniques. Expansion of

CBM models from the consideration of single components to complete systems could be another potential challenge.

3.4 CBM System Description

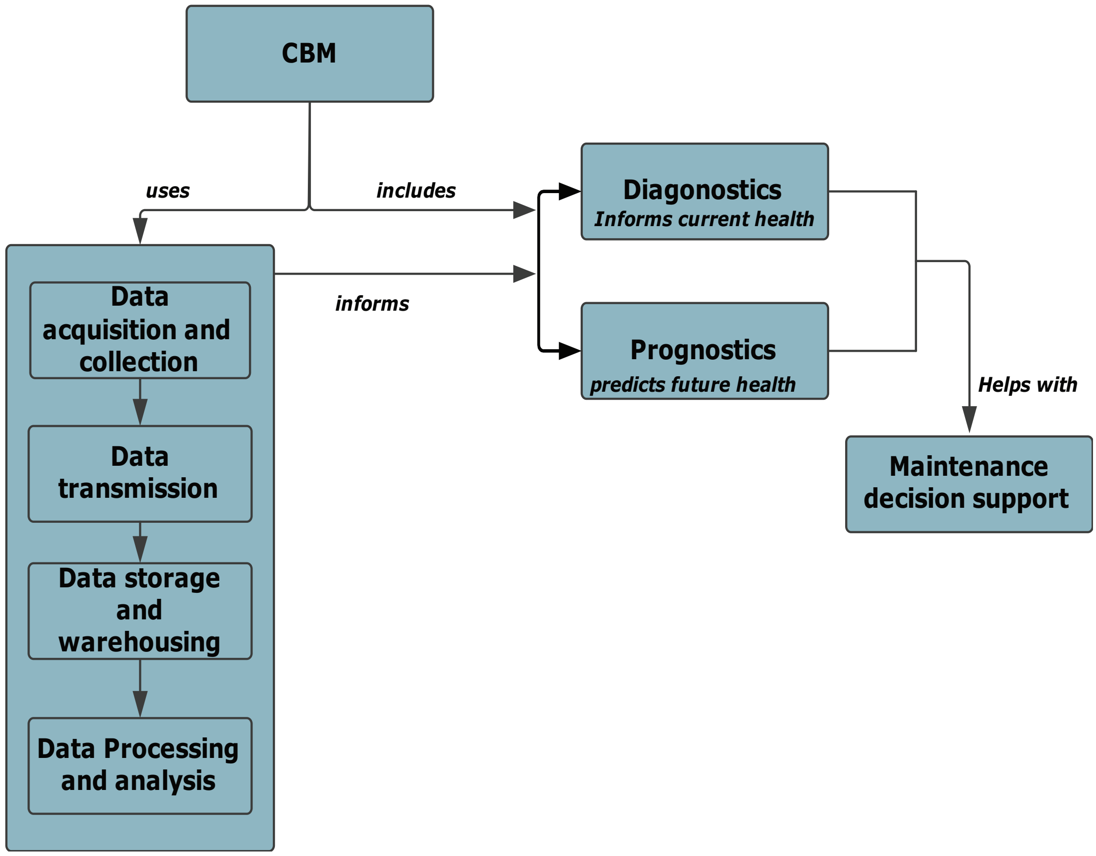

Figure 3.1: *Parts of a CBM system*

Some of the important components of CBM are listed below [11, 48]:

- Data collection and acquisition
- Data transmission and communication
- Data storage and warehousing
- Data processing and analysis
- Maintenance decision support

Figure 3.1 describes the different parts of the a CBM system.

3.4.1 Data Collection and Acquisition

Data acquisition is a process of collecting and storing useful data (information) from targeted physical assets for the purpose of CBM as shown in *Figure 3.1*. This process is an essential step in implementing a CBM program for machinery fault (or failure) diagnostics and prognostics. Data collected in a CBM program can be categorised into two main types: event data and condition monitoring data.

Event data includes information on what happened (e.g. information on the installation, breakdown, overhaul, etc, and what the causes were) and/or what was done to the targeted physical asset (e.g. inspection data, minor repair, oil change, etc.). Condition monitoring data are the measurements related to the health condition/state of the physical asset [11, 48]. A challenge in this area would be identifying the appropriate sensor suite to collect data.

3.4.2 Data Transmission and Communication

Hingst in his article [28] focuses on the ability to 'Connect' and 'Collect' and the way the Australian Defence Force (ADF) can develop these abilities. This is documented extensively in the Network Centric Warfare Roadmap [49].

The Roadmap envisages an ADF in which:

- key logistic function networks within the national support area are linked with those in theater and provide connectivity and a collaborative planning ability with industry and coalition partners
- commanders have end-to-end visibility of the logistic system, allowing them to rapidly and effectively prioritise the resources required to generate and sustain deployed force elements
- automated ordering and replenishment occurs as supplies and ordnance are consumed by platforms and field units
- the deployed force has minimised its vulnerabilities and significantly enhanced its mobility through more effective reachback, optimum force presence and precision sustainment for the majority of logistics requirements [50].

Yet, based on a review of the Network Centric Warfare (NCW) Roadmap and the assumption that the supported projects will achieve their desired states, the ADF will still only partially achieve its goal in the critical area of logistics. This is because of the existence of a residual 'air gap' at the platform end of the logistics continuum preventing commanders from accessing aggregated, real-time logistics data from the tactical environment platform. As a consequence, the decision-making ability of the operational commander may be less than optimal. Critical support costs will also be higher than necessary [28]. In order to activate this aspirational goal it would be important to have an efficient data communication and transmission system connecting all parts of the supply chain for the CBM system to work effectively, as shown in *Figure 3.1*. The challenge for CBM would be to identify ways to connect different parts of the system and move large amounts of data between them in a vulnerable tactical environment where bandwidth comes at a premium.

3.4.3 Data Storage and Warehousing

Data storage, as shown in *Figure 3.1*, can either be done onboard or data could be downloaded to an off-board centre for storage and processing. There are database management programs that can be used to store data and make comparisons between current measurements, past measurements, and pre-defined limits (alarm set points). Data mining techniques can be employed to get useful information from large sets of stored data such as database management programs [51]. Storage of large amounts of data and good data mining techniques to retrieve the right data could be a challenge that needs to be addressed in this area.

3.4.4 Data Processing and Analysis

This involves two processes

- Data Cleaning
- Data Analysis

Data cleaning is the first step of data processing. Data cleaning ensures all data, especially event data (which if entered manually, may contain many errors) is cleaned up, so that error-free data is available for further analysis and modelling. Cleaning up of data is non-trivial and may require manual intervention. Graphical tools and cleaning/scrubbing algorithms can also be used to find and remove data errors [11, 48].

The models, algorithms and tools used for data analysis depend mainly on the types of data collected which could be value type, waveform type or multi-dimensional type.

Data analysis for event data is well known. Reliability analysis fits the event data to a probability distribution of time between events and uses the fitted distribution for further analysis. In CBM, however, condition monitoring data is also available. Thus, it is beneficial to analyse event data and condition monitoring data together. This combined data analysis can be accomplished by building a mathematical model that properly describes the underlying mechanism of a fault or a failure. Models based on both event and condition monitoring data are the basis for maintenance decision support-diagnostics and prognostics. Models that can analyse both event and condition monitoring data include the proportional hazard model. In CBM, the concept known as P-F interval is used to describe the failure patterns in condition monitoring. A P-F interval is the time interval between a potential failure (P), which is identified by a condition indicator, and a functional failure (F). A P-F interval as shown in *Figure 3.2* is a useful tool to determine the condition monitoring interval for periodical condition monitoring [52].

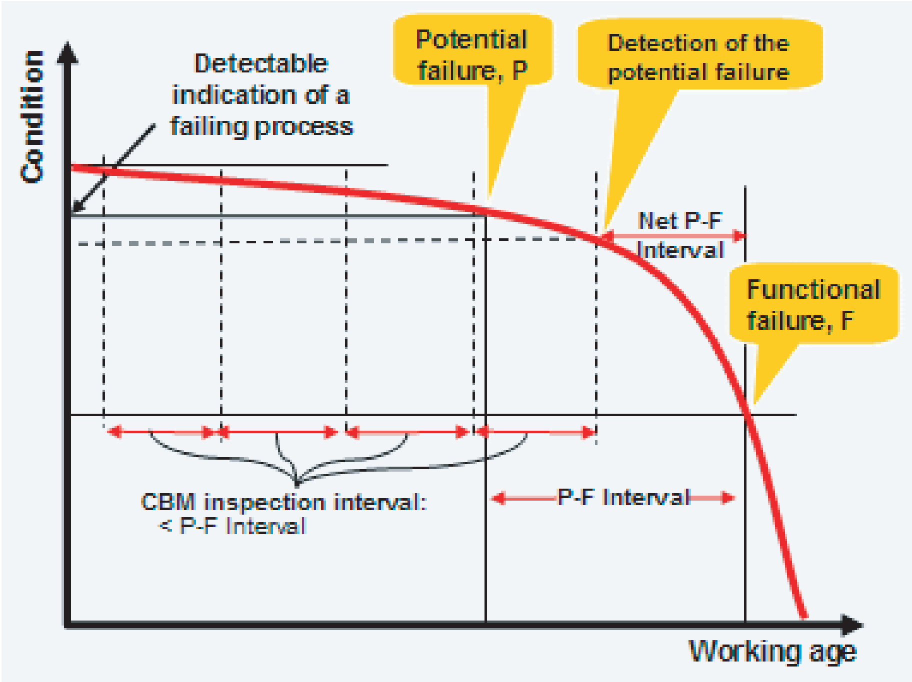

Figure 3.2: *P-F Interval. After'[52]*

3.4.5 Maintenance Decision Support

The last step of a CBM program is maintenance decision-making as shown in *Figure 3.1*. Sufficient and effective decision support would be crucial to maintenance personnel's decisions on taking maintenance actions. RCM is one approach used for establishing a robust maintenance program for equipment fleets based on the underlying failure characteristics of the systems [11, 53]. However, the goal of maintenance is to make economically justifiable decisions and PHM provides a basis to model the condition-based maintenance decision as a semi-markov decision process whereby the issue of minimising total cost (or another appropriate goal such as maximising availability) can be systematically addressed [53]. Maintenance decisions depend very much on actual measured abnormalities and incipient faults, and the prediction of the trend of equipment deterioration [54]. Some examples of decision support models include models using recurrent neural networks [54] and, models using a fully user definable/modifiable set of decision rules capable of automatically analysing any selected parts of a system [55].

Identification of the high maintenance drivers and low Mean Time Between Failures (MTBFs) and cost drivers are very important in making effective maintenance decisions and these are some of the challenges of CBM.

4 CBM Case Studies

Some of the studies have analysed and have come up with numbers which indicate clear potential benefits that can be achieved using CBM method of maintenance. In this section, some examples of such studies are given.

4.1 Aircraft Non-Tangible Benefit Study

Bayoumi *et al* [56] conducted a Cost and Benefit Analysis (CBA) to study the effect of implementation of CBM on aircraft maintenance. This includes studying the cost savings in spare parts, operational support, the increase in mission capability rates, the decrease in scheduled and non-scheduled maintenance, and the increase in total flight time. Based on the data collected, average annual savings of 15,196.88 USD (2007) was noted for maintenance test flights. If this number is totalled for the duration of the data collection period (2000-2007), it can be found that this is a per aircraft savings of 121,575.00 USD over the 8 year period. They have come up with the following results and benefits. Savings can be broken down into 1.4 M USD for spare parts, 2.1M USD for operation support, and additional non-monetary increases in mission capability rates. Non-tangible benefits have been analyzed in the model. These values are based on information and surveys from the Ground Base Station and are used to show the non-tangible benefits that arise from the use of their CBM system such as improved safety, perception of safety, morale, and performance. The study identified that the implementation of CBM will see an increase in aircraft availability, safety, and operational flight hours along with a decrease in premature parts failure, mission aborts, and unscheduled maintenance occurrences.

4.2 Pharmaceutical Industry

Rajan *et al* [57] compared the cost effectiveness of the CBM against reactive or breakdown maintenance and planned preventive maintenance. In the paper, a mathematical model was developed to predict the cost of repairs for batch process plant machinery in the pharmaceutical industry. The model was used to provide an appropriate means for plant engineers to decide whether the use of condition monitoring methods as part of a condition-based maintenance strategy is justified in terms of cost benefit analysis. If so what type of monitoring is best employed, e.g., vibration analysis, using portable data collectors considered as the high level CBM system or noting the condition of lubricating oil considered as the low level CBM system. To test the model against actual plant data, the direct costs of repair and the consequential costs of failure were predicted and compared with known costs. To be able to predict costs, the model proposed is formulated in two parts: a) The costs of damage to the machine itself and the associated direct costs of repair b) The consequential costs in regard to loss of production due to down time, etc. The conclusion they reached is that breakdown maintenance is only marginally more expensive than planned maintenance. A slight increase in pump reliability will bring down breakdown maintenance costs below that of planned maintenance. The break even point rises dramatically between using the low level CBM system and the high level system and hence in the introductory stages a low level system will deliver benefits much more positively than a high level CBM system. It has also been noted that CBM becomes more expensive than breakdown maintenance when consequential costs are not involved [57].

4.3 Helicopters

Land [58] in his cost benefit model for helicopters using HUMS (Health and Usage Monitoring Systems), states that it is important to list all of the potential areas of cost as well as benefits. The costs include those to implement a HUMS program to begin with as well as the recurring costs to maintain the program. On the benefit side there are direct costs that are readily seen and attributable to the HUMS. There are other benefits that may be of equal importance and potentially of even higher value but are less easy to determine. For example, the cost of safety is difficult to assess. This study also concludes that the benefits of CBM show economically justified investments currently but states that as these systems are employed in day-to-day operations, new methods will evolve. In addition, as new technologies emerge, the CBM design must be such that continued evolution is possible to accommodate changes.

4.4 Boeing 737

Feldman *et al* [59] discusses the calculation of Return On Investment (ROI) for Prognostics and Health Management[1] activities and presents a case study conducted using a stochastic discrete event simulation model to determine the potential ROI offered by electronics CBM. The case study of a multi-functional display in a Boeing 737 compared the life cycle costs of a system employing unscheduled maintenance to the same system using a precursor to failure CBM approach. Using a prognostic distance of 475 hours, a discrete event simulation was performed under the assumptions of negligible random failure rates and false alarm indications. A representative support life of 20 years was chosen and a 45 minute turnaround time was taken as the time between flights to construct an operational profile. Using this approach, an estimated 91 percent of failures were avoided. The results of this case study indicates the ROI with CBM is greater than 3.17 with an 80 percent confidence level.

The study analysis made use of a similar ROI framework as used by Banks *et al* [60] where the costs of the CBM-enabled system is compared directly to the total life cycle cost using an unscheduled maintenance policy which is appropriate for electronic systems.

The identified cost drivers were broken up into:

- Non-recurring costs related to the CBM system
  - Hardware and software development
  - Training
  - Documentation
  - Integration
  - Qualification.
- Recurring costs of the CBM system
  - Hardware added to each platform

[1] CBM can also be described using the term Prognostic Health Management

  - Assembly
  - Functional testing of the CBM system
  - Installation.
- Annual infrastructure costs
  - CBM system maintenance
  - Decision support
  - Retraining of personnel that use the CBM system.

The main benefit (i.e. cost avoidance) was characterised by failure avoidance and minimization of the loss of remaining useful life of the system. Failure avoidance in this case was further characterised by the ability to avoid failure during critical operation leading to system loss, or the ability to use prognostics to choose when to conduct maintenance to maximise convenience.

4.5 Advanced Amphibious Assault Vehicle

A study conducted by Banks *et al* [12] assessed the cost of a prognostics and CBM system for the AAAV (Advanced Amphibious Assault Vehicle), its effect on Life Cycle Costs (LCC), resulting ROI, qualitative risk factors, and application in a military environment. This analysis was conducted on the present day Amphibious Assault Vehicle (AAV).

The study specifically looked at a number of cost drivers affected by the introduction of a CBM system, including:

- Acquisition
  - End Item Production - Hardware, software, installation
  - Initial spares and related inventory investment
  - Technical data
  - Training.
- Operations and Support Costs
  - Preventative and corrective maintenance
  - Depot repair and overhaul
  - Transportation costs (not quantified in the study)
  - Inventory investment for retail level supply points (not quantified in the study).
- Opportunity Benefit
  - Operational availability.

This study found that there was a ROI of a factor of 3.7:1 over 10 years. This analysis was based on an assumption that CBM would prevent 15 percent of catastrophic failures, which was used as a basis for comparable reductions in spares and maintenance costs. In addition, the model assumed that there would be an increase in operational availability through a 50 percent reduction in the Mean Logistics Delay Time (MLDT) which was believed to be heavily driven by time awaiting spares (i.e. 75 percent of the MLDT). This related to a 4.2 percent increase in operational availability of the equipment. There is a quantifiable improvement of reliability and operational availability of the vehicle in addition to the qualitative advantages to commanders and staff planners afforded by the implementation of CBM. The results of the analysis show a significant impact on life cycle for the AAV with the implementation of CBM. The LCC saving for the 10, 15 and 20 year life comes to 32M (4.8 percent), 223M (23.5 percent) and 263M (21.8 percent) USD respectively across the 680 vehicle fleet. These values would be higher when considering the savings from increased operational availability, which is not included in the case study.

4.6 Stryker Brigade Combat Team

In [29], the US Army logistics Innovation Center in coordination with the Army community developed a cost benefit analysis derived from a first fielding of a comprehensive set of Common Logistics Operating Environment (CLOE) enablers to a Stryker Brigade Combat Team (SBCT). An overall evaluation of the proposed investment in CLOE enablers using a multi-attribute decision model is provided. It documents the preliminary costs and benefits achieved from installing the CLOE enablers that support logistics transformation by increasing combat readiness, improving efficiency and effectiveness of support operations and giving commanders accurate information about the operational status of their forces. The technical risks are low and implementation costs are reduced because the capabilities can be provided by integrating and modifying existing products or inserting commercial-off-the shelf hardware and software. It includes not only the addition of enablers on the Stryker family of armoured vehicles, but also on the tactical wheeled vehicles that are in the SBCT. The report found that implementing the identified CLOE enablers is a worthwhile investment resulting in a savings of $75M$ USD if implemented across all seven SBCTs. The payback period is achieved in five years. The results of this CBA provides a foundation for a business case for the installation of CLOE enablers on additional army equipment [29]. Further analysis would need to be undertaken to understand if these results are transferable to the ADF with respect to our fleet scales.

4.7 Tactical Wheeled Vehicle Fleet

There has been a drive over the last few years to upgrade the US tactical wheeled vehicles (TWV) with CBM-enabling technologies. This would include many older vehicle types such as the HMMWV [2], FMTV [3], M939 FOV [4], HEMTT [5], HET [6] Tractor and the PLS [7]. The total number of platforms within the TWV fleet is substantial, with some 209,000 plus vehicles requiring a sustainment budget well over USD1B per year. Interestingly based on a complete fit-out of the TWV fleet with low-mid range HUMS solution at 3500 USD per vehicle, and using an assumption of a modest 2 percent savings on the sustainment cost, this was estimated as having a return on investment of over 36 years [61]. There was little analysis given to what level of savings might actually be achieved, nor was the cost of other CBM enabling features included.

It is perhaps more useful to examine the business case for "CBM+" Enablers which included the following factors:

- One time costs
  - Purchase and installation of enablers
  - Development costs of enablers.
- Recurring costs
  - Repair & replacement of enablers
  - Software updates.
- Cost savings
  - Reduced parts orders
  - Lower transportation costs for parts
  - Correct parts ordered
  - Reduced fleet size due to higher vehicle availability.
- Cost avoidance
  - Minimised inspections due to better vehicle health visibility
  - Reduced repairs by avoiding collateral damage equipment failures
  - Fewer recovery missions for field failures
  - Reduced "exposure" time & resulting injuries for users and maintainers.

5 CBM Cost Benefit Analysis

5.1 Overview

CBM requires the installation of monitoring devices on subsystems to measure degradation [62]. Breuker *et al.* notes that a trade off exists between the costs and benefits of

[2] High Mobility Multipurpose Wheeled Vehicle
[3] Family of Medium Tactical Vehicles
[4] Family Of Vehicles
[5] Heavy Expanded Mobility Tactical Truck
[6] Heavy Equipment Transporter
[7] Palletised load system

real-time monitoring. For instance, performing frequent maintenance inspection results in high labor cost; conversely, infrequent maintenance inspection might lead to asset degradation and the possibility of premature failures [63]. It should also be noted that there is a cost associated to doing any maintenance as this can increase the chance of failure due to fitting errors etc. Hence, the costs and benefits of remote monitoring should be compared to the costs and benefits of frequent and infrequent maintenance inspections.

An effective CBM strategy requires a good understanding of asset criticality; failure rate modes and, effects; as well as the total cost of failures. Therefore, understanding what to monitor for a given asset requires reliability and financial related data [64].

5.2 Generic Cost Benefit Analysis Studies

Banks *et al* refined the approach used in the AAAV study in later papers [65, 60] to compare the non-recurring development costs and the costs of implementation. An important step in the process of generating a CBA is the understanding of the cost drivers, and in particular the reliability and failure characteristics of the system. This is very much supported by the "CBM+"Roadmap [4], and the work of Bayoumi *et al* [56] which indicates that such CBM analysis should be based on a deep understanding of the failure mechanisms, i.e. through a reliability centred maintenance approach.

Banks *et al* provided a worked example for automotive batteries in which there was a reported 11 percent failure rate due to serviceability-related misdiagnosis which potentially could have been reduced through the use of battery sensors[8]. Whilst the cost of early replacement of batteries may be small, given the number of vehicle batteries in the DoD exceeds 880,000 per year the potential savings are significant at an estimated level of USD2M per year. Given the cost of development, acquisition and installation of the battery prognostic sensors, it was believed that a return on investment of approximately 14 : 1 was achievable with payback period of 20 months. The analysis provided estimated costs over 25 years of service. In this analysis, neither the costs nor reliability appreciably change over this period of time except with inflation in the case of costs.

The main cost avoidance that is discussed is the reduction in maintenance labour hours due to the introduction of the CBM system. One of the interesting aspects that is introduced here is the challenge of costing unavailability of the equipment. This is generally done by equating the lost capability (operational availability, A_o) to the life cycle costs of that platform, i.e. how many more assets would be required to achieve a given A_o value? Of course, such a calculation assumes that the direct driver for unavailability is the lack of prognostics, and discounts that it might be more cost effective to improve availability through some other non-CBM means. It would also be difficult to equate these availability goals globally, as they would be quite different at the tactical mission level.

5.3 Exemplar B Vehicle Cost Benefit Analysis

DSTO developed a cost-benefit tool for HUMS for ADF helicopters known as HUMSSAVE [66]. This model was later extended to examine the land environment, namely generic B-Class

[8]This is elsewhere recorded as a 22 percent misdiagnosis level

vehicles [67]. There are two major differences that apply between air vehicles and land vehicles: (1) impact of failure, and (2) the fact that air components are generally "lifed" and must therefore be replaced after a certain level of usage. The approach taken within this tool is to linearise costs and benefits over the remaining life of the vehicle in question, such that costs and benefits are reduced to a unit per unit rate of effort, e.g. kilometres driven. The analysis transitions benefits down to measures of monetary value, i.e. cost avoidance, based on:

- Safety: in this case the costs associated with having accidents and vehicle replacement
- Maintenance and Repair
  - Running: the expected reduction in maintenance hours rate with HUMS
  - Consumables: reduction in consumable spares rate due to HUMS
  - Major Line Replaceable Unit (LRU) Repair and Overhaul (R&O): the ability to detect and intervene early with engine overhaul
  - Equipment: the cost of non-HUMS test equipment that is replaced by HUMS.
- Usage Monitoring
  - Recovery Costs: the cost of recovering vehicle and cargo if breakdown occurs
  - Availability: relates the usage-based cost of support to a change in operational availability[9].
- Consequential Benefits
  - Parts consumption: the impact of reduced consumption through the extension of usable life of "lifed" components through CBM
- Fleet Management
  - Spares Stock Management: reduced cost of holding/managing spares due to prediction of spare requirements leading to a reduced demand
  - Replacement: achieving capability through higher utilisation from improved vehicle tracking through satellite tracking as compared to the purchase of additional vehicles[10].

The costs analysis is much simpler:

- Capital costs
  - Fleet-wide "engineering" costs amortised to vehicles[11]
  - Cost of HUMS system per vehicle[12].

[9]This assumes sunk costs may be proportioned across only available assets
[10]The rationale behind this is not clearly articulated
[11]where this may be equated to the cost of implementing a HUMS system external to the vehicle
[12]where this may be equated to sensor costs

- Running costs
  - Training: training all staff per year per vehicle
  - Maintenance: HUMS system maintenance
  - Consulting: consultation to the fleet[13]
  - Software: HUMS software upgrades
  - Ground Stations: Unspecified[14]
  - Central Management: Unspecified[15].

The HUMMSAVE software simply undertakes a direct comparison of all monetary benefit and costs to obtain a net value (positive or negative) per vehicle, and per kilometer travelled. Clearly any econometric model will seek to define all parameters in terms of a dollar value, however translating LCC to a dollar/usage value may not be a suitable metric in the land as compared to air environment. Mission-specific benefits are not captured in this tool, nor are such things the additional benefits of capturing and storing accurate data for inventory management purposes. The model is however designed to provide a simplified view of the cost-benefit trade-off in the land environment. In this case, there is less emphasis placed on a single platform as compared to the entire mission package which might include many related platforms that are all required to be operational. This model does however provide an insight into the methods used in the air environment, and where significant differences exist between the air and land cases.

5.4 Costs

'Capability' in the Defence context is the combined effect of multiple inputs. It is not the sum of those inputs, but the synergy that arises from the way those inputs are combined and applied that determines the level of capability in a particular context. In Defence, the Fundamental Inputs to Capability (FIC), are categorised and broadly defined as: Personnel, Organisation, Support, Command and Management, Collective training, Major systems, Supplies and Facilities [68]. The commitment to implement a CBM program cannot be made until a number of issues are considered including:

- Investments in monitoring hardware,
- Software
- Dedicated manpower
- Training
- Automated and manual computer interfaces
- New procedure development and documentation.

[13]This may be through data analysis
[14]This may represent off-board data receivers/processors
[15]This may represent administrative and contractual overheads

Hence the costs associated with CBM includes:

- Set up costs: purchase of equipment, alteration of plant to gain access, and training. Most of this will be incurred during the initial period of operation [69]. Much of the expense can be avoided by using bought-in monitoring services and expertise, but management effort will still be required.

  The costs involved in the set up of a CBM system could be as follows:

  - Research and development, engineering, testing, and certification of the products required to provide the logistics enablers to the organisation
  - Purchasing hardware or commercial off-the-shelf software, or hardware/software development
  - License fees for products that do not already have government use agreements in place
  - Changes to integrated systems e.g. systems such as Military Integrated Logistics Information System (MILIS)
  - Installation costs for hardware and software
  - Modifications to new equipment training packages to incorporate the enhanced capabilities [29].

- Recurrent Maintenance of CBM System and support costs:

  - hardware maintenance
  - sensor maintenance
  - training
  - upgrades and software licenses
  - network costs
  - power costs.

- Operation costs: collecting and analysing data. In house operation is preferable, but the learning curve may delay the pay back. Regular maintenance review is necessary [69].

5.5 Benefits

The expected benefits must be sufficient enough to justify the CBM system investments. The business case that justifies the installation of monitoring equipment must be developed with enough detail such that there is enterprise wide acceptance of it, and acknowledgement of the value of CBM by management.

The expected benefits from equipment condition monitoring fall into two general categories: Monetary and Soft/Intangible benefits. Monetary benefits and program costs are the fundamental elements of the business case but the soft benefits that may not directly effect the bottom line often enter significantly into the final business decisions [70]. CBM might also offer substantial organizational as well as process-related benefits which could fall under either monetary or soft benefits. These benefits may include establishing an important linkage to the chain of command, providing input to command decision-making, reducing maintenance errors, enhancing the effectiveness and responsiveness of combat service support, obtaining material life cycle advantages, improving safety, and sacrificing transportation space for higher priority combat equipment. Not all of these things are readily transitioned to a monetary value.

Vachtsevanos *et al*'s [71], in their work on CBM, assigned estimates for the cost of on-board embedded diagnostics primarily associated with computing requirements. Advances in prognostic technologies (embedded diagnostics, distributed architectures, etc.) and lower hardware costs (sensors, computing, interfacing, etc.) were believed to bring CBM system set up and operational costs within 1 to 2 percent of a typical Army platform cost [71]. This method evaluated the cost benefit of a CBM system by first establishing a baseline condition and by estimating a cost of breakdown or time-based preventive maintenance from maintenance logs. If preventive maintenance was practiced, an estimate of how many of these maintenance events may be avoided was calculated. The cost of such avoided maintenance events was counted as a benefit of CBM. The intangible benefits alone are then evaluated by assigning severity index to the impact of breakdown maintenance on system operations and by estimating the projected cost of CBM, i.e. cost of instrumentation, computing, etc. The life-cycle costs and benefits were aggregated from the information obtained.

The following benefits of CBM were stated by Vachtsevanos *et al* [72]:

- Unprecedented insight into vehicle/squadron/fleet health
- Less time spent on inspections
- Better ability to plan maintenance
- Simplified training
- Improved fault detection.

A cost benefit analysis typically concentrates on the monetary benefits (cost savings and cost avoidance) from a proposed action. A benefit assessment also includes other quantifiable benefits (such as improvements in operational readiness) and non-quantifiable benefits. Non-quantifiable benefits are primarily associated with providing the war-fighters with capabilities that support operations and logistics such as safety, confidence, trust, mission endurance/success etc. [29].

Potential savings include:

- Increased readiness and operational availability [73]
- Reduced maintenance costs - CBM avoids unnecessary repairs and replacements, saving labour and spare parts. The inconvenience and expense of making plant available for off-line maintenance is avoided

- Damage limitation - if a fault is detected early, the repair may easily cost orders of magnitude less than the consequential damage of a catastrophic failure [69].

A project to implement a CBM strategy/process would be deemed to be successful if the benefits and returns exceed the investment cost over a reasonable time period. This factor is determined using ROI metrics, i.e., the ratio of savings to investment. Savings are generally represented by returns that are quantified in cost or financial terms [74, 75, 59]. Another important challenge of CBM is to identify risks and to identify whether return on investments is more desirable than the long term benefits that are considered to be possible with the implementation of a CBM maintenance policy.

6 Challenges

There are many challenges that need to be addressed and one of the main challenges for CBM could be to identify the actual requirements of the CBM and to understand and implement it such that its benefits outweigh the cost. Some of the more detailed potential challenges are listed below [73]:

- Identification of high maintenance drivers (low MTBFs) and cost drivers
- Identification of the sensor suite
- Storage, transmission and analysis of data
- Identification of tools needed for data analysis
- Accurate identification of the RUL of components
- Reduction of computational requirement
- Increase vehicle level automated computational capability
- Expansion of CBM models from components to systems
- Configuration management
- Common diagnostics / prognostic algorithm development
- Component traceability
- Sensor integration - open framework / configuration of sensors
- Conduct of a cost benefit analysis before CBM process can be implemented [76]
- Transitioning technology without formal requirements
- Overall system integration [73]
- Size of fleets to have CBM implemented on

- Good communications network between the vehicles, the warehouse, supply chain and maintenance centres
- Identification of the amount of data management and data analysis that a CBM system would require in order to make it an effective maintenance option
- Funding, given the very high initial capital costs that may preclude it within short term budgetary constraints [48]
- The lack of an over-arching Army/Defence policy on CBM
- Control mechanisms within the existing information systems capability to utilise condition monitoring effectively in the scheduling of work and anticipatory ordering of spare parts
- Operational security of platforms and missions
- Ownership and maintenance of data
- Expandability of CBM systems
- Proprietary interfaces
- Warranty implications for non-OEM approved items
- Workforce implications, such as the changes to skill requirements or indeed workforce size
- Identification of who needs what data and with what frequency and maximum delay.

7 Conclusion

CBM is an extension of the RCM philosophy whereby knowledge of the system is used to anticipate and optimise the maintenance program. In CBM, the usage and subsequent health of the individual vehicle is used to extend the usable life of the component parts and hence reduce wastage and increase operational availability. This approach has become standard practice in the aerospace environment where system reliability has direct safety and cost implications. The value proposition is less clear in the land environment, and indeed there have been few, if any, validated cost-benefit studies for Army equipment published in the open literature.

The research emphasis has historically been well and truly focussed on the development of technologies, system architectures and signal processing algorithms. Whilst there has been extensive work in the area of extending the diagnostics capabilities to prognostics, there remains less evidence for the efficacy of prognostics in land vehicles. This focus on the sensor and processing technology aspects has also largely avoided the potentially larger challenges of integrating the capability into Army's existing maintenance concepts, IT systems, processes and skill sets. Challenges also include the ability to develop control systems that can maximise the value of condition monitoring for improved maintenance performance.

Whilst there has been a number of systems both in the US and the UK that have implemented different levels of CBM and HUMS, information on the level of improvement versus cost investment remains unclear. Despite the apparent lack of published analysis with demonstrable cost-benefit outcomes, both the US and UK are continuing to invest heavily in both HUMS and CBM. Indeed, an holistic cost-benefit study looking at benefits across the entire sustainment chain, or indeed across the entire equipment life, remains to be done in the Australian context. One of the clear deficiencies remains the lack of consensus on how to conduct cost benefit analysis for CBM in the land environment. In particular, there is no agreed framework as to what factors are to be included, and more importantly how to handle non-economic or intangible benefits within that framework. A further challenge remains the ability to understand likely changes to cost drivers over the life of the equipment given the high degree of uncertainty involved with fleets having 20 to 40 year life-spans and continually changing mission/usage profiles.

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Sreeja Rajesh and Benjamin Francis

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Condition Based Maintenance
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19. ABSTRACT

Condition Based Maintenance (CBM) is a method of both diagnostic and prognostic maintenance that has been used extensively in the air environment. This report describes a literature review of CBM where it relates to the land-based platform maintenance in particular. The review outlines the current state of CBM analysis, and in particular in terms of prognostic fleet management. Emphasis is further placed on an enquiry into the costs and benefits of CBM for land force equipment maintenance. A number of CBM cost-benefit studies are used as case studies to provide a framework for future analysis, including the potential challenges and the issues that CBM could bring to Army if implemented. The insights gained from this review give an understanding of the introduction and implementation of CBM to legacy fleets, but in particular the adoption of CBM into new equipment fleets such as LAND 400.

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