Models and Tools for the Cost/Benefit Analysis of Condition Based Maintenance

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Abstract

Many models and tools have been developed over the years to analyse and support decisions on the adoption of Health and Usage Monitoring Systems (HUMS) and Condition Based Maintenance (CBM). In the military Land domain, the difficulty of establishing a robust business case is frequently cited as a barrier to the adoption of a HUMS/CBM capability. As part of collaborative research in land logistics with The Technical Cooperation Program (TTCP), a survey was conducted of extant HUMS/CBM models and tools to support the development of a value proposition framework, to assist in developing robust business cases.

The tools considered, both qualitative and quantitative, were either designed for cost/benefit analysis or could be adapted for use as cost/benefit analysis tools in the military Land domain. Each tool was considered against criteria regarding its features, capabilities, and applicability to Land CBM cost/benefit analysis. From this survey, a value proposition framework 'skeleton' has been developed, comprising 10 principles. Making use of existing tools and models has the potential to significantly reduce the time and effort required to produce such a value proposition framework, with the added advantage that a number of the tools covered have been validated on military examples.

Keywords: Condition Based Maintenance, Health and Usage Monitoring Systems, Models and Tools, Cost Benefit Analysis, Value Proposition Framework, Land Materiel.

Introduction

Broadly speaking, Condition Based Maintenance (CBM) is a maintenance paradigm that promises to:

- Extend the useful life and reduce the through-life cost of equipment
- Improve fleet operational availability and combat effectiveness
- Reduce overall maintenance burden

The basic premise of CBM is that maintenance is conducted on equipment based on evidence of need, rather than any set time or usage schedule. Evidence of need is provided by knowledge of the condition of the equipment, which can be obtained through direct monitoring of the equipment condition, or derived by monitoring the equipment usage and evaluating it against known failure models. Such monitoring also offers the potential for prognostics to predict the occurrence of failures before they occur, so that maintenance can be conducted at a time and place of choice.

The difficulty of establishing a clear business case for CBM in the military Land domain is frequently, if anecdotally, cited as a reason for its slow pace of adoption when compared to the Air and Maritime domains and commercial sector. Consequently, a significant body of work has been undertaken to both develop software tools for assessing the cost/benefit trade-off of adopting CBM for Land materiel, and to adopt cost/benefit tools developed for Maritime and Air materiel to the Land domain.

In collaboration with The Technical Cooperation Panel (TTCP) Land Group Action Group 5 (now Technical Panel 6), a survey of such models and tools was conducted. Its purpose was to identify and compare their capabilities, suitability and limitations for cost/benefit analysis of Land CBM, and to assess how they may contribute to the establishment of a value proposition framework. The ultimate goal of establishing a value proposition framework is to provide a framework for assessing alternative options for the adoption of HUMS and CBM within the military Land domain, e.g. how much or how little to adopt, at what level of technological complexity, and how this may impact the costs and benefits of doing so.

The survey considered both CBM Return on Investment (ROI) and cost/benefit models and tools that cover:

- The design, development, implementation and operation of CBM systems
- Consider CBM at the enterprise, fleet, and equipment/platform levels
- The application of CBM to both existing and future equipment and platforms

This paper presents a summary of the survey work undertaken (an extended version of which can be found in [1]). The models and tools considered in the survey were categorised as being either qualitative or quantitative. Two qualitative and three quantitative tools are introduced and described, with brief descriptions of seven more quantitative tools. These tools are then further categorised and their features, capabilities and perceived applicability to the development of a value proposition framework compared. Finally, the outline of a value proposition framework for the assessment of options for adopting HUMS/CBM in the military Land domain is presented.

Qualitative Models and Tools

Qualitative models and tools are those based primarily on Subject Matter Expert (SME) judgement and opinions, or similar. Such models and tools may still perform calculations and produce numerical output (e.g. qualitative probabilistic and Bayesian network models [2]), or may be entirely devoid of quantification (e.g. conceptual models such as concept maps [3]). Two qualitative tools of significance that have come to our attention are described below.

KT Box HUMS Cost Benefit Tool

The HUMS Cost Benefit Tool is a qualitative tool developed by researchers at Cranfield University/Defence Academy of the United Kingdom as part of the KT-Box initiative [4, 5]. The stated aim of the tool is to assess the through-life cost/benefit of Health and Usage Monitoring Systems (HUMS) and Systems Information Exploitation (SIE) in the military Land environment [5]. This tool is referred to in the literature variously as the ‘HUMS/SIE Decision Support Tool’ [6], the ‘HUMS Benefit Tool’ [7] and the ‘HUMS Cost Benefit Tool’ [5]. For simplicity, we shall refer to this tool as the ‘HUMS Cost Benefit Tool’ throughout the remainder of this paper.

This tool examines the relationship between the benefit of fitting HUMS to a vehicle fleet and the cost implications of doing so [7]. There is an attempt within this tool to capture a wide range of considerations, from the cost of hardware acquisition to the impact of improving spares provision and personnel utilisation [7]. The tool output is in the form of graphical indicators comparing HUMS adoption and non-adoption for the same vehicle fleet.

Although qualitative in nature, [5] indicates that 'the user could allocate particular costs if necessary'. There is a recognition that true costs for running and maintaining vehicle fleets are unlikely to be available in the military Land environment[1] and that previous similar tools tend to rely on assumed costs. The HUMS Cost Benefit Tool is an attempt to overcome such limitations by performing quantitative analysis at a high level only. Although not able to provide hard cost data, the tool does provide a graphical display of where benefits may be realised through the adoption of HUMS within military Land platforms [5].

The core of the tool is a multi-stage 'benefits map' that has been developed through extensive interaction with the HUMS and maintenance Subject Matter Expert (SME) community. Through this benefits map, using Quality Function Deployment techniques [8], input data describing a fleet and its HUMS solution is translated into a cost/benefit assessment. Each stage of the benefits map comprises a matrix of weights used to assess the impact that one set of variables has on another:

- Mapping the potentially monitored vehicle parameters to 'intermediate' effects[2]
- Mapping intermediate effects to 'final' effects[3]
- Mapping final effects to the Defence Lines of Development (DLoD)[4]

The 'weight' or 'strength' of the impact between each pairwise combination of variables from the relevant sets above is measured on a scale from +9 (strong positive impact) to -9 (strong negative impact), with 0 interpreted as 'no change' from the current situation. These weightings are the result of substantial interaction with the SME community through brainstorming activities, workshops and reviews [5]. To illustrate, the map from HUMS-monitored vehicle parameters to intermediate effects is a matrix with vehicle parameters along one dimension and intermediate effects along the other, with the cells in the matrix specifying the strength of impact that each potentially monitored parameter has on each of the intermediate effects.

In addition to the three matrices mentioned above, a fourth matrix exists in the tool for mapping the through life costs and benefits of the final effects to the cost drivers (in terms of both Capital Departmental Expenditure Limits and Resource Departmental Expenditure Limits, CDEL and RDEL respectively) that sit behind the DLoD.

Fig. 1 shows an example of one of the graphs produced by the tool. This graph depicts a comparison of the ongoing benefit attained from two alternative HUMS variants, broken down into the cost areas depicted on the horizontal axis. Note that the intention of this tool is to compare HUMS options qualitatively, hence no units are given on the vertical axis, but this axis does provide a measure of relative benefit.

[1] Particularly true for new fleets that have not yet entered service.
[2] Effects realised through having monitored a parameter but not considered end benefits of HUMS adoption.
[3] Effects that relate directly to the end benefits of HUMS adoption.
[4] Comparable to Australia's Fundamental Inputs to Capability.

The tool itself is easily customised to individual projects by tailoring the weightings given in each stage of the benefits map, noting that this requires SME input. Further, this tool could be tailored to work with e.g. the Australian Fundamental Inputs to Capability (FIC) categories instead of the DLoD, provided the ground-work is conducted to attain appropriate weightings for a modified benefits matrix to map the strength of impact from final effects to the relevant capability categories.

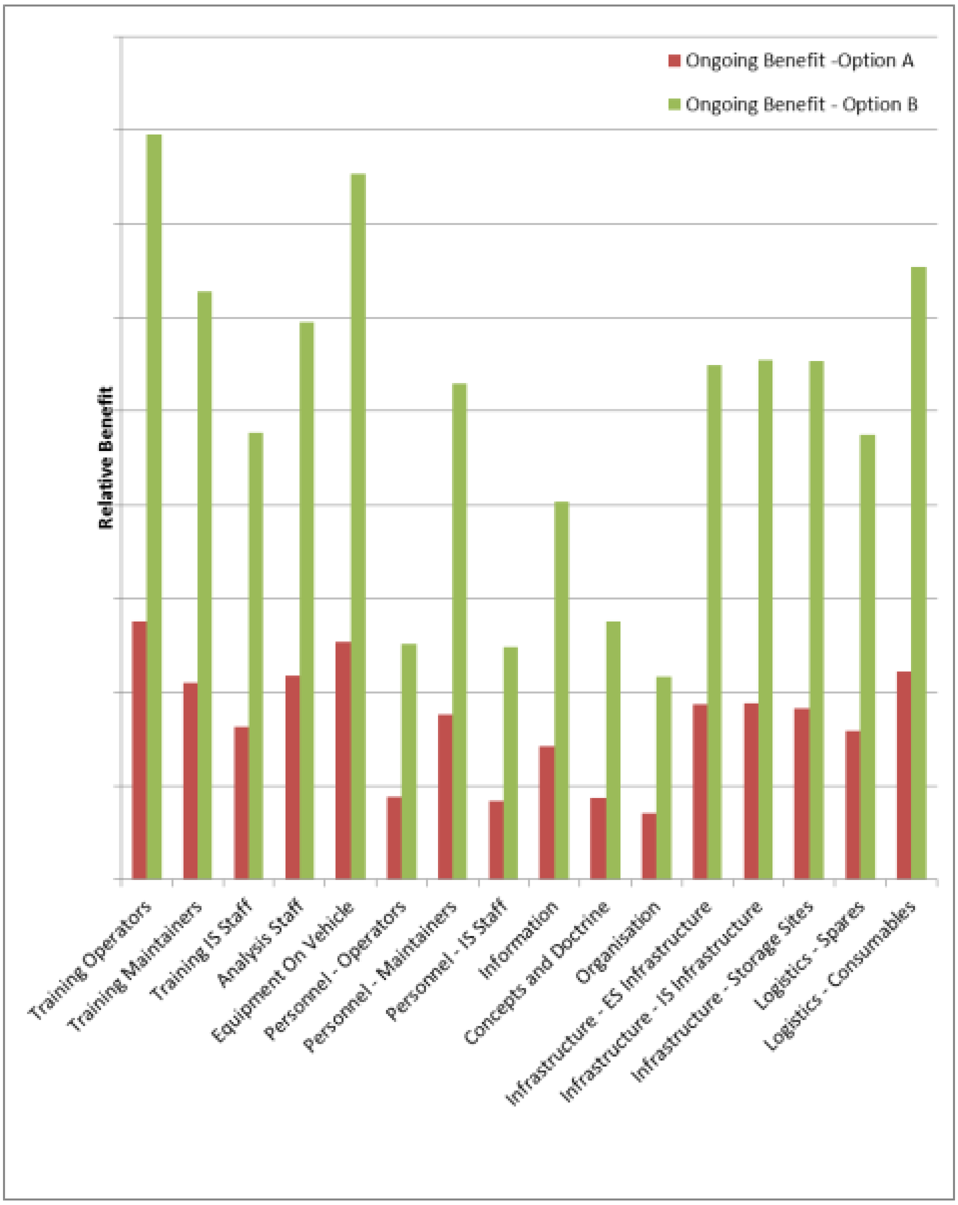

Fig. 1: Example of output from the HUMS Cost Benefit Tool comparing the ongoing benefit of adopting two alternative HUMS variants.

It is important to note that 'human factors' aspects are considered within this tool (e.g. workload, changing tasks) at least to some extent. By following the methodology behind the creation and operation of this tool, the tool itself could be modified even further: to take into account modified beliefs of the strengths of impact specified in each stage of the benefits map; to use expanded, contracted or customised sets of intermediate effects or final effects; to use expanded, contracted or customised sets of vehicle parameters that could be monitored; or to add or remove stages (layers) in the benefits map (i.e. an additional layer between intermediate and final effects, or to remove intermediate effects and provide a mapping directly between monitored parameters and final effects, and so on). This would require revalidation of the relevant stages of the benefits map, and hence would require substantial SME input.

DSTO CBM Technology Impacts Study

This study [9-12], undertaken by DSTO's Land Division, was designed to obtain a comprehensive set of cost/benefit factors, clarify the drivers for adoption, identify the areas of most importance to stakeholders, and determine the critical issues that must be addressed in order for CBM to 'work' in the military Land domain.

A generic 'technology impact' conceptual model [9] was developed and used within the study for studying the impacts of the introduction of a new technology and identifying the key drivers and factors that need to be understood for its adoption to be successful. This conceptual model is shown in Fig. 2. Without going into specific details, the elements of the conceptual model are described below in the context of the CBM study (more details can be found in [9]):

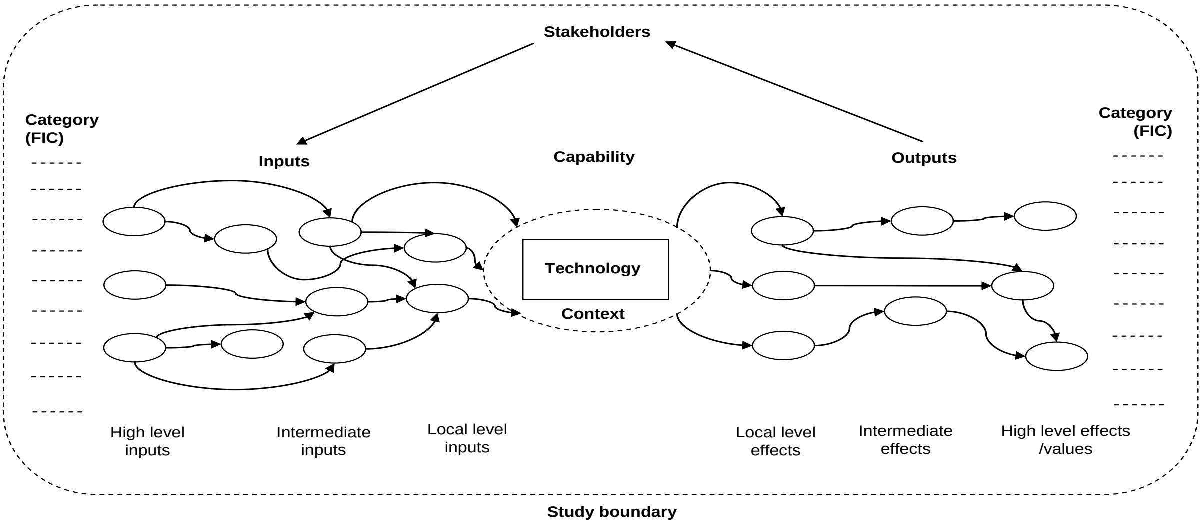

Fig. 2: Generic 'Technology Impacts' Conceptual Model

- *Technology:* an instantiation of CBM technology in the military Land environment, covering data acquisition and collection, data transmission, data storage and warehousing, data processing and analysis, and maintenance decision support [13]
- *Context:* determines the significance or otherwise of the various factors that may influence technology use, and considers the technical, military, socio-cultural and physical environments
- *Capability:* The technology and context define the capability
- *Study Boundary:* includes the expected application of the technology, time horizon, geographical scope, impact sectors, and range of policy options and constraints (doctrine, concept documents, legislation, …)
- *Inputs:* those entities and actions required for CBM to be implemented and used in the military Land domain. Inputs can be used to determine the various costs associated with the introduction of a new technology
- *Outputs:* represent effects that the implementation of CBM will have. Outputs can be used to capture benefits, neutral effects and risks associated with the technology

- *Category*: Both the inputs and outputs can be tagged with the Fundamental Inputs to Capability (FIC) categories which are affected, along with other attributes including temporal, directness, desirability, and strength of supporting evidence
- *Stakeholders:* those individuals or groups that contribute to, or are impacted by, the introduction of the capability.

The major outcome of the study was a comprehensive CBM technology impact map, capturing 40 input and 76 output impacts (organised into 6 input and 11 output impact themes) and associated causal links. The complete map and all details can be found in [10], but for illustrative purposes, Fig. 3 illustrates one particular output impact ('improved ability to more effectively plan and schedule maintenance') and its recorded attributes.

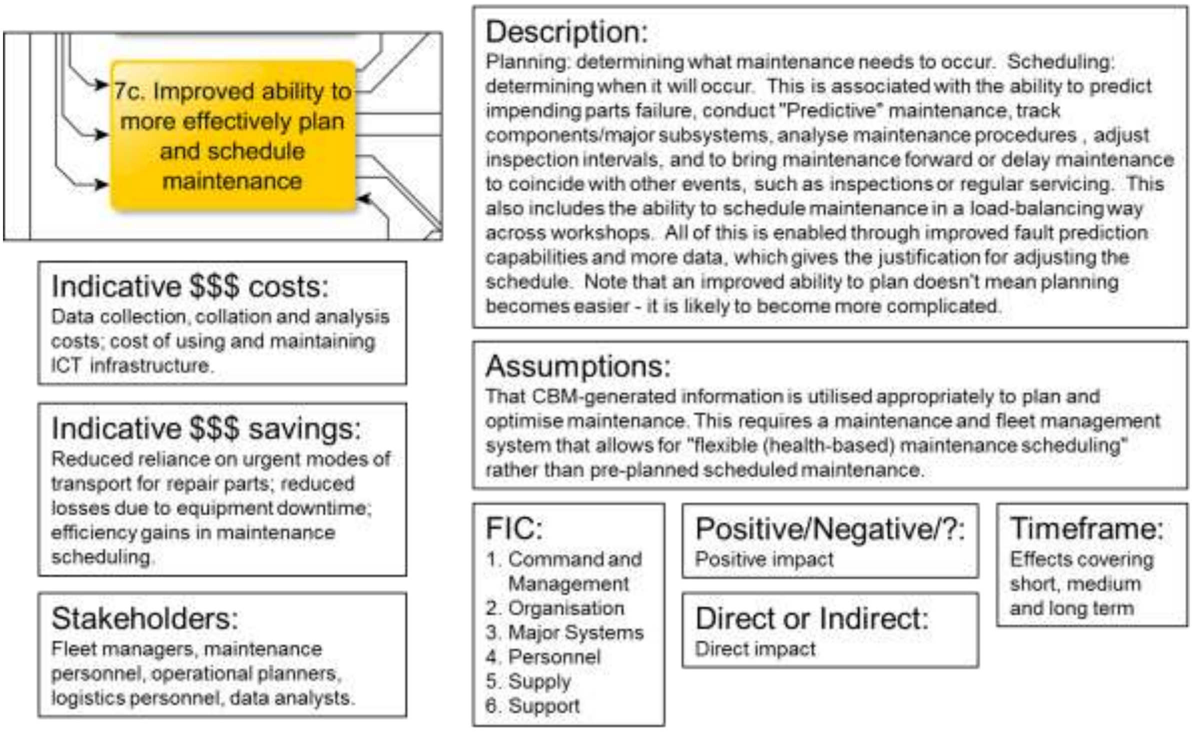

Fig. 3: Example of an output impact and associated attributes

The map was then analysed and assessed in various ways, including:

- Assessment of impact significance
- FIC analysis
- Identification of economic costs and benefits
- Identification of non-economic costs and benefits
- Identification of areas of risk
- Identification of areas of uncertainty
- Analysis of assumptions.

Full details of the study results can be found in [10].

Quantitative Models and Tools

Quantitative models and tools refer to those based primarily on numerical data including, for example, equipment data, probability distributions, or absolute or relative measurements. Such models and tools will normally produce numerical output, but may still incorporate some aspects of qualitative modelling. This work considered 10 quantitative models and tools amenable to the cost/benefit analysis of CBM that have come to our attention through their prominence in the open literature and through interaction with TTCP partners. We describe three of these tools below, followed by an abridged mention of the remaining seven.

EXAKT

Developed by the Centre for Maintenance Optimization and Reliability Engineering (C-MORE) [14] at the University of Toronto in Canada, EXAKT is 'a decision support tool for predicting reliability and optimizing condition based maintenance' [15]. Ostensibly, EXAKT does not sound like a cost/benefit analysis tool, but can be used to assist in cost/benefit calculations if the required maintenance and condition monitoring data is available for an existing fleet.

From [15] EXAKT can predict equipment failure, estimate the Remaining Useful Life (RUL) of equipment, and define the mix of preventive replacement and run to failure in order to optimise costs, optimise reliability, and achieve the optimum risk/cost/reliability balance. Benefits listed in [15] include improved production reliability, accurate maintenance scheduling, and accurate failure prediction.

Use of the EXAKT package requires the following data [16]:

- Equipment and component parameters
- Records of failures (and associated costs) of components
- Records of preventive replacements (and associated costs) of those components
- History of condition monitoring data for those components.

EXAKT then takes this data and uses Proportional Hazards Models (survivability models, in this case based on Weibull hazard distributions) to characterise the probability of failure based on both the equipment/component age and current condition. EXAKT performs covariate analysis to determine which of the 'input signals' (condition monitoring feeds) are 'significant' with respect to equipment failure, and hence EXAKT can help to identify which signals should be monitored, thus eliminating unnecessary condition monitoring equipment [16]. The costs of preventive maintenance actions vs. corrective maintenance actions are incorporated into the model, allowing the user to determine the optimal maintenance action at the time of equipment inspection [16].

Examples of this type of output are the two 'replacement decision charts' given in Fig. 4 (taken from [17], a study on pump failures at a Canadian wood pulp mill). Each chart comprises a graph of equipment status based on recent inspections, overlaid on three 'bands' representing decisions for 'don't replace', 'expect to replace before next inspection' and 'replace immediately'. These three bands have been calculated from historical equipment failure, maintenance and condition monitoring data. The recent set of inspections depicted on each graph for two separate pumps are calculated based on a weighted sum of the significant condition monitoring feeds. The example on the left in Fig. 4 indicates that the component should be replaced immediately, whereas the one on the right indicates that the component should continue to operate without problems at least until the next inspection. EXAKT can also give estimates of RUL of the monitored component, not shown here.

Further, by characterising the condition of components into discrete 'states' (e.g. the vibration of a bearing may be categorised as very smooth, smooth, rough, or very rough)

EXAKT is able to provide a 'transition probability matrix' that shows the probability of going from one state to another in between inspections. More formally, the table 'provides a quantitative estimate of the probability that the equipment will be found in a particular state at the next inspection, given its state today' [16].

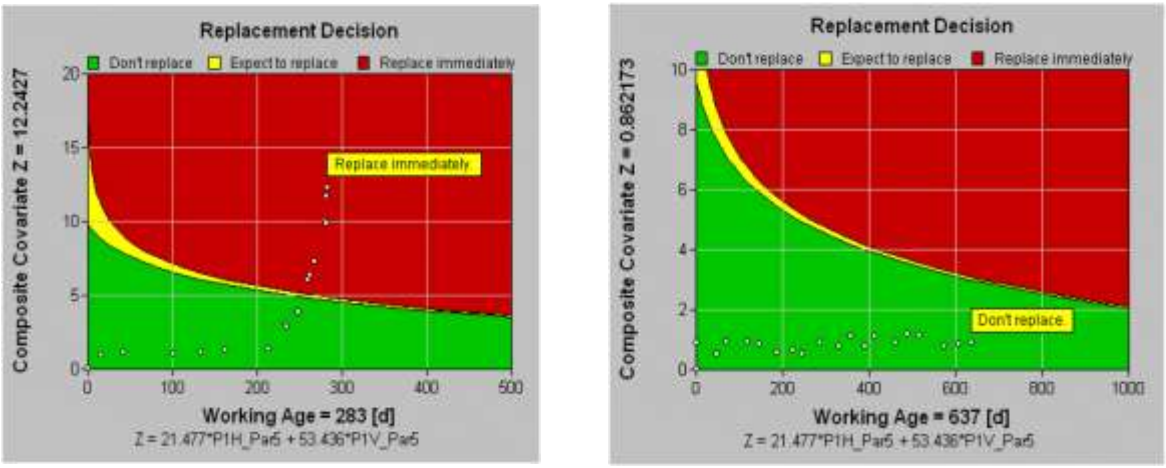

Fig. 4: Examples of EXAKT replacement decision analysis, taken from [17]

EXAKT relies heavily on historical data on component inspections and failures, the costs associated with preventive and corrective maintenance actions, and component condition data. This is required by EXAKT to establish the hazard/survivability function (relating equipment age and condition data with the risk of failure) and for providing a 'replace/do not replace/expect to replace prior to next inspection' recommendation.

This tool may not be immediately suitable for equipment on deployment, whose operation may be characterised by bursts of high activity and irregular inspection intervals, neither of which are conducive to EXAKT analysis. However, for in-barracks or peace-time operations, with good quality maintenance and condition data, EXAKT may prove useful.

Maintenance Aware Design Environment (MADe)

The Maintenance Aware Design environment (MADe) software tool suite [18], produced by PHM Technology, Victoria, Australia, is based on FMEA/FMECA (Failure Modes and Effects Analysis/Failure Modes, Effects and Criticality Analysis) and related analysis techniques. MADe has a suite of supporting tools to facilitate Reliability, Availability and Maintainability (RAM) analysis [19], and Prognostics and Health Management (PHM) optimisation [20].

MADe is designed to be used by engineers to model parts, components, sub-systems and systems in order to identify and assess potential functional and safety issues in the system design [21], prior to hardware being introduced into service. MADe is applicable to all stages of the design process (conceptual, configuration, detail, technology refresh, upgrade) and was developed for complex, integrated, multi-domain systems [21]. MADe provides a framework so that PHM-related software tools can work together to [22]:

- Identify potential operational and diagnostic problems in the conceptual stages of system design and provide aids to making the necessary capability and requirements trade-offs to optimise the design of the final system

- Provide ‘what-if’ analysis of new design concepts as well as pre-existing hardware systems from the point of view of PHM and health management capabilities.

There are four key issues in the design process that MADe may address [19-21]:

1. *Data quality:* ensuring that failure concept and functional descriptions are consistent by providing standardised taxonomies
2. *Data integrity:* ensuring that system dependencies are accurately mapped across domains and hierarchies and ensuring consistency across design iterations and variations
3. *Data currency:* enabling failure analysis results to be available to designers concurrently with the design process, rather than retrospectively after a design is locked in
4. *Data usability:* optimising workflows and reducing design costs using a standardised system model that can integrate with existing design and analysis tools.

Paraphrasing [21], by building up a system model based on FMECA analysis, MADe can simulate system-wide responses to failures through system hierarchies using fuzzy cognitive mapping (a technique to compute the strength of impact of system elements [23]) and bond graph (a graphical representation of a physical dynamic system [24]) simulations. Functional failure modes can be ranked, in order of priority or criticality, based on how they develop and the system responses they generate, by using a number of different criticality and risk analysis approaches.

A useful feature of MADe is its library of parts, components and systems. Generic component and part libraries are supplied, but can easily be customised [21]. MADe RAM [19] provides tools to model the system level failure responses generated by specific failure modes originating at lower functional levels.

Using the results of failure simulations, MADe PHM [20] can attempt to automatically identify and minimise the set of indicators (oil pressure, temperature, flow rates of specific components etc.) required to uniquely identify every failure mode, and aid the user to resolve the identification of failure modes that remain ambiguous. MADe PHM also provides tools to assess candidate sets of sensors for condition monitoring, diagnostics and identification of failure modes. The parts libraries supplied with MADe include libraries of HUMS sensor types as the basis for automatically identifying the equipment monitoring requirements, allocating HUMS sensors to a system, and analysing the coverage provided by any given sensor set of identified equipment failure modes. Assessment of sensor sets against other criteria (e.g. aggregated cost, weight, reliability) is also possible. Details on how the automated design and optimisation of sensor sets is performed is given in [22], along with a simple example of this process applied to a hydraulic actuator.

To achieve the aspirations of data quality and integrity, and for the automation of failures and effects analysis, a standard ‘functions and failures’ taxonomy was developed for MADe and is presented in [25]. The standard taxonomy allows for consistent, repeatable results in automated tools based on FMEA and related techniques. A review and comparison of current usage of terminology to define functions and failures in accordance with those defined in MIL-STD-1629A [26] and the implementation of the standard taxonomy within MADe are also presented in [25].

The MADe methodology can be applied to both new and legacy platforms [27], with examples given in [28-31]. As a cost/benefit tool, it appears that the MADe suite of tools could be useful for performing ‘what-if’ analysis at the design stage, or when designing HUMS retrofits, provided the appropriate FMECA data is available or is able to be obtained. The nature of this tool complements others like EXAKT as it makes use of data at the design stage and emphasises the inclusion of PHM/CBM concepts at the design stage, rather than applying CBM ‘retrospectively’ to an in-service fleet based on operational data. While the emphasis of MADe is its utility at the design stage, operational data can be used to refine and update MADe’s failure models and knowledge base. This is useful for informing mid-life upgrades.

HUMS SIE Cost-Benefit Model

The Command, Inform and Battlespace Management (CIBM) research programme, led by a consortium comprising UK Defence Industry contractors, subject matter experts and academia, was established by Dstl on behalf of the UK MOD with the aim of providing expert technical advice to support the CIBM and Logistics Capability Planning Groups within the UK Ministry of Defence (MOD) [32]. One specific study into the potential benefits of HUMS/System Information Exploitation (SIE) within the Land domain was commissioned by Dstl with the aim of [33] identifying the potential financial benefits derived from HUMS and SIE, supporting the business case for further detailed investment, and understanding if there is any variation in this potential investment across different ‘in service’ platforms.

As a result, the quantitative benefit analysis model, called the HUMS SIE Cost Benefit Model, was developed for financial modelling. It is based on a prior qualitative study that identified 9 key areas of potential benefit that may result from the implementation of SIE [33]: breakdown in the field, 3rd party warranty, smarter maintenance, predictive maintenance, improved fleet utilisation, reduced supply chain costs, reduced fuel/power consumption, improved spare parts management, and improved reliability trials.

The quantitative econometric model developed following the qualitative study is an attempt to quantify the potential benefits in these nine areas. This model has been subsequently applied to several fleets of vehicles within the UK MOD Land domain to provide an indicative assessment of the potential economic benefit of applying HUMS/SIE.

The model requires a substantial degree of input, including (but not limited to) [33]:

- Current costs for fleet support: Major Line Replaceable Units (LRUs) (e.g. transmission ,engine, generator), consumable items, other in-service support costs
- HUMS/SIE implementation costs: infrastructure and one-off implementation costs, ongoing costs, vehicle fit costs based on quotes from multiple potential vendors, other labour costs required for exploitation of SIE
- A ‘benefit realisation profile’ that dictates the time to realise the effect of adoption of HUMS/SIE
- The aggressiveness of implementation and the time to implement the business process changes necessary within the MOD.

The model also supports sensitivity analysis of key input parameters, including [33]:

- Beyond Economic Repair rate for key repairable items

- Major repair cost as a percentage of the new buy replacement cost
- Cost of vehicle fitting, progressing from the cheapest to the most expensive quoted supplier
- Effect of the pace of roll-out, ranging from quick to cautious as above.

This model captures a comprehensive set of cost factors. Consequently, the input information requirement of this model is substantial. The type of information required may, in general, be difficult to obtain or estimate, particularly for new fleets that lack historical maintenance records. However, as observed in [33], this model is able to provide results for a subset of the benefit categories if not all of the input information requirements can be met.

Other Notable Models and Tools

The below models and tools were also included in this survey, described here only briefly (see [TTCP year 2 tools] for more details).

CFAR Autotrend

Provided by Humaware, a UK-based company, this tool automates the analysis of raw HUMS data by providing alarms from threshold exceedances using a Constant False Alarm Rate (CFAR) method [34], and from trends using a local trend detection method [35]. This tool offers the opportunity to perform retrospective analysis of HUMS data to evaluate potential maintenance cost savings, had CFAR Autotrend been employed.

Insight^{AM}

Also from Humaware, this is a decision support tool based on Monte Carlo simulation of an underlying Discrete Event Simulation (DES) model [36]. This tool offers the capability of performing what-if analysis on a wide range of Maintenance, Repair and Overhaul (MRO) network configurations and alternative scenarios.

HUMSSAVE

HUMSSAVE [37] is an econometric model originally developed by DSTO for cost/benefit analysis of specific monitoring systems fitted to air vehicles. The most recent version (version 4) provided a significant expansion in flexibility and customisability by allowing customised templates to be produced for any equipment type, including Land vehicles [38]. The cost formulas within HUMSSAVE are generally based on cost per km, per vehicle, per year, or a combination, hence all have factors that relate to the average distance travelled per year, number of vehicles in the fleet, and/or the expected remaining service life. Many of the formulas require estimates of the percentage improvement afforded by HUMS, such as the expected percentage reduction in required overhauls due to early HUMS detection.

AVENCA COEIA tool

Avenca [39, 40], a UK-based company, have developed a Combined Operational Effectiveness and Investment Appraisal (COEIA) model for the application of HUMS to military Land vehicles. As with Insight^{AM}, this is a DES model that provides the capability of performing what-if analysis of a wide variety of system configurations and operational characteristics, including some aspects of the broader supply chain.

PHM Maintenance Planning Tool

The Prognostics and Health Management Group of the Center for Advanced Life Cycle Engineering (CALCE) at the University of Maryland, USA, is investigating the cost and availability impacts of the incorporation of prognostics and health management into complex systems. A software tool, the CALCE PHM Maintenance Planning Tool [41], has been produced based on stochastic DES modelling techniques. This tool can be used to evaluate the cumulative life-cycle costs of the introduction of Prognostic Health Management and to perform ROI analysis, including ROI as a function of time and evaluation of ROI against implementation costs.

DSTO CBM and Supply Chain Model

Preliminary work has been conducted by DSTO [42, 43] to explore the potential interaction between CBM and military supply chains, including consideration of alternative strategies for taking the foreknowledge afforded by prognostics into account within the supply chain itself. This has been done through the use of parameterised DES models that are able to perform what-if analysis and parameter sweeps. Unlike the models above, these models take details of the maintenance process itself into account.

AMSAA CBM ROI Methodology

The US Army Materiel Systems Analysis Activity (AMSAA) have developed a methodology for investigating the ROI of CBM that focuses on the ‘cost avoidances’ facilitated by CBM [44]. This model has an element of qualitative analysis incorporated through the use of SME judgement to inform the percentages of failures, and hence related costs, likely to be avoided through condition monitoring. However, the authors of the study explicitly point out that non-monetary benefits should not be overlooked by concentrating on cost avoidance alone.

System of Systems Analysis Model (SoSAM)

SoSAM is a DES model, built in Arena, for parametric analysis of the operational availability of assets based on their reliability [45]. The model simulates a mission profile, generates failures for each modelled asset, and simulates the recovery, part acquisition, repair and return to duty of failed vehicles [45]. Notably, SoSAM abstracts from the maintenance network through spare part fill rates. Such a model could be used for cost/benefit analysis of CBM with suitable enhancements and further development.

Assessment of Models and Tools

To compare and contrast the aforementioned models and tools, we consider their attributes and utility for cost/benefit analysis, keeping in mind that this might not be their primary purpose. With hands-on access to only some of the models and tools considered, the assessment is restricted in some cases to perception and implied functionality based on the available literature. For brevity, the assessment is summarised in Table 1. An extended version of the model and tool assessment, including detailed discussion, can be found in [1]. However, it is worth highlighting in this paper the limitations surrounding model input.

Table 1: Summary of CBM Cost/Benefit Model and Tool Assessment

	KT Box HUMS Cost Benefit Tool	DSTO CBM Technology Impacts Study*	EXAKT	MADe	CFAR Autotrend	Insight	HUMS SIE Cost-Benefit Model	HUMSSAVE	Avenca COEIA tool	PHM Maintenance Planning Tool	DSTO CBM and Supply Chain model	AMSAA CBM ROI Methodology	SoSAM
Modelling Paradigm													
Conceptual	~	X		~				~					
Analytic	~		X	X	X		X	X				X	
Discrete Event Simulation				?		X			X	X	X		X
Input Data Requirements													
Subject Matter Expert judgements and opinions	X	X					~	X				X	
Breakdown/maintenance/condition monitoring records			X		X		~	~				X	
Failure Mode, Effects and Criticality Analysis or similar				X									
Estimates of specific costs, savings and avoidances							X	X				X	
Probability distributions that represent system behaviour						X			X	X	X		X
Types of Output													
Identification of barriers to adoption (e.g. technical, cultural)		X											
Indicative economic costs and savings in abstract terms	X	X											
Indicative economic costs and savings in quantified terms							X	X				X	
Non-economic Costs and benefits (impacts)		X											
Identification of key condition indicators that precipitate failures			X	~	X								
Design/Redesign of sensor suite composition and location			~	X									
Retrospective assessment of historical maintenance activities			X		~								
Evaluation of Key Performance Indicators of the system						X			X	X	X		X
Consideration of the Broader Logistics Context													
Synergy and improvements in the supply chain						~			X		X	~?	
Model Features and Breadth of Applicability													
Applicable to the Equipment Design phase	~	~		X		~		X	~		~	X	
Applicable during the Operational phase			X		X	~	X	X	~	~	~	X	~
Applicable during Equipment Re-engineering/Upgrade	~	~		X			X	X				X	
Applicable to Strategic Planning and Fleet Management						X			X	X	X		X
Supply Chain and Spare Parts Warehouses:													
Support for Line Replaceable Units						X	X		~	X	~		~
Multi-Item Supply Chain									?		X		~
Multi-Indenture Supply Chain									?				
Multi-Echelon Supply Chain						X			X		X		
Alternative Spare Parts Stocking Strategies									X		X		
Equipment Fleets:													
Support for Multiple/non-Homogeneous Equipment Fleets	~	X					~	~	?	?	X		?
Representation of Maintenance Workshops						X			X		X		~

*when completed

Legend:
X : fulfilment of the corresponding criteria
~ : Potential or partial fulfilment of the corresponding criteria
? : Fulfilment of the corresponding criteria is unknown at this time

Observations on Tool Input

Tools and models that rely on historical data (e.g. breakdown, maintenance and condition monitoring data) rely on databases and records that may be incomplete, incompatible, come from disparate sources, or have questionable data integrity. It is often the case that significant effort must be expended to 'clean' such historical data to transform it into a usable state. [46-48] report on these difficulties. In the case of new fleets, adequate historical records may not exist, however data from 'like' fleets, the manufacturer, or equivalent in-service fleets from other nations may serve as proxies until sufficient organic records are generated.

Tools that are based on FMECA or related techniques avoid the data integrity problems above but face challenges of their own. The first is that a FMECA or equivalent model of sufficient detail to be useful is produced. The second is that reliability data is regularly updated once the corresponding platform is in service. A further obstacle is that, in practice, FMECA is often not pursued beyond a certain point during the procurement cycle, especially if procurement is of an existing military or suitably modified commercial product.

For tools that rely on estimating the relative importance of cost/benefit factors, or percentage estimates of specific costs, savings and avoidances, it is desirable that these estimates have some experiential or theoretical basis, be it data from trials or pilot studies, theoretical results from desktop analysis, or anecdotal or judgement-based opinions from SMEs.

The use of probability distributions to characterise system behaviour (e.g. time to failure, time to repair, transport delays, etc.) within simulation models avoids the data integrity issues above, but relying on probability distributions can also be problematic. There may be no suitable 'standard' probability distribution that captures the observed behaviour accurately, limited tool support for non-standard probability distributions, or even simply insufficient data to determine the probabilistic nature of the behaviour.

Model and Tool Survey Limitations

Many software models and tools exist for CBM, however this survey was restricted to those either designed specifically for cost/benefit analysis or amenable to cost/benefit analysis. For example, AMSAA's work on a Prognostic Reasoner and Remaining Useful Life (RUL) tool [44, 49] is valuable for developing diagnostic, prognostic and RUL algorithms, but does not perform cost/benefit analysis directly, hence was excluded from this survey.

Both the breadth and depth of exploration of the model/tool space was limited by:

- The models and tools considered are of a mixed pedigree. Some consider the cost/benefit assessment of CBM directly, while others relate more closely to HUMS or to maintenance in general. Some are from the Land domain, while others are (or originated from) other domains
- The models and tools considered in this survey were those offered by TTCP member nations or that have some prominence in the open source literature
- The models and tools are at varying stages of development and hence exhibit varying degrees of sophistication and maturation

- Information collection is limited to that available in the open source literature, via model/tool developers directly, or from TTCP member nation contributions
- The analysis and comparison of models/tools is based on a desktop assessment of the above information. There has been no direct exposure or hands-on use for the majority of the models/tools considered. Fortunately, many of these tools have a significant presence in the literature, and hence reasonable initial judgements of the capabilities and utility of these tools can still be formed.

Value Proposition Framework

Taking the insights gained from the above survey of models and tools, we provide the skeleton of a value proposition framework for CBM in the military Land domain. The proposed framework comprises 10 principles, each of which is described below. A more detailed version can be found in [50].

1. Establish a Cost Baseline: *The value proposition framework should require a cost baseline be established in the absence of HUMS or CBM.*

This cost baseline should include acquisition/procurement costs (if dealing with a new fleet), ongoing fleet support costs, and fleet disposal costs. Determining the ongoing support costs for a new fleet, particularly one that has not yet been acquired or introduced into service, is likely to be difficult. It may be possible to use manufacturer/OEM data, cost data from a 'like' fleet, or data from an in-service fleet of another nation (provided it does not employ HUMS or CBM). SME judgement may play a significant role. The situation for a legacy fleet is more straightforward, as suitable historical data should be available in relevant information systems.

2. Econometric Considerations: *The value proposition framework should take econometric considerations into account.*

For example (taken from the HUMS SIE Cost Benefit Model) this may include factors such as the real discount rate, general benchmark inflation rate, materials inflation rate, labour inflation rate (public and private), and projected price of fuel.

3. Establish a Set of Scenarios to Consider: *The value proposition framework should require that a set of scenarios for analysis be established.*

These scenarios will be used for evaluating alternative implementations of HUMS and CBM, and for evaluating the impact of a given HUMS/CBM solution in different situations under different operating conditions. Sources of such scenarios include existing documents on current and future operating concepts, existing 'current' warfighting or logistics scenarios, existing 'future' warfighting or logistics scenarios, data on the employment of existing fleets, SMEs from logistics, maintenance, Concepts of Operation/Employment and doctrine development, and warfighters.

4. Initial Cost for Implementing a HUMS and CBM Programme: *The value proposition framework should require that the cost of implementing HUMS and CBM be established.*

Breakdown of Costs: This covers the cost of hardware and software procurement, operator training, revision of maintenance processes, etc. (all of the things that deal with initial costs.

For legacy fleets, this also includes the costs associated with retrofitting platforms. Both the HUMS SIE Cost Benefit Model and the CBM Technology Impact study provide a suitable breakdown of these costs.

Estimation of Costs: In terms of estimating the infrastructure costs, no suitable tool was identified. This remains a gap in the value proposition framework. MADe may be useful for vehicle fitment costs, as may EXAKT provided historical usage, failure and maintenance data is available. Other estimates may come from SME judgement and/or tools identified outside of the scope of this study. Implementation schedules should also be recorded.

5. Ongoing Costs for Operating a HUMS and CBM Programme: *The value proposition framework should require that any additional costs of operating a fleet with HUMS/CBM be captured and articulated.*

Breakdown of Costs: The HUMS SIE Cost Benefit Model provides a breakdown of ongoing costs associated with operating a HUMS and CBM programme, including network support (hardware and software), training, and vehicle systems support. The CBM Technology Impact Study provides a more detailed breakdown of ongoing costs that may also be suitable. Non-monetary costs associated with the ongoing operation of a HUMS and CBM programme, such as those related to user acceptance, should also be articulated for consideration as part of the overall value proposition.

Estimation of Costs: No tools have been identified as candidates for estimating these costs. This remains a gap in the value proposition framework. Estimates may come from SME judgement and/or other tools identified outside of the scope of this study.

6. Monetary Benefits Arising from a HUMS and CBM Programme: *The value proposition framework should require the monetary savings and cost avoidances resulting from utilising HUMS and CBM to be articulated and estimated.*

Breakdown of Benefits: The HUMS SIE Cost Benefit Model and CBM Technology Impact Study both provide suitable breakdowns of monetary benefits. This should include not only the immediate, first-order benefits, but also the flow-on effects where quantification is possible (e,g. fewer convoys for resupply of spare parts due to less demand, other supply chain efficiencies facilitated by HUMS). Benefit realisation timescales (i.e. how quickly the benefits are realised) should also be recorded.

Estimation of Benefits: Prior to any in-service data being available for the fleet under consideration, estimates will likely come from SME judgement, data from the equipment manufacturer, data from ‘like’ fleets, data from operational fleets of other nations, and estimates from models and simulation tools as surveyed above. Once data is available from in-service fleets, the estimates obtained from the above sources should be progressively refined as time passes. This is covered under principle 10, described below.

7. Non-Monetary Benefits Arising from a HUMS and CBM Programme: *The value proposition framework should require that non-monetary benefits be articulated.*

While many benefits of HUMS and CBM can be specified in monetary terms, not all benefits can be easily quantified or attributed a monetary value. These primarily relate to having an increased awareness of the health state of individual members of the fleet and the fleet as a whole.

As an example, the CBM Technology Impact Study articulated the following non-monetary benefits:

- An increase in the quality and quantity of equipment/platform status data and associated improvements in the quality of decision support for a range of short-term and long-term functions (e.g. fleet management and utilisation)
- Operator safety, confidence and morale effects
- Cultivation of equipment ownership culture
- Various direct and indirect contributions to overall mission effectiveness.

8. HUMS and CBM Implications for Disposal: *The value proposition framework should articulate the benefits of HUMS and CBM to platform disposal.*

HUMS and CBM implications for the disposal of assets at the end of their service life is currently something of a gap in the value proposition framework skeleton. HUMS and CBM, through better knowledge of asset health and better targeted maintenance over the life of the asset, may enable better outcomes in terms of disposal, and hence should be considered by the value proposition framework. For example:

- Knowledge of a vehicle's usage history may help improve the resale value
- In a phased removal from service programme, HUMS may help determine which parts can be cannibalised for maintenance of the remaining fleet

9. Relative Importance of Non-Monetary Costs and Benefits: *The value proposition framework requires that a judgement be made of the relative worth of the monetary and non-monetary costs and benefits.*

This is, arguably, the most important principle, and one that is overlooked by the majority of cost/benefit tools and models surveyed. SME judgement will be vital in providing this judgement. Tools like the KT-Box HUMS Cost/Benefit Tool may assist.

Consideration of the non-monetary costs may also encompass consideration of areas of risk and uncertainty. The CBM Technology Impact Study identified areas of risk and uncertainty worthy of consideration.

10. Iterative Refinement of the Value Proposition over Time: *The value proposition framework should require the iterative refinement of the value proposition itself over time, as actual acquisition, in-service (and potentially disposal) data becomes available.*

The notion of a value proposition framework is that it provides a framework for assessing the value of various propositions related to the introduction and operation of HUMS and CBM to Land fleets, prior to its introduction. Necessarily, any such value proposition will contain estimates that are determined a priori from models/tools or SME judgement. Refining these estimates over time as data becomes available cannot retrospectively influence past decisions, but can provide more accurate forecasts of the likely costs or savings going forward. This is important for Land fleets that may have an in-service life of 30+ years.

Conclusion

The ability to make use of extant tools and models has the potential for significant savings in the time and effort required to produce a functioning 'value proposition framework' for CBM in the military Land domain, with the added benefit that many of the models/tools mentioned in this paper have been validated on practical examples, including military examples. Tools have been identified that can contribute in the following ways:

- Provide rough first cut costs/savings based on estimates
- Inform the cost of acquisition and fitment of condition monitoring solutions of varying efficacy (in terms of coverage of failure modes)
- Determine data streams to monitor and condition triggers for initiating maintenance, and provide evaluation of historical/pilot study data
- Simulate alternative HUMS solutions and CBM strategies to gain insight into their indicative efficacy and likely impact on costs and benefits
- Assess (or at least indicate likely) non-economic costs and benefits, e.g. human factor effects including acceptance and usability of new technology.

For those factors for which existing cost/benefit models and tools are not evident, the value proposition framework can, at the very least, provide a high-level indication of the likely cost/benefit factors to be considered.

Future directions for this work include completion of the value proposition framework, through fully specifying the inputs required to fulfil each principle, either identifying or creating models or tools to fill the identified gaps, linking the output of appropriate models/tools to the inputs of others, and establishing an overall evaluation process for any given value proposition. Following this, the proposed value proposition framework should be applied to national programmes involving or considering the adoption of CBM.

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