A Conceptual Model for Assessing the Impact of Adopting Condition-Based Maintenance

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Abstract: Condition-Based Maintenance (CBM) involves performing preventive maintenance actions based on evidence of need, rather than more traditional usage or time schedules. The promise of CBM is threefold: to extend the useful life and reduce the through-life cost of equipment, to improve fleet operational availability and mission effectiveness, and to reduce the maintenance burden. While well established in other military domains (particularly Air) and commercial domains, adoption of CBM in the military Land domain has been slow, but is now solidly underway.

It is likely that the introduction of CBM to support Land-based military forces will require the adoption of new technological systems. When anticipating the effects of the adoption of such systems, it is important to consider the associated practices, processes and policies in addition to the technology itself. Quite frequently, factors other than inherent technological merits determine the success or failure of adopting new technologies. The continued successful adoption of Land CBM requires that not only the potential technology barriers be identified and addressed, but also that an appropriate understanding of the nuances of CBM adoption in the military Land domain be attained.

Anecdotally, the two most frequently cited reasons for the slow pace of adoption of CBM within the Land domain are: 1) that different drivers for adoption exist in the Land domain than others such as the Air domain, and consequently 2) the difficulty of establishing a clear business case for adoption in the Land domain. The latter is made more difficult by the former. For example, in the Air domain, safety is the most critical factor and the argument for adoption is clear. Conversely, the consequences of catastrophic equipment failure may at times be perceived as less severe in the Land domain, and hence, the safety argument tends to lose its criticality while more pragmatic economic considerations rise in prominence.

Drawing on a number of established methods and techniques, a general conceptual model has been developed 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 paper presents the conceptual model developed to describe Land CBM and the initial results of a CBM ‘Technology Impacts’ study. The intention of this study is 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.

Following a literature review and a first round of Subject Matter Expert (SME) surveys, a ‘causal impacts’ map has been established. This map considers the impact of the factors that enable a CBM capability and the likely outcomes of adoption of CBM. In addition, the map captures economic and temporal considerations, impacts on stakeholder groups, and impacts on inputs to the development and delivery of military capability. This map will be further refined and analysed as the study progresses. A second round of SME surveys has been prepared that will elicit responses to refine the structure and content of the causal impacts map, and to clarify the position of participants on impacts where a conflict of opinion has been identified.

The study outcomes will inform planning and investment decisions relating to the acquisition of new Land force equipment, and will contribute to collaborative research within The Technical Cooperation Program. Ultimately this study will form a basis for a ‘value proposition’ framework to assess the extent to which CBM should be adopted within the maintenance practices of Land-based military forces.

Keywords: *Condition-Based Maintenance, Causal Impacts Mapping, Cost/Benefit Analysis*

1. INTRODUCTION

Broadly speaking, Condition-Based Maintenance (CBM) is a maintenance paradigm that has the potential to extend the useful life and reduce the through-life cost of equipment, improve fleet operational availability and combat effectiveness, and reduce 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.

However, as yet CBM has not been fully realized in the military Land domain. The difficulty of establishing a clear business case is frequently cited as a reason for its slow pace of adoption when compared to other domains. The safety argument that is clearly evident for aircraft tends to lose its criticality in the Land domain in the face of more pragmatic economic considerations. Further, factors other than inherent technological merit can influence the success or failure of new technologies or technologies in new contexts (Volti 2006; Reed et al. 2007). Hence, Australia's Defence Science and Technology Organisation (DSTO) is undertaking a 'CBM Technology Impacts study' that aims to obtain a comprehensive set of cost/benefit factors, clarify the drivers for adoption in the Land domain, identify the areas of most importance to stakeholders, and identify the critical issues to be addressed for CBM to 'work' in the military Land domain.

The purpose of this paper is twofold: to present a proposal for a new future technology assessment model for use in the CBM Technology Impacts study, and to present the progress and interim outcomes of the study. The final outcomes of the study will inform a number of acquisition projects within the Australian Army, as well as contributing to international collaborative work through The Technical Cooperation Program[1].

2. CBM TECHNOLOGY IMPACTS STUDY

We propose the following steps for our CBM Technology Impacts Study:

1. Overview of technology assessment methods and models based on published literature and consultation with Subject Matter Experts (SMEs) in order to establish a conceptual model for this study (Section 3).
2. Establishment of contacts with SMEs in the relevant field, so as to encourage their future participation.
3. Establishment of study boundaries, including: time horizon, geographical scope, technology description and application, impact sectors, institutional and policy considerations, and study facilitator and participant considerations (Lee and Bereano 1981). This may involve consultation with relevant SMEs.
4. Environmental scanning (literature review) of the current state of military CBM systems, together with 'emerging issues' analysis considering pertinent trends, technology integration issues, identification of stakeholders, refinement of boundaries, and recording of assumptions.
5. Construction of the initial CBM impacts picture using information collected via the literature review and via workshopping with immediately available SMEs (a more comprehensive workshop using SMEs from different locations would be desirable but is unlikely due to resource constraints).
6. Validation of the CBM impacts model, as well as assumptions and boundaries via SME consultation using a semi-structured survey approach based on Delphi survey principles (Helmer 1967). Two survey rounds have been proposed, with more general questions in the first round and more focused questions in the second round. This information would be used to refine the impacts map previously constructed.
7. Data analysis based on identification of themes and strands within the model with discussion of pertinent considerations and areas of uncertainty.
8. Compilation of recommendations for further studies and trials.

At this stage, steps 1 to 5 of the study are complete, with one survey round under step 6 also complete.

3. PROPOSED CONCEPTUAL MODEL

The following 'impacts' model facilitates structuring and analysis of CBM-related information within the study. It is based on various elements of a number of models for technology diffusion (the gradual spread of technology use and its adoption within organisations and society) (Kukafka et al. 2003; Jeyaraj et al. 2006; Fidock 2011) and futures studies on technology assessment (Roessner and Frey 1974; Lee and Bereano 1981; Tran and Daim 2008; Koivisto et al. 2009). It is meant to act as a framework for structuring and validation of CBM-related information that can then be used for further analysis. It is built around the central process of Inputs (generating) → Capability (resulting in) → Outputs, and encompasses consideration of:

- The technology characteristics from the Diffusion of Innovations model[2] (Rogers 1995);

[1] Partnership between the US, UK, Canada, Australia and New Zealand on Defence science and technology.
[2] A model that describes the diffusion of innovations within organisations and society, taking into account the socio-cultural environment, audience and technology characteristics, and communication mechanisms.

- The factors surrounding user beliefs and attitudes, and personal, technical and organizational contexts from the Model of Technology Appropriation[3] (Carroll 2004; Fidock 2011);
- The notion of Inputs being transformed into Outputs from IDEF0[4] modelling (National Institute of Standards and Technology 1993); and
- A mapping of input and output 'impacts', adapted from Benefits Analysis[5] (Mathieson 2004).

A diagrammatic representation of our conceptual model is shown in Figure 1 and described below through its instantiation for the CBM Technology Impacts study.

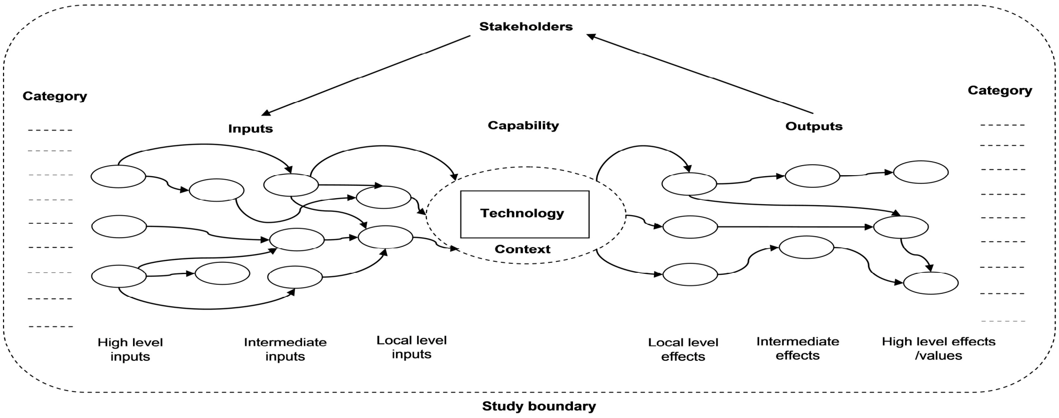

Figure 1: Proposed impacts model for the CBM Impacts study

3.1. Elements of the Conceptual Model

Study Boundary

The selected boundaries for the study include the:

- Expected application of the technology: primarily (but not limited to) military land vehicles;
- Time horizon: out to 20 years from now;
- Geographical scope: in barracks and on deployment;
- Impact sectors: covered in the Stakeholders section below; and
- Range of policy options and constraints: includes such items as doctrine, land vehicle concept documents, and applicable legislation (e.g. Workplace Health and Safety).

Technology

This study considers 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. We also consider those aspects of Health and Usage Monitoring Systems (HUMS) technology that enable CBM, such as embedded sensors and built-in or portable diagnostic equipment. Integration with existing on-vehicle and enterprise systems, on-vehicle processing capabilities, data transmission bandwidth limitations, perceived complexity of the new technology and an ability to demonstrate benefits are all factors that are likely to affect the implementation of CBM.

Context

The context of technology implementation determines the significance or otherwise of the various factors that may influence technology use. These are likely to include the following aspects:

- Technical environment, e.g. rapid development of computer and sensor technologies, reduction in hardware costs, advances in prognostic technologies;

[3] Describes the process of technology adoption being characterised by two phases: decisions on whether to adopt a new technology, and adaption of the technology and of the user practices surrounding the technology.
[4] Integrated Definition Function Modelling (IDEF0): a method for graphically representing functions and activities within an organisation. IDEF0 diagrams depict inputs, outputs, controls and mechanisms.
[5] A method for analysing investment options based on value (rather than e.g. operational characteristics) that depicts the progressive effects of investment, allowing alternative investment options to be compared.

- Military environment, e.g. strategic guidance, specific policies, budgetary constraints, and capability acquisition characteristics (e.g. equipment usage profiles, non-uniformity of usage rates);
- Socio-cultural environment, e.g. current materiel maintenance practices, 'spy-in-the-cab' syndrome[6], perceptions of CBM causing additional workload; and
- Physical environment, e.g. temperature, humidity, noise, vibration, dust, dirt, impact, operational tempo, etc. when operating in barracks, on training exercises, during peace time or on deployment.

Inputs, Outputs and Categories

The input impacts represent those entities required for CBM to be implemented and used. Inputs can be used to determine the various costs associated with the introduction of a new technology. The output impacts, on the other hand, represent effects that the implementation of CBM will have. Outputs can be used to capture benefits, neutral effects and risks associated with the technology. Characteristics of the input and output impacts that are of interest for the CBM study include:

- Temporal characteristics (short-term, medium-term, long-term);
- Directness (primary, secondary, tertiary/indirect, integration effects);
- Desirability (positive, negative, neutral, unknown, mixed);
- Type (e.g. Fundamental Inputs to Capability (FIC)[7] categories);
- Causal relationships to other impacts; and
- Strength of evidence (level of support in the literature and from SMEs).

It is anticipated that the high level inputs will be derived from a set of categories such as FIC, and likewise that the high level effects will feed into similar categories. This is captured on the left and right of Figure 1. A description and brief discussion of the identified inputs and outputs is given in Section 4.

Stakeholders

Our study has identified the following high-level stakeholder groupings: materiel suppliers, capability development/acquisition organisations, research and academic organisations, security organisations (both within and external to Defence), end-users, planning and management, legal and doctrinal, IT and support, maintenance personnel, adversaries, Australian public, and the Australian Defence Force as a public entity.

3.2. Data Analysis

There is significant potential for both formal and informal analysis of the impacts map (Mathieson 2004) Formal network analysis tools can be used to identify the potent nodes, powerful causes and common effects. Informal, expert inspection of the map can be used to draw out themes and strands for further analysis. Further work may relate to evaluation strategies using techniques such as matrix-based scoring, network-based functions, and strand-based multi-method evaluation (Mathieson 2004). However, the outcomes of this initial study will focus on identification of the significant technology impacts and key trends, with specific recommendations for further work.

3.3. Model Advantages

This conceptual model has the following advantages:

- Facilitates further quantitative analysis without significant changes in the conceptual approach;
- Allows for consideration of multiple dimensions/characteristics of technology effects;
- Is based on consistent and doctrine-based categories (e.g. FIC categories); and
- It allows identification of costs, benefits and risks of both an economic and non-economic nature.

It is likely that economic considerations will be significant in any future capability investment decision. The developed conceptual model can be used to develop systematic lists of the expected areas of economic costs (associated with the required inputs) and benefits (that flow from the identified outputs). Further research and modelling would be required to meaningfully quantify measurable items on these lists.

[6] A phenomenon where monitoring of equipment use is considered an 'unwelcome intrusion' by operators.

[7] Australian Defence's Fundamental Inputs to Capability (FIC) categories for the development and delivery of military capability comprise Command and Management, Organisation, Major Systems, Personnel, Supplies, Support, Facilities, and Collective Training.

4. INTERIM RESULTS

A 'First Round' impacts map has been produced based on information from the literature (covering 42 references), an internal DSTO workshop, and the responses (12 in total) to the First Round survey. Figure 2 shows part of the output impacts portion of this map, with impacts arranged into clusters. The two scores given to each impact represent strength of evidence based on the number of items of literature (blue circle) and First Round survey responses (red circle) that mention the impact. Within each cluster the impacts with the highest weight of evidence from literature and from survey responses have been highlighted with blue or red borders, respectively. Causal links between impacts are indicated by arrows. Graphical indications of stakeholders, directness, desirability and temporal characteristics have not been shown on the map. A corresponding map for the input impacts has been produced but is not shown here.

The input impacts have been arranged into seven clusters: leadership at high and local levels, incorporation of CBM requirements into the capability acquisition process, change management, acquisition or modification of HUMS-enabled equipment/platforms, data management strategy, training and personnel certification, and technology integration. There is a reasonable spread of survey responses across these seven clusters. Impacts relating to data management and technology integration are well represented in the literature, whereas both the capability acquisition process and change management are not. Further, impacts were identified by an internal DSTO workshop that were not mentioned in literature or by survey respondents. We will be seeking the thoughts of participants on these impacts in the Second Round survey.

The output impacts have been arranged in to 12 clusters, five of which are shown in Figure 2. Following the (partial) causal relationships depicted in Figure 2, we can see that CBM provides a set of immediate functions (cluster 1) that enable a number of immediate impacts on maintenance (cluster 2). One such impact is 'Improved fault detection' (impact 4b). This may lead to less regular, more proactive maintenance (impact 4b) which then facilitates a number of longer term effects on maintenance (cluster 9), including an improved ability to plan maintenance (impact 9a). This facilitates a number of changes to logistic processes (not shown) including a requirement for changes to supply processes and the potential for reduced logistics footprint. This in turn contributes to improved mission effectiveness (impact 12a).

Of the three promises of CBM, an 'increase in operational availability of equipment/platforms' (not shown in Figure 2) was the most cited impact in the literature, and was also strongly supported by survey respondents. Both the 'increased/more predictable equipment life' (also not shown in Figure 2) and 'reduced overall maintenance burden' impacts received moderate support from literature and survey respondents.

Two conflicts of opinion were discovered from the First Round survey responses: that there would be either a decrease or no change in the number of maintainers, and that there would be negligible impact on supply chain costs despite indications of reduced inventory holdings at supply chain nodes, reduced logistic footprint, more efficient and responsive supply chain processes, and better supply planning.

The Second Round survey has been released to participants, to seek feedback on the structure and content of the impacts map, the strength of evidence ratings, and the areas of conflicting opinion. Based on a preliminary scan of Second Round survey responses, there will be significant changes to the structuring of the impacts, including the clustering of impacts, aggregation of 'like' impacts, dis-aggregation of impacts that are 'not like enough', and a substantial revision of the causal links between impacts.

5. UNCERTAINTY AND SUBJECTIVITY IN FUTURES STUDIES

Studies that attempt to forecast and assess future conditions face more challenges in terms of uncertainty than those focusing on present and past states. Sources of uncertainty for technology evaluations are identified in (Dortmans and Curtis 2004; Mathieson 2004; Volti 2006; Webb et al. 2006). A systematic approach to technology assessment will facilitate identification of the areas of uncertainty and their causes. Some of these may be addressed in follow-up studies and trials, whereas some may have to be managed as risks.

Apart from the issues of uncertainties, it should be noted that this type of analysis inevitably contains elements that are normative, judgement-based, creative and subjective. The authors are aware of the dangers related to forming 'rankings' of input and output impacts based on a small number of responses. Hence, we consider the attribution of the scores described in Section 4 as an indication of the issues that are perceived as important amongst the participating stakeholder groups. If time permits, an SME workshop to validate the final Impacts Map would be desirable. The feasibility of holding such a workshop remains to be determined.

6. CONCLUSIONS

This paper has presented a new conceptual model for assessing the impact of the adoption of new technologies and our initial results from applying this model to conduct a Technology Impacts study on the adoption of CBM in the Land domain. To complete the study, we propose the following remaining tasks:

- Collection, collation and analysis of Second Round survey responses, which may include:
  - Extraction of economic considerations – a ‘money map’;
  - Breakdown and trending of results by timeframe, desirability or other characteristic; and/or
  - Identification of ‘negatives’ in order to highlight possible risks associated with CBM adoption;
- Discussion of the validity of the results, which may include assumptions, risks, sources of bias, uncertainty associated with study outcomes (knowledge gaps, indirect technology impacts and long-term impacts), strength of evidence, and trends among stakeholder groups; and
- Recommendations and identification of future work areas.

Following on from the impacts study, it is our intention to use the results and insights gained to develop a ‘value proposition framework’ for CBM within the Land domain. Such a framework will take into account the quantitative economic factors behind both the positive and negative impacts, as well as the qualitative factors that may influence the decision to adopt CBM. Our intention is for the value proposition framework to assist decision-makers by facilitating ‘what-if’ analysis of different CBM capability options.

ACKNOWLEDGMENTS

The authors would like to acknowledge their colleagues within DSTO’s former Land Operations Division for their feedback on the construction of the study and to the participants who have taken part thus far.

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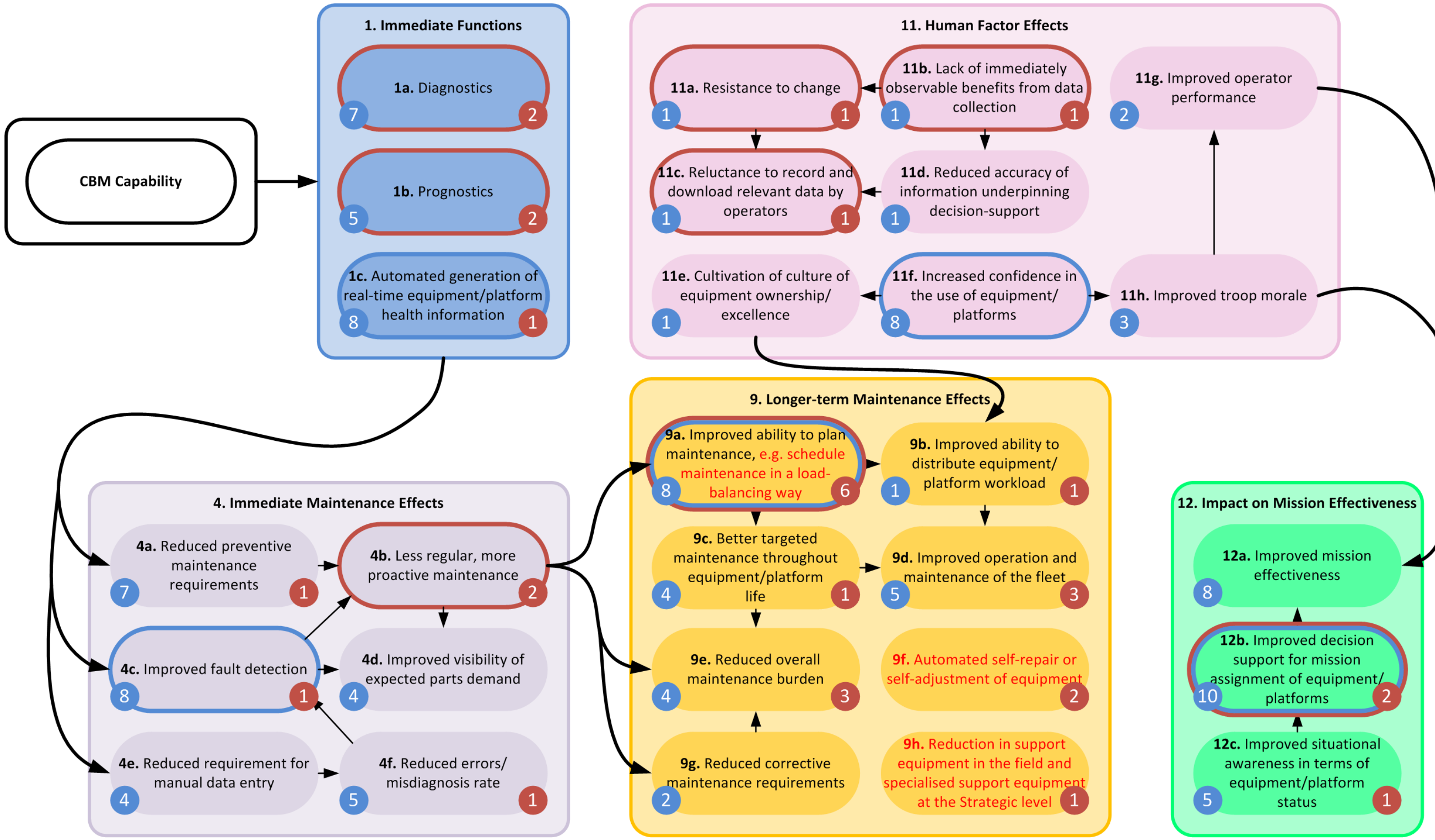

Legend:

Text:		Outlines:		Markers:	
Black text:	Impact identified from literature/internal DSTO workshop	Blue outline:	Top-ranked impact based on literature	X	Number of items in the literature that identified this impact
Bold text:	Cluster heading	Red outline:	Top-ranked impact based on Round One survey responses	Y	Number of survey respondents that identified this impact
Red text:	New impact identified from Round One Survey responses				

Figure 2: Partial Output Impacts Causal Map