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Condition Based Maintenance Technology Impacts Study for the Military Land Environment

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Land Division
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ABSTRACT

This study considered the implications of adopting Condition Based Maintenance (CBM) within the military Land domain. A 'CBM technology impacts map' was developed, capturing the inputs required to generate a CBM-based capability, the expected effects resulting from that capability, and their causal relationships. The map was developed through reviewing the literature, internal DSTO workshops and two rounds of Delphi-based surveys of subject matter experts (SMEs). This map and associated material were then analysed using a triangulation approach to identify the key inputs, effects and issues relating to developing and implementing a CBM-based maintenance capability. Further, the analysis elicited the costs and benefits associated with adopting CBM in the military Land domain, and highlighted key areas of risk and opportunity.

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Executive Summary

Condition-Based Maintenance (CBM) refers to preventive maintenance that is performed based on need, commonly identified by sensors built into equipment or platforms. It is used extensively in commercial and military aircraft and in some commercial vehicles. This study considered the implications for using CBM in the military Land domain, including the technology itself and the associated processes and policies. The study sought to clarify CBM costs and benefits, identify critical issues for implementation and highlight key areas of both risk and opportunity.

The study used a customised conceptual model of technology impacts that examined both the inputs required to generate a CBM-based capability and the expected effects. This conceptual model encompasses causal relationships between the various impacts, with consideration of key stakeholders and relevant contextual factors.

The study method involved constructing a preliminary 'CBM technology impacts map' based on a literature survey and internal DSTO workshops, and refined through two rounds of Delphi-based surveys of subject matter experts (SMEs). A triangulation approach was used in data analysis to identify the most significant issues by considering: strength of evidence; graph analysis of the constructed impacts map; and prioritisation of impacts by the SMEs. The data was further analysed to provide a Fundamental Inputs to Capability (FIC) perspective, identify economic implications and highlight areas of risk and uncertainty. The validity of results was examined in the context of the study method, SME demographics, uncertainties associated with future states, and underlying assumptions.

The study results indicate that developing CBM as a capability needs to involve leadership at both high and local levels. Historical analysis of equipment/platform failures and incidents should also be used to inform CBM requirements. It is these refined requirements that need to be incorporated into the capability acquisition processes for the relevant equipment and platforms. Other significant capability inputs include:

- Developing new supply and maintenance processes with consideration of systems engineering practices
- Acquiring CBM hardware and software

- Training and certifying personnel
- Establishing data management strategies for data transmission, analysis and use in decision-support
- Developing prognostic and diagnostic algorithms
- Integrating CBM hardware and software with equipment/platforms as well as with Defence Information and Communication Technology (ICT) infrastructure.

The identified benefits of CBM stem from its immediate functions of diagnosing, prognosing and automatically generating real-time equipment health and usage information. This would improve detection of faults and provide a greater awareness of equipment and platform condition, both for individual units and at the fleet level. Furthermore, CBM-generated data is expected to facilitate maintenance planning at local and fleet levels, improve overall operation and maintenance of the fleet and result in a longer and more predictable equipment life.

At the operational level, CBM is expected to reduce catastrophic failure rates for equipment and platforms and increase their operational availability and operator safety. The data generated by CBM can be used for decision support across a range of functions, including mission assignment of equipment and platforms with the flow on contribution to the overall mission effectiveness of the force.

There is a divergence of opinions regarding the expected effects of CBM on the overall maintenance burden and on the inventory levels at supply chain nodes. However, agreement exists on establishment of more efficient and responsive supply processes for spare parts.

A FIC-based perspective of all expected impacts with prioritisation is provided as part of the post-activity data analysis for this study. Further data analysis draws out the key economic considerations for implementation of this capability. In particular, a summary is provided for recurring and non-recurring acquisition costs, as well as costs relating to administrative functions, training, research and development, support, fleet maintenance, data management and associated logistic functions.

The financial savings expected from CBM implementation are based on efficiencies to be gained through improved maintenance planning, a more responsive supply chain, optimised asset utilisation, and associated reduction in use of resources such as fuel. In the longer term, this capability has the potential to reduce overall fleet costs for maintenance, upgrades and replacement. CBM-generated data use in decision support may result in efficiencies in fleet management and future capability acquisitions. At the same time, CBM would help reduce costs associated with equipment and platform failures. In addition to the potential economic benefits of CBM, significant non-quantifiable benefits would include operator safety, confidence and morale effects, and the various contributions to the overall mission effectiveness.

This CBM impacts study identified two potential areas of risk. The first is that these expected benefits are dependent on the successful implementation by the organisation and effective use by the operators. Consequently, any human or organisational factors that affect implementation (such as lack of leadership 'buy-in', failure to effectively manage change, or resistance to uptake) can have flow-on effects on the quality of CBM-generated information and other expected benefits. The second area of risk lies in the data management aspects and the requirement to manage an increase in data transmission and analysis requirements, while ensuring data security and addressing data ownership issues.

Thus the study results should be viewed in the context of the uncertainty associated with all future technology assessments and with recognition of the significant judgement-based component inherent therein. Recognising these limitations, this study was designed to explore CBM impacts in a consistent, iterative and logical manner involving multiple validation activities, a diverse range of SMEs and a critical approach to examination of results. While the study does not claim to make exact predictions, the findings can be used to clarify the cost-benefit picture for CBM, identify critical issues in implementation and highlight areas of risk.

Recommendations for further work in the assessment of a CBM capability for the Land domain include:

- Historical analysis of equipment failure points that can be addressed by CBM in support of development of capability options
- Quantitative economic modelling in support of establishment of a business case
- Modelling of required changes to maintenance and supply processes
- Establishing a detailed data-management strategy.

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Ksenia Ivanova joined the Australian Army in 1999 and completed Bachelor of Pharmacy with First Class Honours in 2001. During her service as Specialist Service Officer within combat service support and health support units she undertook a number of courses in military logistics and administration, training and assessment, and business management. Ksenia deployed to East Timor in 2006, where she managed the medical logistics support for the Australian Joint Task Force. Ksenia transferred to the Active Reserves in 2008 and commenced employment with Land Operations Division, DSTO, in June 2010. She currently works as part of the Land Logistics Group of DSTO's Land Division. Ksenia has worked on projects related to Combat Health Support, logistics for Amphibious Operations, logistics for Land environment, and assessment of technological impact for Condition-Based Maintenance. She is currently completing a Masters of Operations Research and Systems programme through the University of New South Wales at ADFA.

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Guy Edward Gallasch received a Bachelor of Computer Systems Engineering (with Honours) in 2002 and a PhD in Computer Systems Engineering in 2007, both from the University of South Australia (UniSA). From 2006 to 2011 he worked at UniSA as a research lecturer and research fellow, and from 2011 to 2014 as an Adjuct Senior Research Fellow, in the area of discrete-event modelling and analysis of concurrent and distributed systems. During this time he worked on a range of projects spanning the verification of internet communication protocols; modelling and analysis of logistics physical networks, operational planning and Army maintenance processes; and the development of advanced state space reduction methods, including parametric verification techniques and aggregation techniques for performance analysis. In February 2011 he joined DSTO and currently works within the Land Logistics Group of DSTO's Land Division.

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Sreeja Rajesh graduated from the University of Adelaide in 2008 with a PhD in Electronic Engineering after completing her Bachelor's degree in Electrical and Electronic Engineering with a distinction. She was awarded a US Air Force Funded scholarship to pursue her PhD studies. She joined DSTO's Land Operations Division in 2007 to undertake Operations Research and Analysis work in support of concept and capability development for the Australian Army. She has since worked on the development of conceptual models in the area of Counter Improvised Explosive Devices (CIED), vehicle protection and vehicle maintenance. She is currently working in the complex future research and analysis area within the Joint and Operations Analysis Division.

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Contents

Acronyms

ADF	Australian Defence Force
AHQ	Army Headquarters
ASD	Australian Signals Directorate
CBM	Condition Based Maintenance
CDG	Capability Development Group
DIO	Defence Intelligence Organisation
DLIS	Defence Logistics Information System
DMO	Defence Materiel Organisation
DOTMLPF	Doctrine, Organisation, Training, Materiel, Leadership, Personnel, Facilities
DSTO	Defence Science and Technology Organisation
FIC	Fundamental Inputs to Capability
FORCOMD	Forces Command
GPS	Global Positioning System
HR	Human Resources
HUMS	Health and Usage Monitoring Systems
IDEF0	Integrated computer aided manufacturing Definition Function Modelling
ICT	Information and Communication Technology
IT	Information Technology
MILIS	Military Integrated Logistics Information System
MOD	Ministry of Defence (UK)
MOE	Measures of Effectiveness
NSB	National Support Base
OEM	Original Equipment Manufacturer
POL	Petrol, Oil and Lubricants
PRICIE	Personnel, Research and development, Infrastructure and organisation, Concepts, doctrine and collective training, Information management, Equipment and material
RAEME	Royal Corps of Australian Electrical and Mechanical Engineers
SCC	Strongly Connected Component
SDSS	Standard Defence Supply System
SME	Subject Matter Expert
SOP	Standard Operating Procedure
SPO	Systems Program Office
SWaP	Space, Weight and Power
TEPIDOIL	Training, Equipment, Personnel, Information, concepts and Doctrine, Organisation, Infrastructure and Logistics
TTCP	The Technical Cooperation Program
TTP	Tactics, Techniques and Procedures
UK	United Kingdom
US	United States
WHS	Work Health and Safety

1. Introduction

The key concept of Condition Based Maintenance (CBM) is preventive maintenance based on evidence of need. This means that maintenance activity is triggered by indicators of deteriorating equipment condition or performance, in contrast to the traditional approach based on usage and time schedules. Furthermore, the direct monitoring of equipment condition and comparison of usage with known failure models has the potential for prognosis and prevention of equipment failure.

CBM technology has been used extensively in commercial and military aircraft and is being implemented in commercial vehicles with the expectation of improved maintenance efficiency, extension of equipment life and greater operational availability. The relatively slow pace of adoption of CBM in the military Land domain is attributed to the difficulty of establishing a clear business case for the technology in this particular environment.

A small number of economic cost-benefit studies for CBM in the military Land domain have been conducted by other nations, e.g. [1-4]. Also of relevance is a report [5] produced by The Technical Cooperation Program (TTCP) Land Group Action Group 5 that articulates definitions, drivers and a technology framework for CBM in the military Land domain, and an evaluation of the maturity of Land CBM technology. In an Australian context, a Defence Science and Technology Organisation (DSTO) report [6] presented a literature review of CBM for land-based platform maintenance, as well as a framework for future analysis of CBM in the Australian Army. The study presented in this report continues on from the work in [6] by focusing on the potential impacts of CBM in the military Land domain. This study analyses the impacts within a consistent assessment framework that considers the technology itself, as well as its associated practices, processes and policies.

The study aims are as follows:

- Develop an understanding of the costs and benefits of CBM with consideration of both economic factors and its impact on mission effectiveness
- Clarify the drivers for adoption of CBM in the military Land domain
- Identify CBM impacts that are the most important to the relevant stakeholders
- Identify the critical issues that need to be addressed so as to improve CBM relevance and effectiveness in the military Land domain.

Details of the study method development and some preliminary results can be found in an interim report [7]. The final report presented here provides a brief summary of this information within the relevant sections, but focuses in more detail on the subsequent data collection and analysis activities. Overall conclusions and recommendations for further study are summarised at the end of this publication.

2. Study Method

2.1 Study Framework

The study framework was developed via analysis of and extension to existing technology assessment studies, as outlined in the interim report [7]. It is based on the following steps:

1. Establishing the relevant conceptual model for structuring of information (see Section 2.2)
2. Developing a subject matter expert (SME) network to facilitate comprehensive data collection in this and other studies
3. Allocating study boundaries in relation to: temporal and geographical scope, technology subsets and applications, impact sectors, institutional and policy considerations, and study participants
4. Conducting a literature survey of the current state of CBM in military systems, with consideration of the elements described in the conceptual model with thematic analysis and coding of information based on the methods described in [8]
5. Constructing the baseline CBM impacts model using information collected via the literature survey and a series of iterative workshops with DSTO-based SMEs as detailed in Section 2.3
6. Validating the baseline CBM impacts model and its boundaries, via two iterations of a Delphi-like SME survey process described in Section 2.4
7. Data analysis and evaluation of the validity of study results, outlined in Section 2.5
8. Summating of the key findings and development of recommendations for further studies.

The interim report [7] presents a detailed account of the first five steps of the study, as well as the results and the preliminary data analysis following the first round of the SME surveys in Step 6. This report follows on to describe the data collection in the second round of the SME surveys and the subsequent data analysis conducted in Steps 7 and 8.

2.2 Conceptual Model

The conceptual model used to structure and analyse the information within this study is outlined in Figure 1.

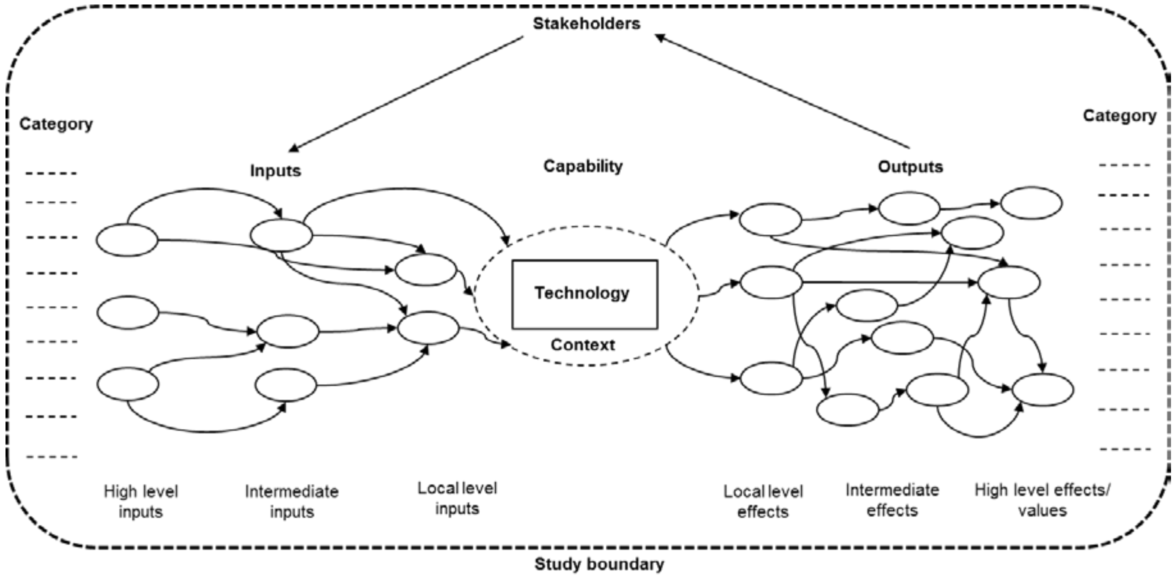


Figure 1: Technology Impact Model used for the CBM Technology Impacts Study

The model was developed through analysis and aggregation of the relevant elements of models described in other technology assessment studies [9-21]. Some key contributing concepts included:

- Technology characteristics within the Diffusion of Innovations model [15, 17]
- Factors surrounding user beliefs and attitudes, and consideration of personal, technical and organizational contexts in the Model of Technology Appropriation of [10]
- The process of 'Inputs' being transformed into 'Outputs' from the Integrated Definition IDEF0 function modelling method [19, 20]
- Mapping of 'impacts' used in the Benefits Analysis Model of [21].

Section 3 of the interim report provides an overview of all the contributing studies, and outlines the reasoning behind construction of the model [7]. The resulting model is built around the central concept of **Inputs (generating) → Capability (resulting in) → Outputs**, and encompasses the following elements and concepts:

- The technology that is being studied
- The context of technology use
- The boundary (scope) of the study with respect to technology applications, temporal and geographical scope, impact sectors, and policy options and constraints
- Inputs required to achieve a capability based on this technology
- Outputs expected to be seen once the capability has been achieved

- Links between the various inputs, the resulting capability, and the expected outputs, that highlight significant causal relationships
- The stakeholders affected by introduction of the technology.

Inputs to capability can be thought of as various types of costs (economic or otherwise) that can be expected to impact the implementing organisation and other stakeholders. Outputs are the anticipated effects (both positive and negative) of the new capability. Together they form an 'impacts map' for the given technology. Various categories and coding can further be used to group and analyse the impacts as part of the subsequent data analysis as outlined in Section 2.5.

2.3 Construction of CBM Impacts Maps

The process used for construction of the CBM impacts maps in this study is based on the principles described by Boyatzis [8] and Pincombe et al [22]. It includes inter-round thematic analysis, de-duplication of information, checks for consistent terminology, and exploration of various clustering options. The allocation of causal links and grouping of impacts within key themes was conducted in a heuristic manner via iterative workshops with DSTO-based SMEs.

Although multiple iterations of the CBM impacts map were created during the conduct of the study, there are three key instantiations presented in this report:

- The 'baseline map' constructed following completion of the literature survey
- The 'first-round map' developed by incorporating the results of the first round of SME surveys
- The 'finalised map' that was completed after adjustments following the second round of SME surveys.

2.4 Survey Design

The survey process used in this study is based on the Delphi technique outlined by Helmer [23], and Rowe and Wright [24]. The underlying principle of the technique is the collection of independent SME opinions through questionnaires. The results are usually revealed in a de-identified manner and debated openly. The SMEs are then asked to provide their (potentially revised) opinions again, thus going from divergence of opinions to gradual convergence over several iterations of the surveys. The median of the responses is normally accepted as the group's decision [23].

The survey process in this study was limited to two rounds due to time and resource constraints. The first round survey contained open-ended questions designed to encourage divergence of opinions and collection of a comprehensive set of data. The questions related to:

- Appropriate applications for CBM within the military Land domain

- Inputs required for CBM to be implemented, structured by the Fundamental Inputs to Capability (FIC)
- Expected positive and negative impacts of CBM.

The first-round survey template is presented in Appendix A.

Following analysis and modification of the impacts map, the second-round survey was constructed with the aim of moving toward a common understanding of CBM impacts. The questions focused on confirming the relative significance of the impacts and exploring the reasons behind any conflicts of opinion. The participants were also asked to review and comment on the first-round impacts map and the allocated causal links. The second-round survey template can be found in Appendix B.

The survey design, method of distribution and collection followed the guidelines outlined in the DSTO Human Research Ethics Approval Process. All responses were collated, analysed and reported in a de-identified manner. A list of contributors is presented at the end of the report, with participants' consent.

2.5 Data Analysis Techniques

The data collected within this study is an aggregation of SME opinions regarding potential impacts of CBM in the military Land domain, together with the relevant contextual information and literature survey results. This information is largely qualitative and represents the results of a literature survey and two rounds of SME surveys, as outlined in Section 2.1.

During the data collection process, the following coding was applied to each unit of impacts-related information in order to facilitate subsequent data analysis:

- Numerical identifier
- References
- Relevant FIC[1] category
- Assignment of desirability (i.e. identifying the impact as being positive, negative, or undetermined)
- Temporal coding (short-term, medium-term or long-term impacts)

[1] The FIC categories describe inputs considered fundamental to the development and delivery of military capability and comprise Command and Management; Organisation; Major Systems; Personnel; Supplies; Support; Facilities; and Collective Training. They are similar in nature to the US DOTMLPF categories (Doctrine, Organisation, Training, Materiel, Leadership, Personnel, Facilities), the UK MOD TEPIDOIL categories (Training, Equipment, Personnel, Information, concepts and Doctrine, Organisation, Infrastructure and Logistics), and the Canadian PRICIE categories (Personnel, Research and development, Infrastructure and organisation, Concepts, doctrine and collective training, Information management, Equipment and material).

- Whether the output was direct or indirect
- Affected stakeholder groups.

Additionally, a note was made of any reported associated economic effects (both costs and savings) and assumptions underlying the recorded insights. The structure used for data capture can be seen in Appendix C. Both the information capture spreadsheet and the resulting technology impacts maps were then used to conduct further data analysis as summarised in Table 1.

Table 1: Data analysis techniques used in the CBM technology impacts study

Data Analysis Technique	Method	Application within the Study Framework
Evaluation of study methodology	Discussion of the underlying assumptions, strengths and weaknesses of the selected techniques and futures studies in general.	This evaluation was conducted during design of the study method as part of the overall evaluation of study validity.
Construction of technology impacts maps	Hierarchical grouping of impacts within key themes and allocation of causal paths during a series of iterative workshops with DSTO SMEs (see Section 2.3).	Numerous iterations were conducted throughout the study, with the key map instantiations produced following: 1. Literature survey ('baseline map', Step 4); 2. First-round SME surveys ('first-round map', Step 6); and 3. Second-round SME surveys ('finalised map', Step 6).
Strength of evidence analysis	• Recording the number of literature references and SME survey responses that confirm the particular unit of information on the impacts maps[2]; • Identification of the most cited and the least cited impacts, as well as conflicts of opinion; and • Re-evaluation of the relative importance of impacts and conflicting opinions within the second round of SME surveys.	Strength of evidence analysis was conducted at three points within the study: • Following literature survey; • Following the first round of SME surveys, in order to gain initial understanding of the critical factors and to determine the points for further discussion and clarification (Step 6); and • Following the second round of SME surveys, so as to facilitate construction of the finalised impacts map and to identify the issues of most importance to the stakeholders (Steps 6-8).
FIC analysis	Aggregation of impacts in accordance with their FIC coding and discussion of the most important impacts for each FIC category.	FIC analysis was conducted following completion of all data collection activities, as part of the post-activity data analysis (Step 7).
Graph analysis	Analysis of the finalised impacts map was conducted using custom written Java code so as to identify isolated impacts, strongly-connected components, paths and cycles within the map, leading to identification of the	Graph analysis was conducted during and after construction of the finalised impacts map, as part of the post-activity data analysis (Step 7).

[2] Construction of a relative ranking scale for the literature survey references was determined to be outside the scope of this study.

	critical nodes.	
Overall cost-benefit analysis	• Grouping of impacts in accordance with their desirability coding; • Identification of the most cited (from strength of evidence analysis) and the critical (from graph analysis) impacts in the positive group so as to highlight the areas of opportunity; and • Identification of the most cited and the critical impacts in the negative group so as to determine potential risk areas.	Overall cost-benefit analysis and the associated identification of areas of risk and opportunity were conducted as part of post-activity data analysis (Step 7) and formation of recommendations (Step 8).
Economic impacts analysis	• Identification and hierarchical categorisation of recurring and non-recurring economic costs associated with implementation of CBM technology; and • Identification of the types of expected savings following CBM implementation.	Information relating to the economic impacts of CBM was collected throughout the study, with the final groupings determined during post-activity data analysis (Step 7). Requirements for quantitative modelling of financial costs and benefits were considered as part of Step 8.
Mission-effectiveness impact analysis	Identification and categorisation of non-quantifiable CBM impacts on mission effectiveness of military Land forces.	Mission-effectiveness impact analysis was conducted as a more detailed sub-set of the overall cost-benefit analysis (Step 7).
SME demographic analysis	Trend analysis of SME self-appraisal information from the surveys, so as to identify the range of expertise and experience with respect to CBM.	These forms of analysis formed part of the examination of the areas of uncertainty and knowledge gaps during study validity evaluation. They were conducted at the same time as the post-activity data analysis (Step 7).
Directness of impact analysis	The most cited and the critical issues identified during the study were further grouped according to their directness coding and used to identify areas of uncertainty.	
Temporal analysis of impacts	Impacts identified during the study were further grouped according to their temporal coding, as short-term, medium-term and long-term impacts and used to identify areas of uncertainty.	
Assumptions analysis	Identification of assumptions (as noted during data collection) associated with the most cited and with critical issues identified during the study.	

Because of the large judgement-based component in determining which impacts are significant, a triangulation approach was used in this study, comprising three different methods:

- Prioritisation of impacts by SMEs in the second round of SME surveys
- Post-activity strength of evidence analysis
- Post-activity graph analysis of the finalised impacts map.

This approach aimed to provide a more comprehensive picture of CBM aspects that need to be addressed in more detail if CBM is to be implemented in a widespread coordinated way by Army.

2.6 Study Scope

The scope of the study was determined with consideration of the key elements within the conceptual model described in Section 2.2. It was drafted during the study method design and refined following consultation with DSTO-based SMEs. Key considerations in setting the study scope included:

- System centrality in terms of how critically the given subsystem or relationship would impact or be impacted upon by the larger systems
- Availability of information and proven methodologies for data collection and analysis
- Inherent limitations of futures studies
- Resource availability with respect to time and funding
- Availability of the various SMEs
- Likely relevance to the military Land domain.

The selected study boundaries are summarised in Table 2.

Table 2: Selected study boundaries for the CBM Technology Impacts Study

Boundary Type	Boundary Details
Survey design	Use of two iterations was considered to be the minimum acceptable number for a Delphi-like process; time and SME availability did not allow the preferred option of three iterations.
Approach to data analysis	Data analysis was restricted to that summarised in Table 1 and focused on clarification of the overall impacts picture. More detailed modelling of specific aspects of CBM, such economic cost-benefit analysis was determined to be beyond the scope of this study, but may form part of further separate studies.
CBM technology subset under consideration	This study considers the instantiation of CBM technology for land-based equipment, covering data acquisition and collection, data transmission, data storage and warehousing, data processing and analysis, and maintenance decision support. The key reference used in determination of this boundary was [5]. In addition, aspects of Health and Usage Monitoring System (HUMS) technology that enable CBM were considered, including the embedded sensors and built-in or portable diagnostic equipment.
CBM applications and context of use	The focus of this study is primarily on CBM use in military Land vehicles, although some consideration was given to its use in other equipment in the military Land domain. This includes consideration of integration with existing on-vehicle and enterprise systems, on-vehicle processing capabilities, and data transmission bandwidth limitations. Contextual factors for CBM use covering technological, strategic, socio-cultural and physical environments are summarised in Appendix D.
Time horizon	The study considers technology impacts up to twenty years into the future, as impacts beyond that point carry a very high degree of uncertainty.
Geographical scope	CBM technology is considered for use by the military Land forces both in barracks and on deployments across the globe.
Impact sectors	The study looks at the military organisation (in this instance the ADF) as the primary stakeholder under consideration, including capability developers, implementers and users. Additionally, consideration is given to the associated organisations, technical support providers, research and academia, public entities, and potential adversaries. A more comprehensive list of potential stakeholders is provided in Appendix E.

Policy options and constraints	These include the relevant military doctrine, Land vehicle concept documents, and legislation covering: Work Health and Safety (WHS), maintenance, environmental impacts, data protection, auditability, accountability, security and storage, data access, and legal status of data.

3. Results

3.1 Literature Survey and Baseline Impacts Map

3.1.1 Literature Survey Results

An initial literature survey was undertaken with the aim of developing a baseline understanding of the potential impacts of CBM in the military Land domain. This was supplemented by several preliminary workshops with DSTO-based SMEs. The key capability input and output themes are summarised in Table 3.

Table 3: Key capability input and output themes identified during the literature survey

Input Themes	Output Themes
• Leadership at various levels • Incorporation of CBM requirements into the capability acquisition process • Change management requirements • Acquisition of HUMS/CBM hardware and software with associated maintenance • Training and certification of personnel • Integration of technologies • Development of data management strategy	• Immediate functions of diagnostics, prognostics, and generation of real-time equipment health data • Immediate maintenance effects • Changes in logistics processes • Long-term maintenance effects • Equipment/platform availability • Human factor effects • Data-collection/transmission/analysis • Integration impacts • Effects on maintenance skills • Impact on overall mission effectiveness

Within the inputs for CBM implementation, the most cited requirements included development of new maintenance and supply processes (within the change management theme), acquisition and maintenance of relevant hardware and software, training and certification requirements, and development of algorithms for diagnostic and prognostic functions. Some mention was given to integration of various technologies and various aspects of data management, with very few references to the capability acquisition process and leadership aspects.

In terms of outputs, there was a general agreement on the three immediate functions of CBM (prognostics, diagnostics and generation of real-time equipment health information). The most cited higher-level effects included a reduction in maintenance burden, reduced error rates, more efficient logistic processes, better maintenance planning and increased operational availability of equipment. This was expected to result in improved situational awareness and decision support on operations, with positive impacts on the overall mission effectiveness of Land forces. While there is a consensus regarding greater availability and better quality of equipment health and usage data, there is little analysis of the associated data management requirements. Effects on maintenance skills were seldom mentioned.

Appendix C provides details of the references, thematic analysis, additional information (associated assumptions and financial impacts), as well as the coding applied to the impacts identified during the literature survey process.

3.1.2 Baseline Impacts Map

Several iterative workshops with DSTO-based SMEs were used to refine the thematic analysis, de-duplicate data and assign causal links between the various impacts identified in the literature. The resulting baseline impacts map is shown in Figure 2 (Capability Inputs portion) and Figure 3 (Capability Outputs portion). The maps show causal links between high-level thematic clusters. The subthemes are shown in associated boxes.

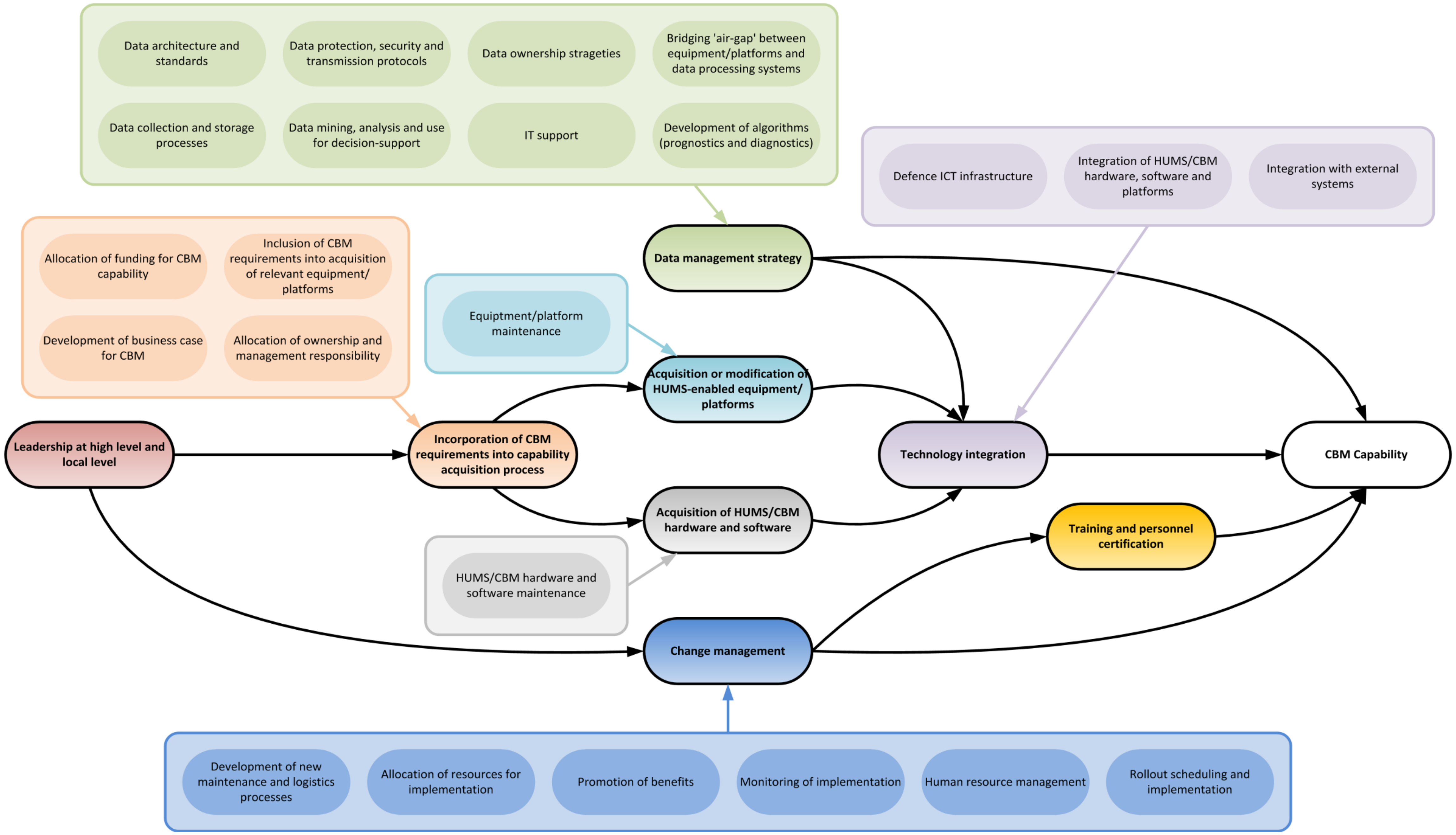


Figure 2: Capability inputs portion of the baseline impacts map

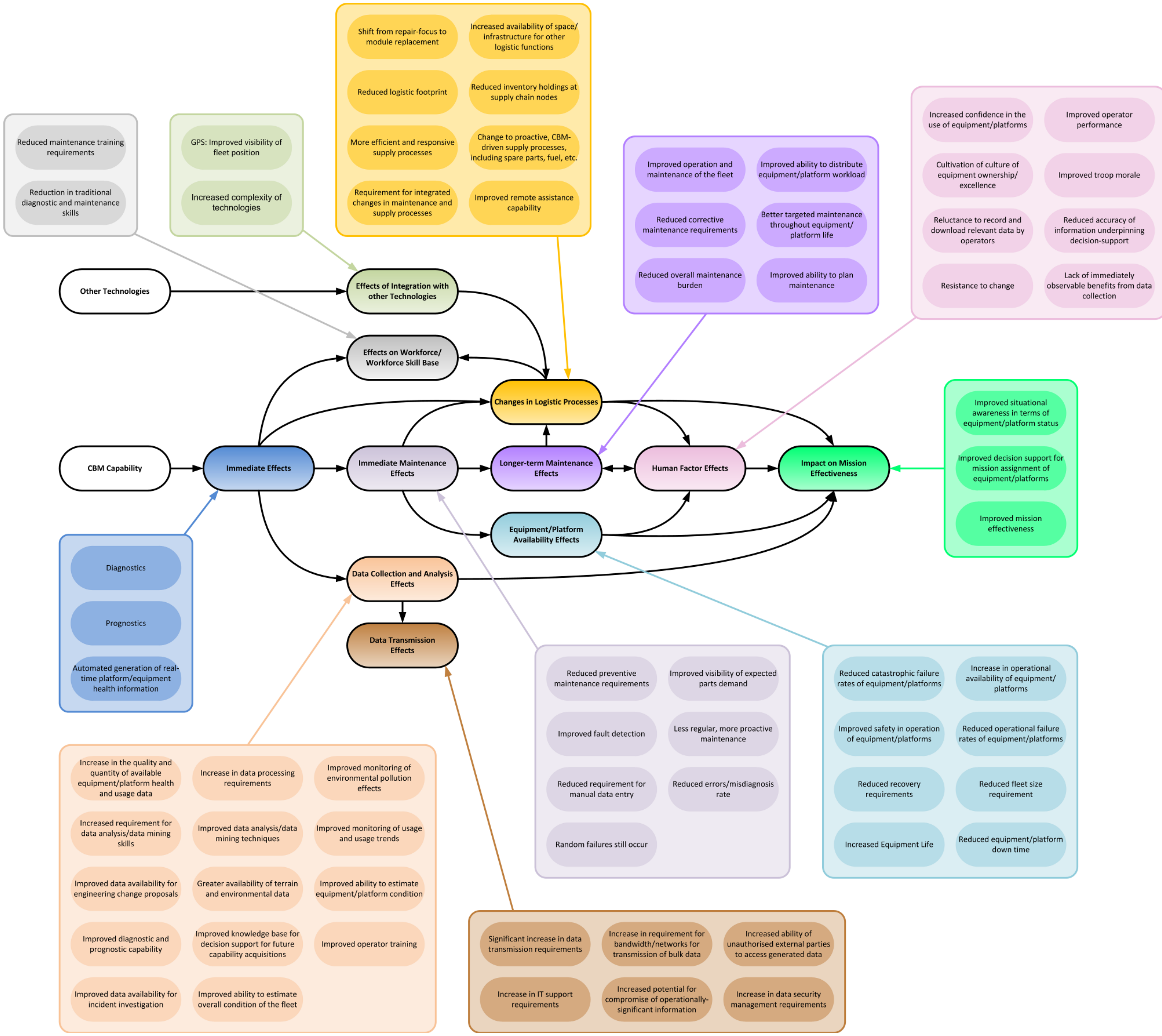


Figure 3: Capability outputs portion of the baseline impacts map

3.2 First-round SME Survey and First-round Impacts Map

3.2.1 First-round Survey Results

Participants in the first round of SME surveys answered a range of open questions regarding CBM applications, required inputs to develop CBM as a capability, and the expected impacts, as outlined in Section 2.4 (survey template is provided in Appendix A). Fourteen responses were received altogether from a cohort of 42 initial contacts and referrals. The research team analysed each response in order to extract the impacts and apply coding similarly to the data capture process used for the literature survey. The number of survey respondents who mentioned a particular impact was recorded prior to de-duplication of data.

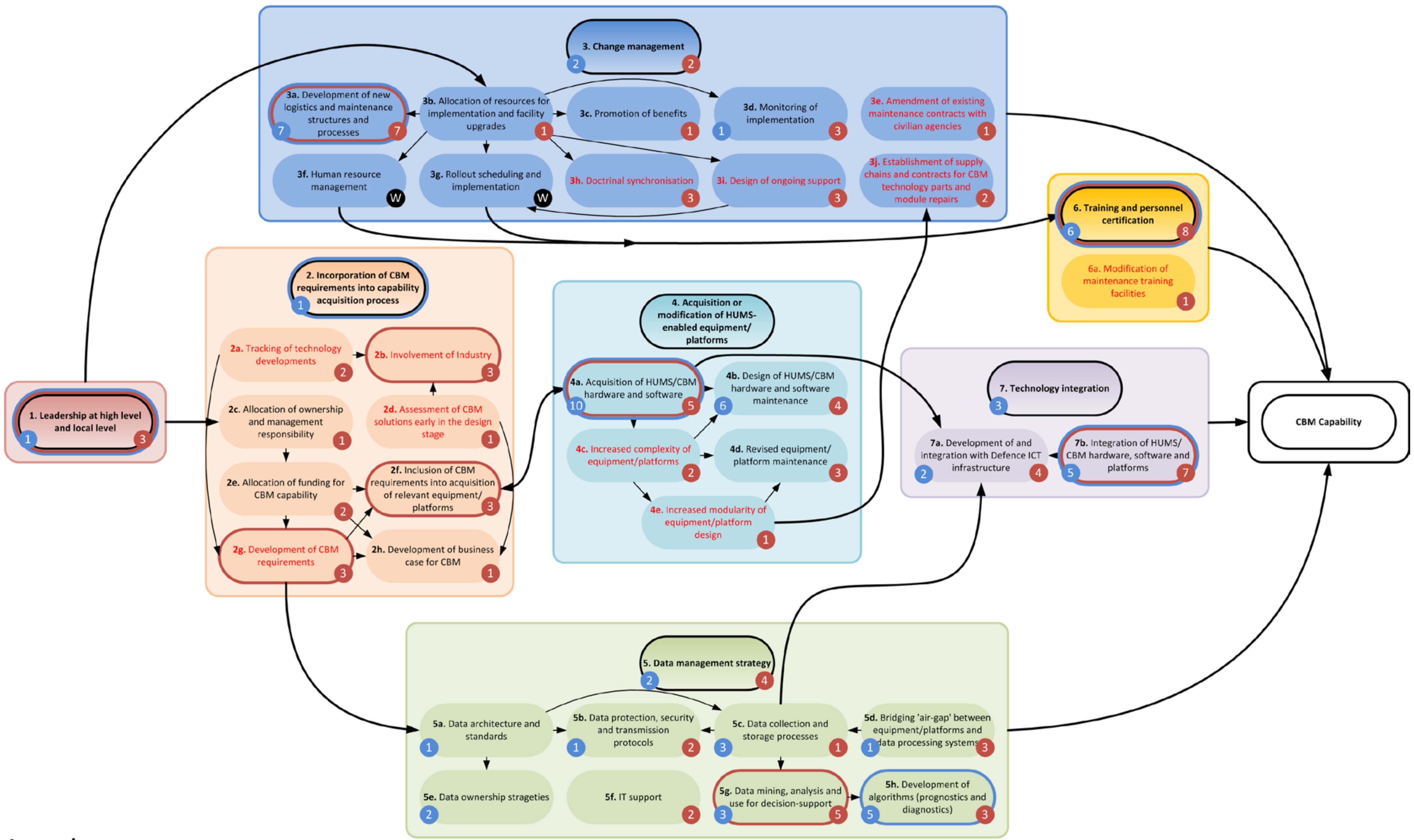
3.2.2 First-round Impacts Map

Following analysis of first-round survey responses, a series of internal workshops were conducted in order to make the necessary adjustments to the baseline impacts map. Further thematic analysis resulted in the addition of two new key themes and numerous new impacts to the map. The causal relationships were examined in more detail and extended to links within (as well as between) the thematic groupings.

The resulting first-round impacts map is depicted in Figure 4 (capability inputs portion) and Figure 5 (capability outputs portion). Apart from a representation of CBM impacts and their causal relationships, the map contains the following additional information:

- Unique identifier assigned to each impact based on its thematic grouping
- Strength of evidence for each impact shown with scores in red and blue circles corresponding to the citation counts for literature survey and SME survey responses respectively
- Impacts with high scores within each thematic grouping highlighted through red and blue borders to reflect a high number of citations in the literature survey and SME survey respectively
- Red text used to show additions or modifications to the baseline impacts map
- Impacts identified only during internal workshops identified by the letter 'W' within a black circle
- Conflicts of opinion highlighted by orange circles with two scores representing the level of support for each of the opposing views.

Additional information regarding the affected stakeholders and the directness, desirability and temporal coding applied to the impacts are not shown on the map.



Legend:

Text:		Outlines:		Markers:	Arcs:
Black text:	Impact identified from literature/internal DSTO workshop	Black outline:	Cluster heading	(X) Number of items in the literature that identified this impact	→ : Inter-cluster causal relationship
Bold text:	Cluster heading/high level impact	Blue outline:	Top-ranked impact based on literature	(Y) Number of survey respondents that identified this impact	→ : Intra-cluster causal relationship
Red text:	New impact/cluster heading identified from Round One Survey responses	Red outline:	Top-ranked impact based on Round One survey responses	(W) An impact that was identified through an internal DSTO workshop but without support in the literature or Round One survey responses	

Figure 4: Capability inputs portion of the first-round impacts map

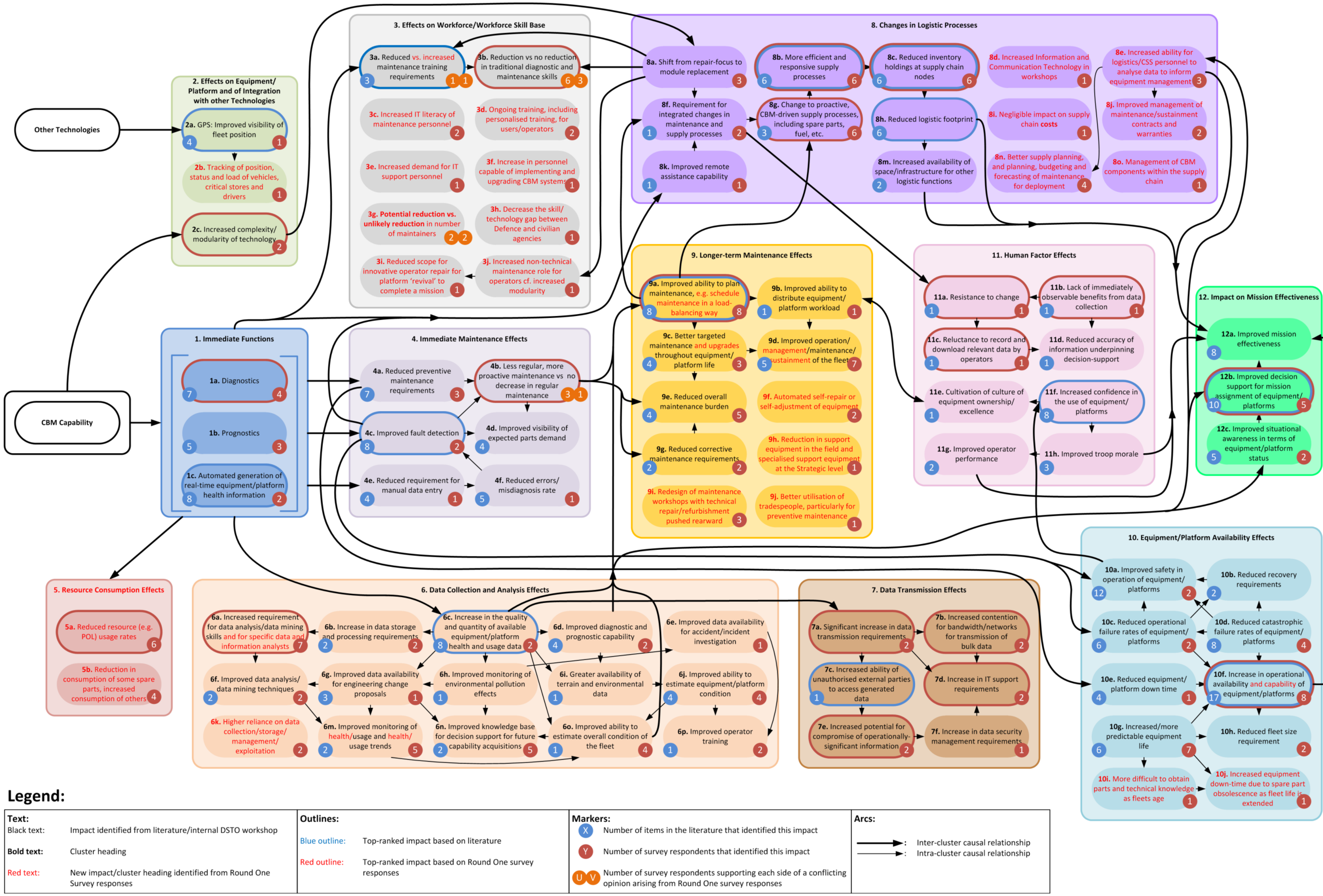


Figure 5: Capability outputs portion of the first-round impacts map

3.2.3 Preliminary Data Analysis

Following analysis of the first-round SME survey responses, the capability input and output key themes remained largely the same as before, with the addition of two new outputs themes: 'Effects on equipment/platform, and of integration with other technologies' and 'Resource consumption effects'.

Results of the strength-of-evidence analysis are summarised in Table 4 (most cited impacts) and Table 5 (least cited impacts).

Table 4: Capability input and output impacts with the highest combined score following the first round of SME surveys

ID	Most Cited Input Impacts	Combined Citation Score	ID	Most Cited Output Impacts	Combined Citation Score
4a	Acquisition of HUMS/CBM hardware and software	15	**10f**	Increase in operational availability of equipment/platforms	24
3a	Development of new logistics and maintenance structures and processes	14	**9a**	Improved ability to plan maintenance	16
6	Training and personnel certification	14	**12b**	Improved decision support for mission assignment of equipment/platforms	15
7b	Integration of HUMS/CBM hardware, software and platforms	12	**10a**	Improved safety in operation of equipment/platforms	14
4b	Design of HUMS/CBM hardware and software maintenance	10	**8c**	Reduced inventory holdings at supply chain nodes	12
5g	Data mining, analysis and use for decision-support	8	**1a**	Diagnostics (as immediate function)	11
5h	Development of algorithms for prognostics and diagnostics	8	**8b**	More efficient and responsive supply processes	11
			9d	Improved operation and maintenance of the fleet	11

Table 5: Capability input and output impacts with the lowest combined score following the first round of SME surveys

ID	Least Cited Input Impacts	Combined Citation Score	ID	Least Cited Output Impacts	Combined Citation Score
2c	Allocation of ownership and management responsibility	1	**2b**	Tracking of position, status and load of vehicles, critical stores and drivers	1
2d	Assessment of CBM solutions early in the design stage	1	**3e**	Increased demand for IT support personnel	1
2h	Development of a business case for CBM	1	**3f**	Increase in personnel capable of implementing and upgrading CBM systems	1

3b	Allocation of resources for implementation and facility upgrades	1	**3h**	Reduction in the skill/technology gap between Defence and civilian agencies	1
3c	Promotion of benefits	1	**3i**	Reduced scope for innovative operator repair for platform 'revival' to complete a mission	1
3e	Amendment of existing maintenance contracts with civilian agencies	1	**3j**	Increased non-technical maintenance role for operators	1
3f	Human resource management	1	**6e**	Improved data availability for accident/incident investigation	1
3g	Rollout scheduling and implementation	1	**6h**	Improved monitoring of environmental pollution effects	1
4e	Increased modularity of equipment/platform design	1	**6i**	Greater availability of terrain and environmental data	1
5a	Data architecture and standards	1	**7c**	Increased ability of unauthorised external parties to access generated data	1
6a	Modification of maintenance training facilities	1	**7f**	Increase in data security management requirements	1
			8d	Increased ICT in workshops	1
			8i	Negligible impact on supply chain costs	1
			8o	Management of CBM components within the supply chain	1
			9h	Reduction in support equipment in the field and specialised support equipment at the strategic level	1
			9i	Redesign of maintenance workshops with technical repair/refurbishment pushed rearwards	1
			9j	Better utilisation of tradespeople, particularly for preventive maintenance	1
			10i	Difficulty in obtaining parts and technical knowledge as fleets age	1
			10j	Increased equipment down-time due to spare part obsolescence as fleet life is extended	1
			11d	Reduced accuracy of information underpinning decision support	1
			11e	Cultivation of culture of equipment ownership/excellence	1

In terms of capability inputs, there is a reasonable spread of support from the survey respondents across the seven key themes. Impacts relating to data management and technology integration are also well supported by the literature. However, the issues relating to incorporation of CBM requirements into the capability acquisition process and change management are almost exclusively mentioned by survey respondents only.

In terms of capability outputs, there is also a reasonable spread of overall support for the impacts within each key theme. However, the majority of support for workforce impacts comes from SME surveys. On the other hand, most of the citations for impacts relating to human factor effects come from literature. Improved operational availability of equipment and platforms was the most cited impact in literature and was strongly supported by SME survey participants. Expectations of increased equipment life and reduced overall maintenance burden received moderate support in both cases.

Five areas with conflicts of opinion were identified following the first round of SME surveys. These related to:

- The effect of the introduction of CBM on supply chain costs
- Whether the introduction of CBM would reduce or increase maintenance training requirements
- What effect the introduction of CBM may have on traditional diagnostic and maintenance skills
- The effect on the number of maintenance personnel
- Whether there would be any reduction in regular maintenance activities.

Review of the relative importance of various impacts, as well as exploration of reasons behind the conflicts of opinion formed part of the second iteration of SME surveys.

3.3 Second-round SME Survey and Finalised Impacts Map

3.3.1 Second-round SME Survey Results

3.3.1.1 Conduct of the Second-Round SME Surveys

Second-round SME surveys were released several months after the first round and contained targeted questions geared toward establishment of consensus (see Appendix B for the survey template). The survey focused on evaluating the relative significance of impacts and the reasons behind conflicting views. Additionally, the participants were asked to consider and comment on the first-round impacts map and the causal links within the map.

Several late first-round survey responses were received after the second-round survey had been promulgated. Consequently, some adjustments had to be made both to the first-round impacts map and to the design of the second-round survey before sending them to these 'second cohort' participants. Specifically, the list of impacts not covered by literature or first-round responses (i.e. identified in internal DSTO workshops only) was reduced in the surveys for the second cohort due to some impacts having been identified in the first-round responses of the second cohort[3].

Overall, seven responses were received to the two variations of the second-round SME survey. These were pooled and analysed together.

3.3.1.2 Refined Prioritisation of Capability Input and Output Impacts

The survey responses were analysed in detail in order to evaluate the relative significance of CBM impacts. The evaluation process with selected quotes from the survey responses are outlined in detail in Appendix F. Some additional considerations based on Air domain experience are also included in the appendix.

As a result of analysis and integration of the proposed changes, a refined prioritised impacts list was developed as summarised in Table 6 (most important impacts) and Table 7 (least important impacts). Note that some of the suggestions in survey responses were integrated as comments to existing impacts rather than as new impacts in their own right.

As can be seen from the tables, re-evaluation of impact priorities resulted in a more comprehensive list of significant impacts, at the expense of a much shortened list of less important CBM effects following a review by the participants.

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[3] When the second round survey was initially developed, there were seven impacts that were not covered in literature or the first-round SME survey responses:

- 2c. Allocation of ownership and management responsibility
- 2e. Allocation of funding for CBM capability
- 3b. Allocation of resources for implementation
- 3c. Promotion of benefits
- 3f. Human resource management
- 3g. Rollout scheduling and implementation
- 4d. Revised equipment/platform maintenance.

Following analysis of the 'second cohort' first-round responses, this list was reduced to include impacts 3c, 3f and 3g only; this was reflected in the adjusted second-round survey sent to these participants.

Table 6: Most important capability input and output impacts following the second round of SME surveys

ID	Most Important Input Impacts	ID	Most Important Output Impacts
1	Leadership at high level and local level	9a	Improved ability to plan maintenance, e.g. schedule maintenance in a load-balancing way
New#4	Identification of common failures/incidents (from past fleet usage or maintenance records) that result in vehicle breakdown or mission failure that can be addressed by monitoring systems	12b	Improved decision support for mission assignment of equipment/platforms
2f	Inclusion of CBM requirements into acquisition of relevant equipment/platforms	1a	Diagnostics
7b	Integration of HUMS/CBM hardware, software and platforms	1b	Prognostics
New#2	Design of CBM hardware and software	1c	Automated generation of real-time equipment/platform health information
4b	Design of HUMS/CBM hardware and software maintenance	10a	Improved safety in operation of equipment/platforms
3a	Development of new logistics and maintenance structures and processes	8c	Reduced inventory holdings at supply chain nodes
6	Training and personnel certification	6j	Improved ability to estimate equipment/platform condition
5g	Data mining, analysis and use for decision-support	9e	Reduced overall maintenance burden
5h	Development of algorithms (prognostics and diagnostics)	11f	Increased confidence in the use of equipment/platforms
5d	Bridging the 'air gap' between equipment/platforms and data processing systems	8b	More efficient and responsive supply processes
3g	Rollout scheduling and implementation	6c	Increase in the quality and quantity of available equipment/platform health and usage data
2a	Tracking of technology developments	9d	Improved operation and maintenance of the fleet
4a	Acquisition of HUMS/CBM hardware and software	4a	Reduced preventive maintenance requirements
New#3	Good systems engineering practices/processes to cover all aspects of the CBM life-cycle	4c	Improved fault detection
		10f	Increase in operational availability and capability of equipment/platforms
		8g	Change to proactive, CBM-driven supply processes
		9j	Improved utilisation of tradespeople, particularly for preventive maintenance
		8o	Management of CBM components within the supply chain
		11e	Cultivation of equipment ownership/excellence
		8h	Reduced logistic footprint

Table 7: Least important capability input and output impacts following the second round of SME surveys

ID	Least Important Input Impacts	ID	Least Important Output Impacts
3e	Amendment of existing maintenance contracts with civilian agencies	3e	Increased demand for IT support personnel
4e	Increased modularity of equipment/platform design	3f	Increase in personnel capable of implementing and upgrading CBM systems
6a	Modification of maintenance training facilities	3h	Decrease the skill/technology gap between Defence and civilian agencies
		3i	Reduced scope for innovative operator repair for platform 'revival' to complete a mission
		3j	Increased non-technical maintenance role for operators due to increased modularity
		6h	Improved monitoring of environmental pollution effects
		8d	Increased ICT in workshops
		9h	Reduction in support equipment in the field and specialised support equipment at the strategic level
		9i	Redesign of maintenance workshops with technical repair/refurbishment pushed rearward
		10i	Difficulty in obtaining parts and technical knowledge as fleets age
		10j	Increased equipment down-time due to spare part obsolescence as fleet life is extended
		11d	Reduced accuracy of information underpinning decision support (due to inefficient system use)

3.3.1.3 Examining Conflicts of Opinion

Detailed responses were given by the participants examining the divergence of opinions within the five areas outlined in Section 3.2.3, which pertain to the effects of CBM on:

- Supply chain costs
- Maintenance training requirements
- Traditional diagnostic and maintenance skills
- Numbers of personnel required for maintenance
- Reduction in regular maintenance requirements.

A summary of the responses is given as a set of histograms in Figure 6. In each case, the opinions of the survey participants have been categorised into three general thrusts. Where a respondent has expressed multiple views, their vote is distributed evenly over each relevant category. To depict this visually, a different colour is used for each respondent[4].

[4] Note that there is no deliberate consistency in respondent colour across the subfigures of Figure 6.

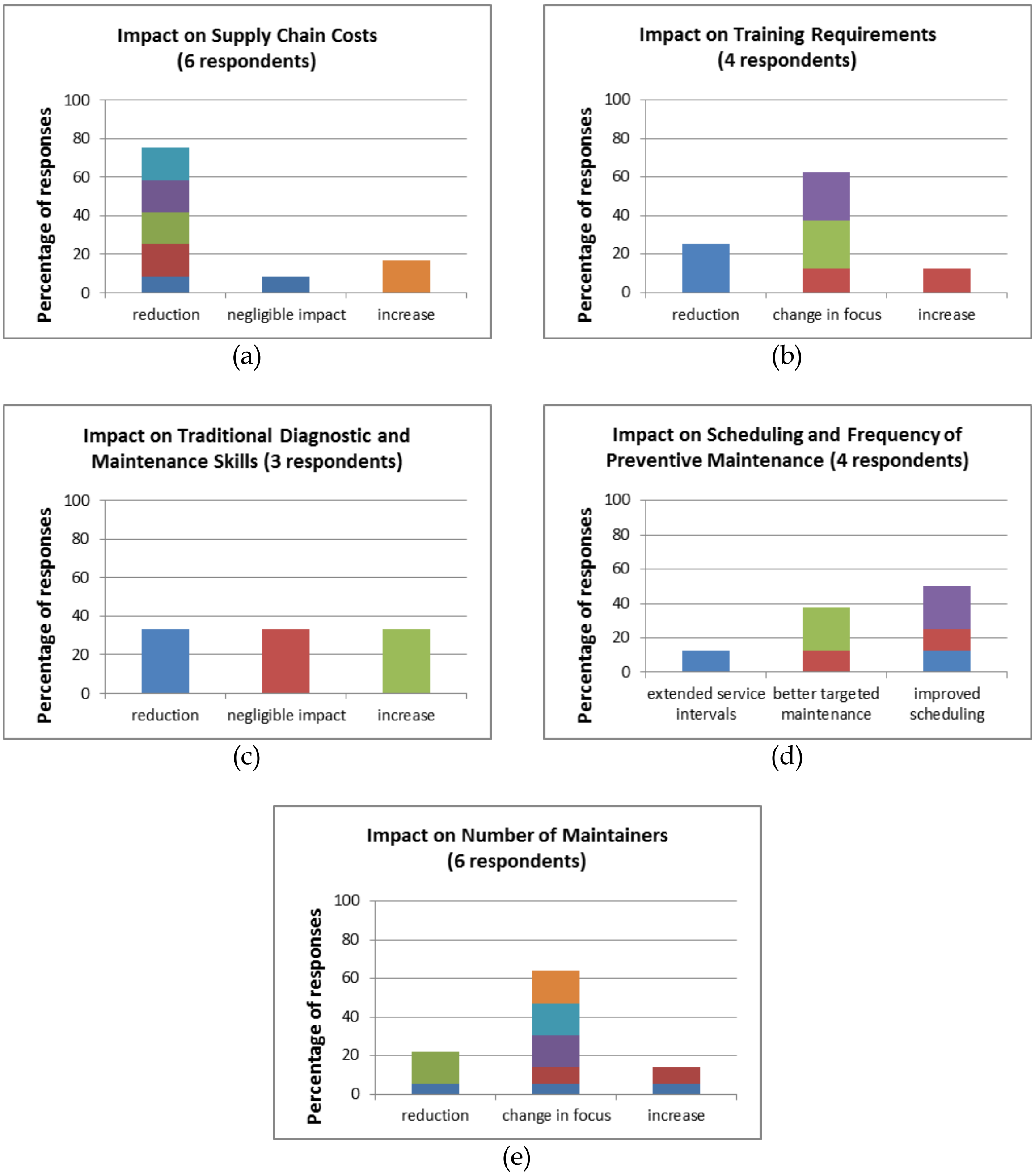

Figure 6: A summary of survey responses on diverging opinions related to the impact of CBM

There was a majority consensus that supply chain costs (Figure 6(a)) would be reduced with the introduction of CBM due to reduced spare parts and POL (Petrol, Oils and Lubricants) consumption, supply chain and Defence Logistics Information System (DLIS) integration efficiencies, automatic data collection and preventive approach to maintenance.

Opposing arguments as to why supply chain costs may increase included:

- Increasing modularity of equipment and platforms may mean that the storage costs for entire modules may exceed those of the higher fidelity spare parts as well as the modules themselves being more costly to procure
- Data analysis may drive an increase in stockholdings at some nodes
- Human-dependent variables may reduce expected supply chain improvements.

The divergence in opinions, in this instance, reflects a large degree of uncertainty about the relative magnitudes of influence of the various confounding factors on the overall supply chain costs.

Responses pertaining to the effects on maintenance training requirements (Figure 6(b)) suggested that the overall training burden would not reduce, rather, that the focus of the training would change due to an increase in demand for data analysis skills and other new training requirements driven by introduction of HUMS and CBM technology. The one dissenting opinion related to the trend toward modularisation which should move the technical workload rearward (potentially to contractors).

The topic of effects on the traditional diagnostic and maintenance skills (Figure 6(c)) resulted in a significant divergence of opinions. The various confounding factors included overall changes in the maintenance system as a gradual progression, improved understanding of the effects of different conditions on equipment, and improvements in dealing with growing complexity of the systems.

Figure 6(d) depicts a summary of the responses regarding the scheduling and frequency of preventive maintenance. One respondent suggested that CBM would facilitate longer service intervals; two respondents suggested that CBM would facilitate better targeted maintenance. Three participants suggested that CBM would facilitate planning and scheduling of maintenance activities, so that they would occur at more appropriate times. Two of these three participants further noted that maintenance planning was likely to become more complex with CBM, and emphasised the need for decision support tools to support this. In this case, the diversity in the responses reflected to some extent the uncertainty of what CBM would look like and how it would be implemented. It was clear, however, that the participants did not believe that CBM would entirely replace the need for scheduled preventive maintenance.

Human resource management (Figure 6 (e)) was flagged as a potentially sensitive issue for the Services. The majority of respondents supported the view that the number of maintainers would be unchanged but with a different focus (different skill sets/roles). Contributing influences included modularisation moving the technical workload to OEM contractors, potential multi-skilling of maintainers, changes in distribution of workforce requirements between servicing and repairs, broad skill range requirement, efficiency gains in maintenance, and increased IT support roles.

3.3.2 Finalised Impacts Map

Initial collation and analysis of the second-round SME survey responses was conducted via a series of internal workshops by the study team. This heuristic approach resulted in construction of an interim 'second-round' impacts map shown in Appendix G. This interim map incorporated the following changes:

- Merging, splitting, renaming and relocation of impacts with appropriate changes to their unique identifiers
- Refining of causal links
- Acknowledgement of unresolved differences in opinions in some of the impact names[5]
- Removal of the thematic grouping 'Effects on equipment/platform and of integration with other technologies' and redistribution of its components within other key themes.

This interim map was then subjected to a detailed graph analysis with the use of custom written Java code and via further internal workshops. This map refinement process examined in detail the positioning of the impacts within themes, allocation of causal links, and the resulting impact paths, cycles, isolated impacts and impacts not connected to the 'CBM Capability'. In construction of the finalised map, the headings of the thematic groupings were no longer considered as impacts in their own right and subsequent analysis was applied only to constituent impacts. Full details of the process can be found in Appendix H.

The finalised version of the CBM impacts map is presented in Figure 7 (capability inputs portion) and Figure 8 (capability outputs portion), with a spreadsheet of the impacts given in Appendix I. The yEd software package [25] is used for construction of the finalised map in place of Microsoft Visio due to its superior automatic layout algorithms. Similarly to the interim 'second-round map', the impacts are no longer shown within thematic groupings, but separated so as to better illustrate the causal flow from left to right. Colour-coding is used to show belonging of specific impacts to key themes.

[5] For example, impact 3a was renamed from 'Reduced vs increased maintenance training requirements' to 'Potential impact on maintenance training requirements'. Analogous name changes were made to other impacts where opinions diverged.

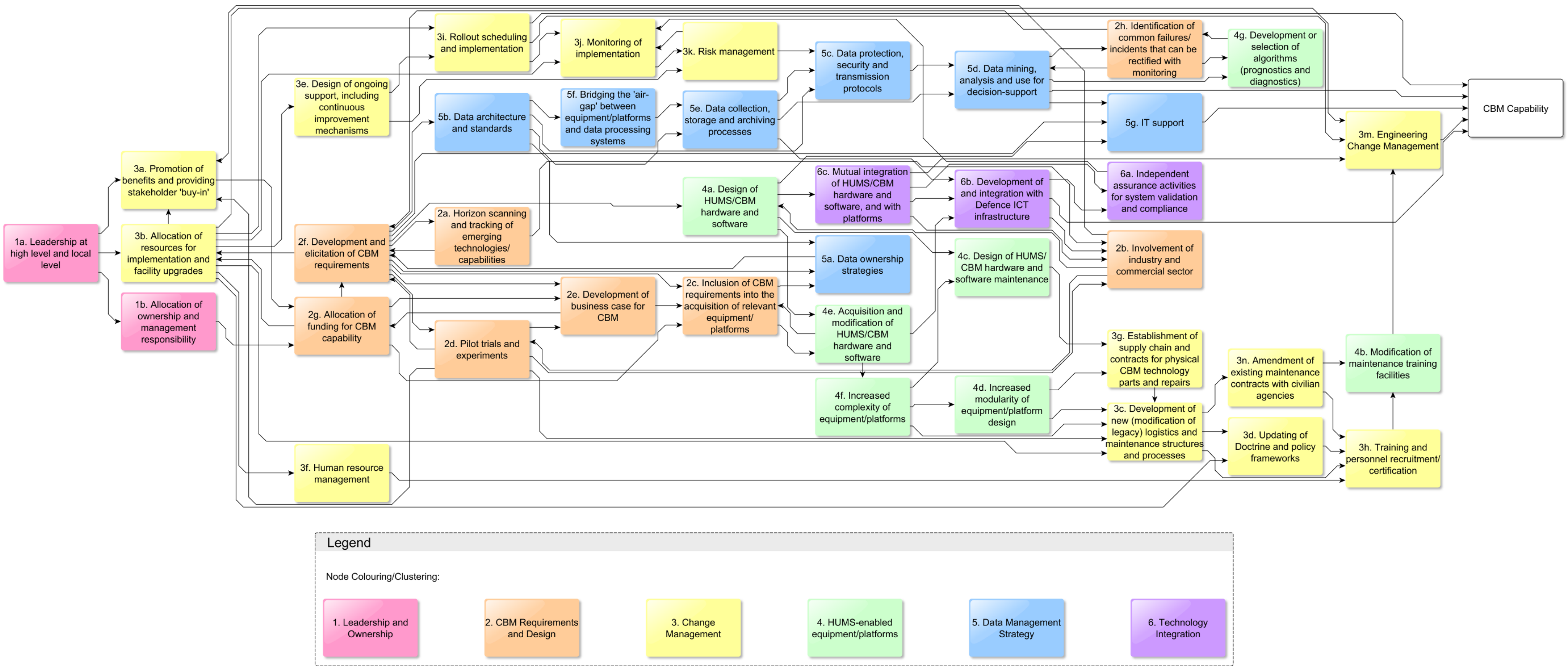

Figure 7: Capability inputs portion of the finalised CBM impacts map

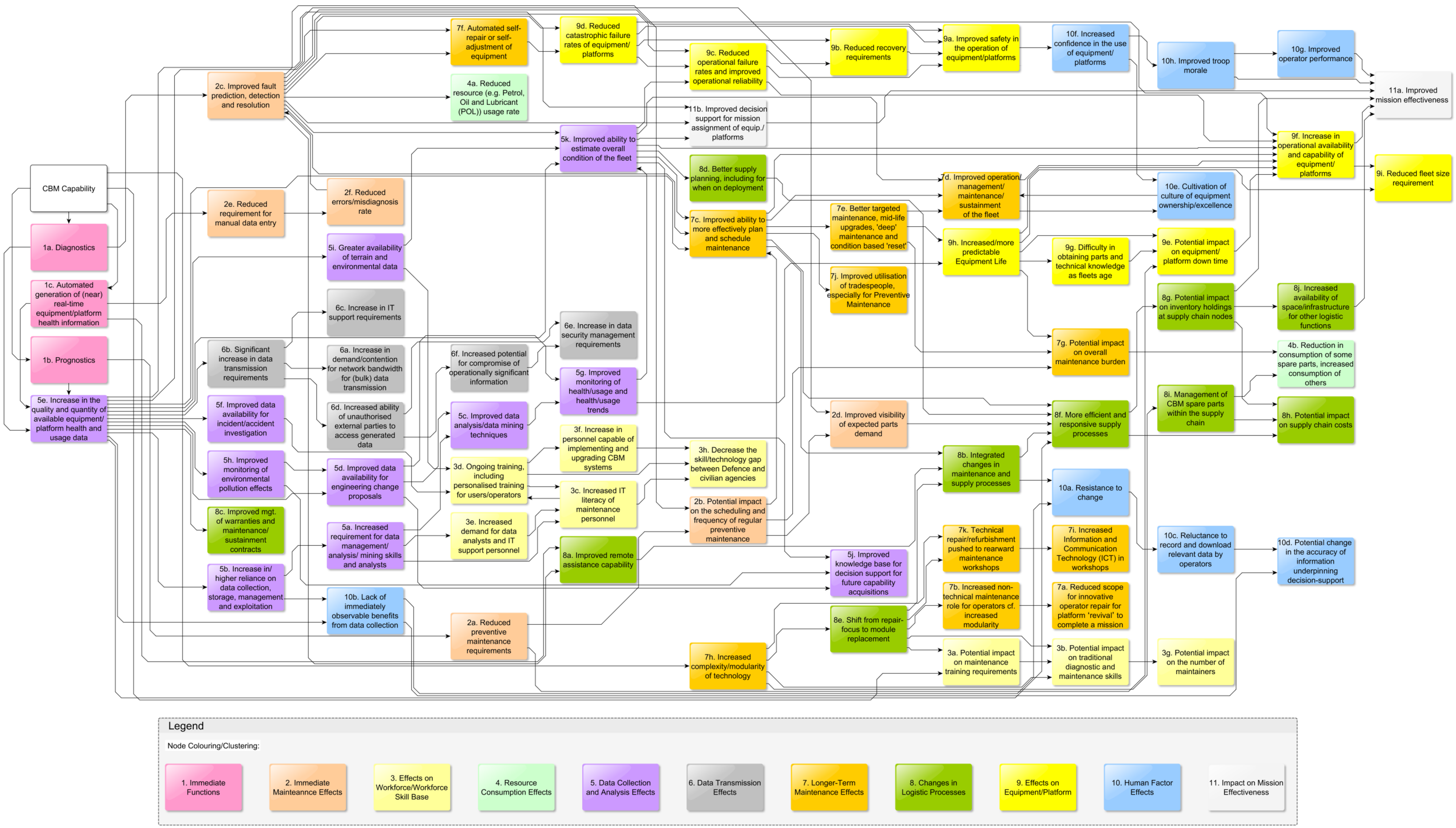

Figure 8: Capability outputs portion of the finalised CBM impacts map

4. Post-Activity Data Analysis

4.1 Strength of Evidence Analysis

Strength of evidence analysis was conducted on the finalised impacts map using the methods outlined in Section 2.5. A tabular representation and comparison with the first-round scores is provided in Table 8 (highest scores) and Table 9 (lowest scores).

Table 8: Capability input impacts with the highest combined citation score from the finalised impacts map

Most Cited Input Impacts			
Finalised Map	**Combined Citation Score**	**First-Round Map**	**Combined Citation Score**
4e. Acquisition of HUMS/CBM hardware and software	16	4a. Acquisition of HUMS/CBM hardware and software	15
3c. Development of new (and modification of legacy) logistics and maintenance structures and processes	15	3a. Development of new logistics and maintenance structures and processes	14
3h. Training and personnel recruitment/ certification	14	6. Training and personnel certification	14
6c. Mutual integration of HUMS/CBM hardware and software, and with platforms	13	7b. Integration of HUMS/CBM hardware, software and platforms	12
4c. Design of HUMS/CBM hardware and software maintenance	11	4b. Design of HUMS/CBM hardware and software maintenance	10
5d. Data mining, analysis and use for decision-support	8	5g. Data mining, analysis and use for decision-support	8
4g. Development or selection of algorithms (prognostics and diagnostics)	8	5h. Development of algorithms for prognostics and diagnostics	8
6b. Development of and integration with Defence ICT infrastructure	7	7a. Development of and integration with Defence ICT infrastructure	6
		5. Data management strategy	6
		3. Change management	4
1a. Leadership at high level and local level	4	1. Leadership at high level and local level	4
3j. Monitoring of implementation	4	3d. Monitoring of implementation	4
5f. Bridging the 'air-gap' between equipment/platforms and data processing systems	4	5d. Bridging ‘air gap’ between equipment/platforms and data processing systems	4
5e. Data collection, storage and archiving processes	4	5c. Data collection and storage processes	4
2c. Inclusion of CBM requirements into acquisition of relevant equipment/platforms	4	2f. Inclusion of CBM requirements into acquisition of relevant equipment/platforms	3

Table 9: Capability input impacts with the lowest combined citation score from the finalised impacts map

Least Cited Input Impacts			
Finalised Map	**Combined Citation Score**	**First-Round Map**	**Combined Citation Score**
1b. Allocation of ownership and management responsibility	1	2c. Allocation of ownership and management responsibility	1
3a. Promotion of benefits and providing stakeholder 'buy-in'	1	3c. Promotion of benefits	1
3n. Amendment of existing maintenance contracts with civilian agencies	1	3e. Amendment of existing maintenance contracts with civilian agencies	0
3f. Human resource management	1	3f. Human resource management	1
3i. Rollout scheduling and implementation	1	3g. Rollout scheduling and implementation	1
4b. Modification of maintenance training facilities	1	6a. Modification of maintenance training facilities	1
3b. Allocation of resources for implementation and facility upgrades	1	3b. Allocation of resources for implementation and facility upgrades	1
5b. Data architecture and standards	1	5a. Data architecture and standards	1
4d. Increased modularity of equipment/platform design	1	4e. Increased modularity of equipment/platform design	1
2d. Pilot trials and experiments	1	2d. Assessment of CBM solutions early in the design stage	1
2h. Identification of common failures/incidents that can be rectified with monitoring (new node)	1		
3k. Risk management (new node)	1		1
3m. Engineering change management (new node)	1		1
4a. Design of HUMS/CBM hardware and software (new node)	1		

The changes from the first-round map are highlighted in red and are due to the removal of thematic headings as impacts in their own right (as mentioned in Section 3.3.2) and the addition of four new impacts.

Similarly, Table 10 and Table 11 depict the combined strength of evidence measure for the output impacts. Changes highlighted in red are due to the merging of impacts during the construction of the finalised impacts map, as noted in the tables.

In this instance, the only significant difference in terms of strength of evidence for output impacts between the first-round and finalised impacts maps is due to the merging of impacts.

Table 10: Capability output impacts with the highest combined citation score from the finalised impacts map

Most Cited Output Impacts			
Finalised Map	**Combined Citation Score**	**First-Round Map**	**Combined Citation Score**
9f. Increase in operational availability and capability of equipment/platforms	24	10f. Increase in operational availability and capability of equipment/platforms	24
7g.Potential impact on overall maintenance burden	23	Merging of: 9e. Reduced overall maintenance burden 9g. Reduced corrective maintenance requirements Comments on "Reduced overall maintenance costs"	9 4 11
8f. More efficient and responsive supply processes	21	Merging of: 8b. More efficient and responsive supply processes 8g. Change to proactive, CBM-driven supply processes, including spare parts, fuel, etc.	12 9
8g. Potential impact on inventory holdings at supply chain nodes	18	Merging of: 8c. Reduced inventory holdings at supply chain nodes 8h. Reduced logistic footprint	12 6
7c. Improved ability to more effectively plan and schedule maintenance.	17	9a. Improved ability to plan maintenance, e.g. schedule maintenance activities in a load-balancing way	16
6o. Improved ability to estimate overall condition of the fleet	16	Merging of: 6o. Improved ability to estimate overall condition of the fleet 6j. Improved ability to estimate equipment/platform condition 12c. Improved situational awareness in terms of equipment/platform status	5 8 7
11b. Improved decision support for mission assignment of equipment/platforms	15	12b. Improved decision support for mission assignment of equipment/platform	15
2c. Improved fault prediction, detection and resolution	14	Merging of: 4c. Improved fault detection 6d. Improved diagnostic and prognostic capability	10 6
9a. Improved safety in the operation of equipment/platforms	14	10a. Improved safety in operation of equipment/platforms	14
9h. Increased/more predictable Equipment Life	13	10g. Increased/more predictable Equipment Life	13
7d. Improved operation/ management/maintenance/ sustainment of the fleet	12	9d. Improved operation/ management/maintenance/ sustainment of the fleet	12
9d. Reduced catastrophic failure rates of equipment/platforms	12	10d. Reduced catastrophic failure rates of equipment/platforms	12
2a. Reduced preventive maintenance requirements	12	4a. Reduced preventive maintenance requirements	10

Table 11: Capability output impacts with the lowest combined citation score from the finalised impacts map

Least Cited Output Impacts			
Finalised Map	**Combined Citation Score**	**First-Round Map**	**Combined Citation Score**
1c. Automated generation of (near) real-time equipment/platform health information (incorporates 2b from the first-round map)	11	2b. Tracking of position, status and load of vehicles, critical stores and drivers	1
9e. Potential impact on equipment/platform down time (incorporates 10j from the first-round map)	6	10j. Increased equipment down-time due to spare part obsolescence as fleet life is extended	1
7k. Technical repair/refurbishment pushed to rearward maintenance workshops (incorporates 9h. from the first-round map)	3	9h. Reduction in support equipment in the field and specialised support equipment at the strategic level	1
5f. Improved data availability for incident/accident investigation	2	6e. Improved data availability for incident/accident investigation	1
3e. Increased demand for data analysts and IT support personnel	1	3e. Increased demand for IT support personnel	1
3f. Increase in personnel capable of implementing and upgrading CBM systems	1	3f. Increase in personnel capable of implementing and upgrading CBM systems	1
3h. Decrease the skill/technology gap between Defence and civilian agencies	1	3h. Decrease the skill/technology gap between Defence and civilian agencies	1
5h. Improved monitoring of environmental pollution effects	1	6h. Improved monitoring of environmental pollution effects	1
5i. Greater availability of terrain and environmental data	1	6i. Greater availability of terrain and environmental data	1
6d. Increased ability of unauthorised external parties to access generated data	1	7c. Increased ability of unauthorised external parties to access generated data	1
6e. Increase in data security management requirements	1	7f. Increase in data security management requirements	1
7a. Reduced scope for innovative operator repair for platform 'revival' to complete a mission	1	3i. Reduced scope for innovative operator repair for platform 'revival' to complete a mission	1
7b. Increased non-technical maintenance role for operators cf. increased modularity	1	3j. Increased non-technical maintenance role for operators cf. increased modularity	1
7i. Increased ICT in workshops	1	8d.Iincreased ICT in workshops	1
7j. Improved utilisation of tradespeople, particularly for Preventive Maintenance	1	9j. Better utilisation of tradespeople, particularly for Preventive Maintenance	1
8h. Potential impact on supply chain costs	1	8i. Negligible impact on supply chain costs	1
8i. Management of CBM spare parts within the supply chain	1	8o. Management of CBM components within the supply chain	1
9g. Difficulty in obtaining parts and technical knowledge as fleets age	1	10i. More difficult to obtain parts and technical knowledge as fleets age	1
10d. Potential change in the accuracy of information underpinning decision-	1	11d. Reduced accuracy of information underpinning decision-support	1

support			
10e. Cultivation of culture of equipment ownership/excellence	1	11e. Cultivation of culture of equipment ownership/excellence (20)	1

Overall, post-activity strength of evidence analysis suggests that critical issues in terms of implementing CBM revolve around:

- Acquisition and maintenance of relevant software and hardware
- Change management associated with revision of logistic processes and training of personnel
- Integration of CBM technology both with Defence technology and Defence infrastructure and processes
- Data management strategies for analysis, translation into decision support and prognostic algorithms.

For the expected effects of CBM implementation, most weight is assigned to:

- Benefits in terms of improved operational availability of equipment and vehicles combined with extended equipment life
- Improved planning of maintenance at both local and fleet management levels, and overall reduction in maintenance burden
- Efficiencies in the supporting supply chain
- Better awareness of fleet condition and associated use for decision support on operations
- Reduced catastrophic failure rates with improved operator safety.

It is interesting to note that only positive effects are listed in the most cited table, with the unstated underlying assumption of successful implementation of the new technology.

4.2 Graph Analysis

Java code was written to perform graph analysis on the input and output impacts maps. For completeness, the code and the associated output for the finalised map is presented in Appendix J. This section focuses on the use of graph analysis for identification of critical impacts.

4.2.1 Ingress, Egress and Prevalence Analysis of Capability Input Impacts

The capability inputs portion of the finalised impacts map comprises a directed graph with 41 nodes and 99 edges (causal links). Graph analysis revealed the statistics shown in Table 12 on arc incidence, representing the cumulative sum of the number of causal links leading to (ingress) and from (egress) each capability input impact. Arc incidence provides a measure of how 'connected' an impact is to other impacts, i.e. the number of other impacts on which a given impact directly depends (ingress) and the number of other impacts that directly depend upon a given impact (egress). This can be interpreted as a proxy for the importance of an impact. The complete list can be found in Appendix J.

Table 12: Highest and lowest arc incidence for capability input impacts in the finalised impacts map

Input Impacts with Highest Arc Incidence	Incidence	Input Impacts with Lowest Arc Incidence	Incidence
2f. Development and elicitation of CBM requirements	14	1b. Allocation of ownership and management responsibility	2
3b. Allocation of resources for implementation and facility upgrades	11	3f. Human resource management	2
3c. Development of new (and modification of legacy) logistics and maintenance structures and processes	8	1a. Leadership at high level and local level	3
2b. Involvement of industry and commercial sector	7	2a. Horizon scanning and tracking of emerging technologies/capabilities	3
2d. Pilot trials and experiments	7	3d. Updating of Doctrine and policy frameworks	3
2g. Allocation of funding for CBM capability	7	3e. Design of ongoing support, including continuous improvement mechanisms	3
5d. Data mining, analysis and use for decision-support	7	3g. Establishment of supply chain and contracts for physical CBM technology parts and repairs	3
2c. Inclusion of CBM requirements into acquisition of relevant equipment/platforms	6	3n. Amendment of existing maintenance contracts with civilian agencies	3
4a. Design of HUMS/CBM hardware and software	6	4b. Modification of maintenance training facilities	3
6b. Development of and integration with Defence ICT infrastructure	6	4c. Design of HUMS/CBM hardware and software maintenance	3
		4d. Increased modularity of equipment/platform design	3
		4g. Development or selection of algorithms (prognostics and diagnostics)	2
		5f. Bridging the 'air-gap' between equipment/platforms and data processing systems	3
		6a. Independent assurance activities for system validation and compliance	3

It must be noted that high-level impacts and those without predecessors (such as (1a Leadership at high level and local level) may rank poorly by this metric. This is compensated for by examination of impact prevalence within paths, discussed next.

There are 14991 paths in the finalised map, ranging in length from 4 to 31 impacts, where a path is defined as a causal sequence of impacts, without cycles, starting with an impact that has no predecessors and terminating in an impact (or CBM Capability) that has no successors. For each impact, counting the number of paths in which that impact appears provides a proxy for the importance of that impact. Table 13 lists the impacts with the highest and lowest prevalence within these paths (see Appendix J for the complete list). A prevalence of 100% for impact 1a and the 'CBM Capability' node corresponds to the fact that all paths in the capability input impacts map start from impact 1a and terminate in 'CBM Capability'.

Table 13: Highest and lowest prevalence of capability input impacts within paths in the finalised impacts map

Input Impacts with <u>Highest</u> Prevalence within Paths	Number (%) of paths	Input Impacts with <u>Lowest</u> Prevalence within Paths	Number (%) of paths
1a. Leadership at high level and local level	14991 (100%)	3f. Human resource management	29 (0.2%)
CBM Capability	14991 (100%)	5g. IT support	675 (5%)
2f. Development and elicitation of CBM requirements	14748 (98%)	6a. Independent assurance activities for system validation and compliance	926 (6%)
3m. Engineering Change Management	13439 (90%)	5a. Data ownership strategies	1174 (8%)
3b. Allocation of resources for implementation and facility upgrades	13055 (87%)	5f. Bridging the 'air-gap' between equipment/platforms and data processing systems	2059 (14%)
4b. Modification of maintenance training facilities	13026 (87%)	2a. Horizon scanning and tracking of emerging technologies/capabilities	2243 (15%)
3c. Development of new (and modification of legacy) logistics and maintenance structures and processes	12968 (87%)	3d. Updating of Doctrine and policy frameworks	3271 (22%)
5d. Data mining, analysis and use for decision-support	12844 (86%)	6c. Mutual integration of HUMS/CBM hardware and software, and with platforms	3288 (22%)
5c. Data protection, security and transmission protocols	12784 (85%)	1b. Allocation of ownership and management responsibility	3618 (24%)
3k. Risk management	12694 (85%)	4c. Design of HUMS/CBM hardware and software maintenance	3844 (26%)
4e. Acquisition and modification of HUMS/CBM hardware and software	12570 (84%)	5e. Data collection, storage and archiving processes	4118 (27%)
2g. Allocation of funding for CBM capability	12524 (84%)	5b. Data architecture and standards	4148 (28%)
2h. Identification of common failures/incidents that can be rectified with monitoring	12272 (82%)	4d. Increased modularity of equipment/platform design	5080 (34%)
2b. Involvement of industry and commercial sector	11344 (76%)	3e. Design of ongoing support, including continuous improvement mechanisms	5942 (40%)
2c. Inclusion of CBM requirements into acquisition of relevant equipment/ platforms	10160 (72%)	3i. Rollout scheduling and implementation	6000 (40%)
4f. Increased complexity of equipment/platforms	9784 (68%)	4g. Development or selection of algorithms (prognostics and diagnostics)	6136 (41%)

There are also 445 elementary cycles within the map, ranging in length from 2 impacts to 18 impacts. An elementary cycle is a causal sequence of impacts, starting and ending in the same impact, where no impact (other than the starting/ending impact) appears more than once. In a similar way to paths, prevalence of impacts within elementary cycles can be calculated by counting the number of such cycles within which each impact appears. This can also be used as a proxy for the importance of an impact. Table 14 lists the impacts with the highest and lowest prevalence within cycles (see Appendix J for the complete list).

Table 14: Highest and lowest prevalence of capability input impacts within cycles in the finalised impacts map

Input Impacts with Highest Prevalence within Elementary Cycles	Number (%) of cycles	Input Impacts with Lowest Prevalence within Elementary Cycles	Number (%) of cycles
2f. Development and elicitation of CBM requirements	428 (96%)	5f. Bridging the 'air-gap' between equipment/platforms and data processing systems	43 (10%)
2b. Involvement of industry and commercial sector	350 (79%)	2a. Horizon scanning and tracking of emerging technologies/capabilities	54 (12%)
2g. Allocation of funding for CBM capability	349 (78%)	5a. Data ownership strategies	54 (12%)
2h. Identification of common failures/incidents that can be rectified with monitoring	335 (75%)	5e. Data collection, storage and archiving processes	86 (19%)
5d. Data mining, analysis and use for decision-support	334 (75%)	5b. Data architecture and standards	89 (20%)
5c. Data protection, security and transmission protocols	328 (74%)	6a. Independent assurance activities for system validation and compliance	90 (20%)
3k. Risk management	323 (73%)	3e. Design of ongoing support, including continuous improvement mechanisms	116 (26%)
6b. Development of and integration with Defence ICT infrastructure	289 (65%)	3i. Rollout scheduling and implementation	116 (26%)
3j. Monitoring of implementation	265 (60%)	6c. Mutual integration of HUMS/CBM hardware and software, and with platforms	116 (26%)
2d. Pilot trials and experiments	261 (59%)		
3b. Allocation of resources for implementation and facility upgrades	246 (55%)		
3a. Promotion of benefits and providing stakeholder 'buy-in'	245 (55%)		

4.2.2 Ingress, Egress and Prevalence Analysis of Capability Output Impacts

The finalised capability outputs map can be viewed as a directed graph with 77 nodes and 147 edges (causal links). Graph analysis reveals the statistics shown in Table 15 on the arc incidence or each output impact. The complete list can be found in Appendix J.

As before, it should be noted that high-level impacts, particularly those without successors, would rank poorly by this metric. This is mitigated to some extent by examining the prevalence of the impacts within paths.

Table 15: Highest and lowest arc incidence for capability output impacts in the finalised impacts map

Output Impacts with Highest Arc Incidence	Incidence	Output Impacts with Lowest Arc Incidence	Incidence
5e. Increase in the quality and quantity of available equipment/platform health and usage data	16	3g. Potential impact on the number of maintainers.	1
2c. Improved fault prediction, detection and resolution	13	4a. Reduced resource (e.g. POL) usage rate	1
5k. Improved ability to estimate overall condition of the fleet	11	6a. Increase in requirement for bandwidth/networks for transmission of bulk data, including contention for bandwidth	1
7c. Improved ability to more effectively plan and schedule maintenance.	10	6c. Increase in IT support requirements	1
9f. Increase in operational availability and capability of equipment/platforms	9	7a. Reduced scope for innovative operator repair for platform 'revival' to complete a mission	1
8f. More efficient and responsive supply processes	7	7i. Increased ICT in workshops	1
9h. Increased/more predictable equipment life	7	7j. Improved utilisation of tradespeople, particularly for Preventive Maintenance	1
3d. Ongoing training, including personalised training for users/operators	6	8c. Improved management of maintenance/sustainment contracts, and of warranties for components/platforms	1
7d. Improved operation/ management/maintenance/ sustainment of the fleet	6		
8e. Shift from repair-focus to module replacement	6		
9c. Reduced operational failure rates and improved operational reliability of equipment/platforms	6		
9d. Reduced catastrophic failure rates of equipment/platforms	6		
11a. Improved mission effectiveness	6		

There are 1668 paths within the finalised map for capability outputs. These paths range in length from 4 to 16 impacts. Table 16 lists the impacts with the highest and lowest prevalence within these paths (see Appendix J for complete list).

Table 16: Highest and lowest prevalence of capability output impacts within paths in the finalised map

Output Impacts with Highest Prevalence within Paths	Number (%) of paths	Output Impacts with Lowest Prevalence within Paths	Number (%) of paths
CBM Capability	1668 (100%)	7b. Increased non-technical maintenance role for operators cf. increased modularity	1 (0.06%)
5e. Increase in the quality and quantity of available equipment/platform health and usage data	1287 (77%)	7a. Reduced scope for innovative operator repair for platform 'revival' to complete a mission	1 (0.06%)
5k. Improved ability to estimate overall condition of the fleet	1035 (62%)	4a. Reduced resource (e.g. Petrol, Oil and Lubricant (POL)) usage rate	2 (0.12%)
5g. Improved monitoring of health/usage and health/usage trends	795 (48%)	7k. Technical repair/refurbishment pushed to rearward maintenance workshops	2 (0.12%)
9f. Increase in operational availability and capability of equipment/platforms	794 (48%)	3a. Potential impact on maintenance training requirements	2 (0.12%)
11a. Improved mission effectiveness	779 (47%)	8i. Management of CBM spare parts within the supply chain	2 (0.12%)
7c. Improved ability to more effectively plan and schedule maintenance.	775 (46%)	7i. Increased Information and Communication Technology (ICT) in workshops	2 (0.12%)
5d. Improved data availability for engineering change proposals	642 (38%)	6f. Increased potential for compromise of operationally-significant information	3 (0.18%)
1c. Automated generation of (near) real-time equipment/platform health information	599 (36%)	6a. Increase in requirement for bandwidth/networks for transmission of bulk data, including contention for bandwidth	3 (0.18%)
1a. Diagnostics	594 (36%)	6c. Increase in IT support requirements	3 (0.18%)
5c. Improved data analysis/data mining techniques	477 (29%)	8c. Improved management of maintenance/sustainment contracts, and of warranties for components/platforms	3 (0.18%)
1b. Prognostics	461 (28%)	3b. Potential impact on traditional diagnostic and maintenance skills.	4 (0.24%)
9i. Reduced fleet size requirement	443 (27%)	3g. Potential impact on the number of maintainers.	4 (0.24%)
8f. More efficient and responsive supply processes	388 (23%)	6d. Increased ability of unauthorised external parties to access generated data	6 (0.36%)
9h. Increased/more predictable Equipment Life	368 (22%)	6e. Increase in data security management requirements	6 (0.36%)
7e. Better targeted maintenance, mid-life upgrades, 'deep' maintenance and condition based 'reset'	341 (20%)	5f. Improved data availability for incident/accident investigation	9 (0.54%)

This analysis of impact ingress, egress and the prevalence of impacts in paths constitutes one of the three ways in which the significance of impacts is assessed in this study. Strength of evidence analysis and prioritisation of impacts by SMEs complete this triangulation approach, which is summarised in Section 4.3.

4.3 Triangulation Analysis in Assessment of Impact Significance

The three different methods of assessing significance of impacts in this study comprise of:

- Prioritisation of impacts by SMEs in the second round of SME surveys
- Post-activity strength of evidence analysis
- Post-activity graph analysis of the finalised impacts map.

The separate results for each of these approaches have been provided in the previous sections of the report, and are brought together in a tabular form in this section so as to provide a quick visual reference.

The most significant impacts according to the three methods are summarised in Table 17 (capability inputs) and Table 18 (capability outputs). In both of these tables, the impacts identified as most significant for each of the three methods are represented by cells shaded in green. For the graph analysis, impact significance was based on the presence of an impact in one or both of the tables documenting the impacts with the highest ingress/egress count and prevalence in paths. Cycle prevalence was not used as it considers only a subset of impacts (i.e. only those that form cycles). Where the description of the impact changed during the study process, this is indicated in the corresponding cell.

Table 17: Summary of the most significant inputs to CBM capability

Capability Input Impact	SME Judgement	Strength of Evidence	Graph Analysis
Leadership and ownership			
Leadership at high level and local level			
CBM requirements and design			
Allocation of funding for CBM capability			
Tracking of technology developments			
Historical analysis of common failures/incidents that result in vehicle breakdown or mission failure that can be addressed by monitoring systems			
Development and elicitation of CBM requirements			
Inclusion of CBM requirements into acquisition of relevant equipment/platforms			
Involvement of industry and commercial sector			
Pilot trials and experiments			
Change management			
Allocation of resources for implementation and facility upgrades			
Modification of maintenance training facilities			
Development of new logistics and maintenance structures and processes			
Rollout scheduling and implementation			

Training and personnel certification			
Good systems engineering practices/processes to cover all aspects of the CBM life-cycle			*Engineering change management*
Monitoring of implementation			
Risk management			
Promotion of benefits and providing stakeholder 'buy-in'			
HUMS-enabled equipment/platforms			
Design of CBM hardware and software			
Acquisition of HUMS/CBM hardware and software			
Maintenance of CBM hardware and software			
Increased complexity of equipment/platforms			
Data management strategy			
Data collection, storage and archiving processes			
Bridging the 'air gap' between equipment/platforms and the data processing systems			
Data mining and analysis for decision support			
Development of prognostic and diagnostic algorithms			
Data protection, security and transmission protocols			
Technology integration			
Integration of HUMS/CBM hardware, software and platforms			
Development of and integration with Defence ICT infrastructure			

Table 18: Summary of the most significant expected effects of CBM implementation

Capability Output Impact	SME Judgement	Strength of Evidence	Graph Analysis
Immediate functions			
Diagnostics			
Prognostics			
Automated generation of real-time equipment/platform health information			
Immediate maintenance effects			
Improved fault detection		*'Improved fault prediction, detection and resolution'*	*'Improved fault prediction, detection and resolution'*
Reduced preventive maintenance requirements			
Effects on workforce			
Ongoing training, including personalised training for users, operators			
Data collection and analysis effects			

Improved ability to estimate equipment/platform/fleet condition			
Increase in the quality and quantity of available equipment/platform health and usage data			
Improved monitoring of health/usage and health/usage trends			
Improved data availability for engineering change proposals			
Improved data analysis/data mining techniques			
Longer-term maintenance effects			
Improved ability to plan maintenance			
Reduced overall maintenance burden		*'Potential impact on overall maintenance burden'*	
Improved operation and maintenance of the fleet			
Improved utilisation of tradespeople, particularly for preventive maintenance			
Better targeted maintenance, mid-life upgrades, 'deep' maintenance and condition based 'reset'			
Changes in logistic processes			
Management of CBM components within the supply chain			
Change to proactive, CBM-driven supply processes			
Reduced inventory holdings at supply chain nodes		*'Potential impact on inventory holdings at supply chain nodes'*	
Reduced logistic footprint			
More efficient and responsive supply processes			
Shift from repair-focus to module replacement			
Effects on equipment/platform			
Increase in operational availability and capability of equipment/platforms			
Increased/more predictable equipment life			
Reduced catastrophic failure rates of equipment/platforms			
Reduced fleet size requirements			
Reduced operational failure rates and improved operational reliability of equipment/platforms			
Human factor effects			
Improved safety in operation of equipment/platforms			
Increased confidence in the use of equipment/platforms			
Cultivation of equipment ownership/excellence			

Impact on mission effectiveness			
Improved decision support for mission assignment of equipment/platforms			
Improved mission effectiveness			

The study results consistently show that the following aspects of CBM need to be addressed in more detail to ensure successful implementation:

- Leadership for implementation, both at high and local levels
- Incorporation of the CBM requirements into the capability acquisition process
- Development of new logistic and maintenance structures and processes
- Design and/or acquisition of the CBM hardware and software
- Development of data-mining and analysis capability for decision support.

The expected benefits of CBM following implementation consistently include:

- Improved detection and correction of faults
- Greater awareness of the fleet condition with associated improvement in decision support
- Better ability to plan maintenance
- Improved overall operation and maintenance of the fleet
- More efficient and responsive supply processes
- Increased operational availability and capability of equipment and platform.

These expected benefits represent the key areas of opportunity when considering CBM implementation. It is interesting to note that the expected effects of CBM rarely include negative effects, which may be due to the underlying assumption that the capability will be implemented successfully and without major delays and cost over-runs.

Some of the expected impacts only appear in the graph analysis column of the table. These often represent impacts that form logical links in the causal pathways between other, more commonly cited impacts, or are consequences of the latter.

4.4 FIC Analysis

FIC analysis was completed by grouping the capability input impacts into their respective FIC categories and applying the impact criticality assessment summarised in Section 4.3. This represents application of the FIC perspective to the previously identified CBM capability inputs as summarised in Table 19. The table is set out to show the impacts in order of decreasing significance (according to study results) going from left to right. There is some duplication across the different FIC categories as some capability inputs necessarily fall into more than one category.

In examining this representation of the necessary inputs to developing CBM as a capability, it should be kept in mind that all inputs would need to be addressed and planned for within the capability acquisition process. The ones highlighted in the left column represent those inputs that the study participants (and authors of previously published studies) consider particularly important in avoiding risks and maximising opportunities associated with the new technology.

Table 19: FIC breakdown and prioritisation of capability inputs for CBM

Most significant inputs from triangulation analysis	Other significant inputs from triangulation analysis	Inputs not identified as significant
COMMAND AND MANAGEMENT		
Leadership at high level and local level; Development of new logistics and maintenance structures and processes; Training and personnel certification; Application of good systems engineering practices/processes to cover all aspects of the CBM life-cycle; and Development of and integration with Defence ICT infrastructure.	Allocation of resources for implementation and facility upgrades; Rollout scheduling and implementation; Monitoring of implementation; Risk management; and Promotion of benefits and providing stakeholder 'buy-in'.	Allocation of ownership and management responsibility; Updating of Doctrine and policy framework; and Development data ownership strategies.
ORGANISATION		
Leadership at high level and local level; Training and personnel certification; Application of good systems engineering practices/processes to cover all aspects of the CBM life-cycle; Design of CBM hardware and software; and Development of and integration with Defence ICT infrastructure.	Development and elicitation of CBM requirements; Rollout scheduling and implementation; and Monitoring of the implementation.	Development of business case for CBM; Human resource management; Modification of maintenance training facilities; Development of data ownership strategies; and Provision of IT support.
MAJOR SYSTEMS		
Historical analysis of common failures/incidents that result in vehicle breakdown or mission failure that can be addressed by monitoring systems; Inclusion of CBM requirements into acquisition of relevant equipment/platforms; Design of CBM hardware and software; Acquisition of CBM hardware and software; Bridging the 'air gap' between equipment/platforms and the data processing systems;	Allocation of funding for CBM capability; Tracking of technology developments; Development and elicitation of CBM requirements; Involvement of industry and commercial sector; Pilot trials and experiments; Allocation of resources for implementation and facility upgrades; Rollout scheduling and implementation; Determining data collection,	Development of business case for CBM; Design on ongoing support, including continuous improvement mechanisms; Provision of IT support; and Independent assurance activities for system validation and compliance.

Development of prognostic and diagnostic algorithms; Integration of HUMS/CBM hardware, software and platforms; and Development of and integration with Defence ICT infrastructure.	storage and archiving processes; and Data protection, security and transmission protocols.	
PERSONNEL		
Leadership and high level and local level; Training and personnel certification; Data mining and analysis for decision support; Integration of HUMS/CBM hardware, software and platforms; Development of and integration with Defence ICT infrastructure; and Development of new logistics and maintenance structures and processes.	Development and elicitation of CBM requirements; Allocation of resources for implementation and facility upgrades; Modification of maintenance training facilities; Rollout scheduling and implementation; Maintenance of CBM hardware and software; and Data collection, storage and archiving processes.	Allocation of ownership and management responsibility; Human resource management; IT support; and Independent assurance activities for system validation and compliance.
SUPPLY		
Acquisition of HUMS/CBM hardware and software; and Development of new logistics and maintenance structures and processes.	Development and elicitation of CBM requirements; Allocation of resources for implementation and facility upgrades; and Rollout scheduling and implementation.	Establishment of supply chain and contracts for physical CBM technology parts and repairs; and Increased modularity of equipment/platform design.
SUPPORT		
Historical analysis of common failures/incidents that result in vehicle breakdown or mission failure that can be addressed by monitoring systems; Development of new logistics and maintenance structures and processes; Training and personnel certification; Design of CBM hardware and software; Acquisition of HUMS/CBM hardware and software; Bridging the 'air gap' between equipment/platforms and the data processing systems; Data mining and analysis for decision support; Development of prognostic and diagnostic algorithms; Integration of HUMS/CBM hardware, software and platforms; and Development and integration with Defence ICT infrastructure.	Allocation of funding for CBM capability; Tracking of technology developments; Development and elicitation of CBM requirements; Pilot trials and experiments; Allocation of resources for implementation and facility upgrades; Rollout scheduling and implementation; Maintenance of CBM hardware and software; Increased complexity of equipment/platforms; Data collections, storage and archiving processes; and Data protection, security and transmission protocols.	Design of ongoing support, including continuous improvement mechanisms; Establishment of supply chain and contracts for physical CBM technology parts and repairs; and Amendment of existing maintenance contracts with civilian agencies.

FACILITIES		
Development of new logistics and maintenance structures and processes; Training and personnel certification; Design of CBM hardware/software; Acquisition of HUMS/CBM hardware and software; Bridging the 'air gap' between equipment/platforms and the data processing systems; Integration of HUMS/CBM hardware, software and platforms; and Development of and integration with Defence ICT infrastructure.	Allocation of funding for CBM capability; Development and elicitation of CBM requirements; Involvement of industry and commercial sector; Pilot trials and experiments; Allocation of resources for implementation and facility upgrades; Modification of maintenance training facilities; and Rollout scheduling and implementation.	Development of business case for CBM; Design of ongoing support, including continuous improvement mechanisms; and Independent assurance activities for system validation and compliance.
COLLECTIVE TRAINING		
Training and personnel certification; Design of CBM hardware and software; Data mining and analysis for decision support; Integration of HUMS/CBM hardware, software and platforms; and Development of and integration with Defence ICT infrastructure.	Development and elicitation of CBM requirements; Allocation of resources for implementation and facility upgrades; Modification of maintenance training facilities; Rollout scheduling and implementation; Promotion of benefits and providing stakeholder 'buy-in'; and Data collection, storage and archiving processes.	Independent assurance activities for system validation and compliance.

4.5 Economic Cost-Benefit Analysis

4.5.1 Economic Costs of CBM

Information on the economic aspects of CBM implementation was collected throughout the study, as evidenced by tables in Appendix C and Appendix I. As part of the post-activity data analysis, this information was collated and categorised in accordance with broad categories of recurring and non-recurring costs as well as further sub-categories as shown below:

1. **Non-recurring acquisition costs:**
    a. Purchase of technology
    b. Development of technology
    c. Modification of technology
    d. Initial spare parts supply
    e. Engineering (including advanced engineering)
    f. Installation and assembly

   g. Testing/trials
   h. Certification
   i. Technology integration.

2. **Recurring acquisition costs:**
   a. Ongoing spare parts supply
   b. Specialised tools and equipment
   c. Non-HUMS/CBM equipment
   d. Software licensing
   e. Software updates
   f. HUMS/CBM maintenance
   g. Insurance
   h. Disposal
   i. ICT infrastructure running/ maintenance costs
   j. Signal/bandwidth management.

3. **Initial and ongoing administrative costs:**
   a. Labour
   b. Administration
   c. Program monitoring
   d. Contract management
   e. Travel
   f. Documentation development
   g. Documentation distribution
   h. Use of facilities
   i. Associated supplies and support.

4. **Initial and ongoing training costs:**
   a. Training of operators and training of trainers
   b. Associated supplies and support
   c. Use of facilities
   d. Certification and maintaining qualifications.

5. **Initial and ongoing R&D costs:**
   a. Research
   b. Trials and pilot studies
   c. Monitoring and data analysis

   d. Optimisation studies
   e. Further development of CBM algorithms.

6. **Initial and ongoing support costs:**
   a. IT support
   b. Technical Support
   c. Engineering support.
7. **Ongoing fleet maintenance costs:**
   a. Overall maintenance costs
   b. Preventive maintenance
   c. Corrective maintenance (including due to secondary damage)
   d. Unnecessary maintenance
   e. Unplanned maintenance
   f. Module replacement
   g. Mid-life upgrade/deep maintenance
   h. Outsourced/contracted repairs.
8. **Ongoing data management costs:**
   a. Data collection
   b. Data transmission
   c. Data storage
   d. Data analysis
   e. Data security management
   f. Data security breaches
   g. Data purchase from the OEM.
9. **Operational logistics costs:**
   a. Transportation of spares
   b. Urgent transportation of spares
   c. Transportation of equipment/ vehicles
   d. Recovery of equipment/ vehicles
   e. Inventory holding and management.

Some of the costs involved with implementation of CBM present trade-off opportunities between the initial non-recurring costs and on-going capability support costs. For example, investment in development of a business case, horizon scanning, pilot trials, change management planning and promotion of the capability can be expected to reduce the costs associated with delays in implementation and slow user uptake, improve the targeting of capability options and facilitate achievement of other technology benefits.

4.5.2 Economic Benefits of CBM

The expected economic benefits from implementation of CBM can be viewed from two perspectives. Firstly, financial savings can be found in efficiencies achieved from:

- Improvements in maintenance planning and scheduling
- Improvements in supply chain efficiency and responsiveness
- Optimal asset utilisation by the operators
- Associated optimisation of resource usage (e.g. fuel)
- Use of CBM-generated information for decision support in fleet management and capability acquisitions
- Reduction in overall fleet costs for maintenance, upgrade, replacement and maintenance.

At the same time, economic benefits come from the avoidance of potential equipment/platform failures, including:

- Equipment downtime
- Equipment replacement
- Injury management
- Delays
- Recovery
- Repair
- Insurance claim payouts.

Various models exist for quantitative economic modelling of CBM impacts [26]. While this is beyond the scope of the current study, economic modelling is included in a recommendation for further work as an essential step for formulation of a business case for this capability.

At the same time, it is important to remember that not all benefits of a new technology can be formulated in economic terms and not all can be easily quantified. Some of the more significant effects of this nature identified during the study include increase in the quality and quantity of equipment/platform status data and associated improvements in quality of decision support for a range of short-term and long-term functions. They further encompass operator safety, confidence and morale effects, cultivation of equipment ownership culture, and the various direct and indirect contributions to the overall mission effectiveness.

4.6 Identifying Areas of Risk for CBM Implementation

The potential areas of risk associated with implementation of CBM were elicited by examination of the negatively coded impacts listed in the spreadsheet form of the finalised impacts map (see Appendix I). These were then examined in the context of the most significant impacts summarised in Section 4.3.

This analysis draws attention to two main areas of concern. The first one addresses the underlying assumption for all expected benefits of CBM – successful implementation and effective use by the operators. A potential risk identified in the study is resistance to change and adoption that may arise for a number of reasons ranging from personal and cultural beliefs, previous experience, 'spy-in-the-cab' syndrome, and lack of observable benefits. Ineffective use of the new technology (such as failure to record and download relevant data) has flow on effects on the accuracy of information underpinning the decision-making processes and the ability to accurately estimate fleet condition. It is therefore logical that leadership buy-in and change management strategies have been identified as critical requirements in implementation. Technology maturity was not identified as a specific risk in this study as HUMS and CBM are used extensively in other sectors (e.g. commercial road transport), however it should be noted that work remains on diagnostic and prognostic algorithm development.

The second aspect of CBM requiring careful consideration is the data management strategy. Potential risks exist in the ability to manage the increased data transmission requirements and provide relevant IT support. Furthermore, data security, ownership and access need to be addressed. This is echoed by the consistent identification of a data-mining and analysis capability as a critical input to the overall success of CBM (Table 17).

Another impact that has been assigned a negative coding, but that has not been flagged as critical, is the potential reduction in the scope for innovative operator repair where platform revival[6] may be required to complete a mission. There may also be some difficulties in obtaining parts and technical knowledge as the fleet ages. This study did not show consensus on these issues, as they are more likely to be the result of the overarching trends toward technology modularisation, rather than specific CBM effects.

5. Discussion

5.1 Validity of Study Method

The method used in this study can be subjected to critical assessment from a number of angles. Firstly, studies that attempt to forecast and assess future conditions face greater

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[6] A term used to describe ad-hoc (sometimes unconventional) repairs, usually undertaken in the field, in order to return an inoperable platform to a state capable of completing a mission.

challenges in terms of uncertainty than those focusing on the present and the past states. The sources of uncertainty for technology evaluations may be due to:

- The learning process that occurs with new technologies, whereby problems are identified and overcome and improvements are implemented [27]
- Far-reaching consequences of small changes and improvements [27]
- Political and social factors as well as budget constraints [27]
- Difficulty in predicting technology integration and future uses [28]
- General reduction in the accuracy of predictions with increases in forecasting time [29]
- Subjectivity in evaluation of impacts as positive, negative or neutral [21]
- Indirectness of cause and effect chains and difficulty in measuring complex effects produced by military action [21].

In addition, the Delphi-style survey method used for validating the baseline impacts map can potentially affect the generated data [30], as outlined in Table 20.

Table 20: Potential criticisms of Delphi-style surveys and the relationship to the current study

Delphi questionnaire artefacts	Relationship to the current study
Instability of panel membership may impede convergence of opinions.	The panel membership in the two survey iterations used in this study was relatively consistent, with only one new respondent to second round questionnaire. However, the number of respondents to the second round was half that of the first, which may mean misrepresentation of true panel consensus. Three iterations would have been preferred for this study but were not feasible within the available time and resource constraints.
Large time lapse between successive rounds can reduce the quality of responses.	The time allowed between the two survey iterations (approximately three months) was significantly longer than the recommended maximum of one month; this was partly due to delays in collecting and analysing first-round responses. This may have contributed to the reduced panel membership for the second round. On the other hand, the respondents were essentially presented with a new set of information to consider. This means that effects of the delay on their memory of the first survey questions was not a significant issue.
Ambiguous questions can result in different interpretations by the SMEs.	Question formulation was kept deliberately open in the first round of questions so as to avoid leading the participants in their answers and to generate a wide range of views. The second round presented much more focused questions aimed at generating group consensus. On the other hand, the extended length of the second-round questionnaire may have contributed to reduced panel membership.
Respondents' competence in particular areas affects the reliability of their estimates.	It was expected that the survey respondents would focus on their area of expertise, potentially at the expense of other (albeit important) considerations. This was taken into account in participant demographic analysis discussed in the next section.
Self-fulfilling and self-defeating prophecies can occur following the publishing of results.	It is expected that the study results would be used to inform and potentially influence the decision-making process. It should be kept in mind, however, that political and ethical biases in responses may influence the collected data.
Consensus by undue averaging may	This particular form of bias is not as relevant to the current study

occur with the standard Delphi approach which uses the median as a descriptor of the group opinion and the quartile range as a measure of the degree of consensus, with undue bias against far-out predictors.	design, due to focus on qualitative trend analysis in responses. Conflicts of opinion and outliers are examined in what is an inclusive approach to data analysis.
Achieving substantive breadth of enquiry is often constrained by the available time and resources.	Resource and time limitations were a major factor in conduct of this study, both from the perspective of the study team and in terms reducing availability of SMEs. Areas that required further study and potentially quantitative modelling are therefore included in recommendations for further work.

Finally, exploration of the potential impacts of a new technology is essentially a judgement-based process. Judgement was applied in the development of the conceptual model and study framework, in allocation of boundaries and survey design, in map construction and determination of causal links, and in coding and evaluation of impacts. While quantitative methods may be relevant in some parts of the study (such as the Java-based graph analysis), their use does not in itself add objectivity to subjective judgements.

Recognising these potential sources of bias and influence, this study was designed to explore the potential CBM impacts in a consistent and justifiable manner. Judgement-based elements of the study were subjected to validation via multiple iterations of internal workshops and two iterations of external SME surveys. Furthermore, data analysis incorporated a triangulation approach to identification of the most significant issues: exploration of the strength of evidence, SME-generated impact rankings, and Java-based graph analysis of the finalised impacts map. Consistent study framework underpinned by a clear conceptual model, combined with a critical appraisal of the quality of the generated data was used throughout the process.

5.2 Validity of Study Results

5.2.1 Demographics Analysis

In conducting a judgement-based study, the nature of the respondents and their previous experience becomes a significant influencing factor. Examination of participant demographics shows that out of the fourteen respondents, eleven worked in the Land domain and three in Air domain. Seven came from DSTO, five from the Army and two were civilian/external consultants. Only two SMEs had less than five years of experience with CBM; almost two-thirds of the respondents had over ten years of experience.

The total number of respondents was smaller than preferred, with many SMEs being unavailable for the required period of time. However, the demographics analysis for this study showed a reasonable spread of perspectives, underpinned by considerable experience.

5.2.2 Areas of Uncertainty

In attempting to conduct forecasting activities, it is expected that more certainty is associated with short-term direct effects of a particular change than with longer-term indirect effects confounded by external processes and factors. Examination of the impacts summarised in Appendix I with respect to their directness and temporal coding identifies the following impacts as having a higher level of uncertainty:

- Workforce effects: impact on maintenance training requirements, traditional maintenance skills, IT literacy, and the skill/technology gap between Defence and civilian agencies
- Resource consumption: reduced resource (e.g. POL) usage rates
- Long-term data collection and analysis effects: improvements in data analysis/data mining techniques, improved data availability for engineering change proposals, incident investigation and terrain and environment analysis; improved knowledge base for decision support for future capability acquisitions
- Long-term maintenance effects: reduction in scope for innovative operator repair and increased non-technical maintenance role for operators due to increased modularity and complexity of technology
- Long-term logistic process changes: more efficient and responsive supply chains, effects on inventory holdings and availability of space for other logistic functions
- Long-term effects on equipment/platforms: improved safety in operation, difficulty obtaining parts and technical knowledge as fleets age, increased and more predictable equipment life, and associated reduction in fleet size requirements
- Human factor effects: cultivation of culture of equipment ownership/excellence, increased confidence in use of equipment/platforms, improved operator performance and morale.

Not surprisingly, some of the impacts listed above resulted in conflicts of opinion during SME surveys. The detailed graph analysis outlined in Appendix H and the associated discussion further highlights the difficulty of dealing with causal relationships within a complex sociotechnical system. A number of causal relationships and impact sets needed to be explored further in a third iteration of SME surveys, but could not be done due to resource and time constraints. Alternatively, this can be addressed in further studies with a narrower focus on more specific aspects of CBM that can look at construction of detailed causal maps or influence diagrams.

5.2.3 Assumptions Analysis

Assumptions underpinning specific impacts and groups of impacts were collected throughout the study as can be seen in Appendix I. Collective analysis of the assumptions highlights the fact that many of the expected benefits are predicated on effective use of the CBM technology and the data it generates. The specific assumptions include:

- Accurate and consistent collection and automatic transmission of CBM-generated data by the operators
- Concerted efforts to analyse and utilise the collected data for functions such as decision support, training, incident investigation, capability management, and supply parts procurement
- Trust in CBM-generated information
- Establishment of processes to deal with the Human Resources (HR) and legal implications of the collected data.

The deliberate establishment of processes and allocation of personnel and funding underpin the achievement of both short-term benefits and longer-term impacts, such as overall fleet management and effects on capability acquisition processes.

5.2.4 Application of Study Results

Taking into account the factors discussed above, it is clear that the results of the study cannot be used to make exact predictions. Rather, the study should be used to develop an understanding of the expected impacts, costs and benefits, as well as their implications for the military Land domain. It provides a systematic evaluation of the technology impacts and their probability, severity and distribution. In this, the study results can be used to support the decision-making process with regard to CBM implementation, with a view to maximising the desired benefits, minimising negative impacts and addressing critical issues in generating effective capability.

6. Conclusions

6.1 Key Inputs and Costs for Implementation of CBM

The study results have highlighted a number of inputs as being critical to the successful implementation of CBM in the military Land domain. These inputs start with leadership 'buy-in' and championing of the technology implementation at high and local levels. Furthermore, it is essential to identify and include CBM requirements into the equipment/platform capability acquisition process so as to facilitate timely acquisition of CBM hardware and software. The latter then requires integration with the platforms and with Defence ICT infrastructure and processes.

Key change management strategies for timely and efficient implementation include necessary modifications to the supply and maintenance processes and training of personnel. Effective use of CBM also requires establishing a data management strategy, including ensuring automatic transmission of data, analysis and use for decision support, and further development of relevant prognostic and diagnostic algorithms.

Additional considerations based on past experience with CBM in the Air domain include incorporating allowances for the short life-cycle of CBM technology with associated rapid obsolescence rates, and ensuring clear contractual arrangements for data ownership and data mining.

The recurring and non-recurring costs associated with this capability include initial research and development, acquisition, integration and maintenance of the technology, change management administrative and training costs, and data management costs.

6.2 Expected Benefits and Savings

Once implemented, CBM can be expected to provide the key immediate benefits of improving fault-detection and correction through its diagnostic and prognostic functions, as well as generating real-time equipment/platform health and usage information through underpinning HUMS technologies. This information allows timely correction of faults and prevention of equipment and platform breakdowns, including possible prevention of catastrophic failure.

CBM-generated data can be further utilised to improve maintenance planning for both day-to-day operations and longer-term fleet management. It can also be linked to decision support functions at operational and tactical levels, thus contributing to the overall mission effectiveness.

As a flow-on effect, CBM implementation can be expected to facilitate efficiencies in the supply and maintenance processes, improve operator safety and provide data for long-term planning in capability acquisition processes.

In economic terms, CBM will provide efficiencies in maintenance and supply processes, fleet management, decision-support, optimised equipment use and informed capability acquisition processes. Savings can also be expected in avoidance of equipment/platform failures, including catastrophic failures on operations.

All the expected benefits and savings are predicated on the assumption of successful and timely implementation of CBM and effective utilisation of the technology by all stakeholders. This includes the assumption of resource and time allocation for development of the supporting processes in logistic and data management space.

6.3 Areas of Risk and Uncertainty

The assumptions that underpin the expected benefits of CBM also highlight the two key areas of risk for implementation of this technology. The first area relates to the human factors (such as resistance to change and technology underutilisation) that can influence the success of CBM implementation. This has flow on effects in terms of the accuracy of information collected and all the associated benefits. This risk can be mitigated through effective championing of the technology and consideration of change management strategies mentioned in Section 6.1.

The second area of risk lies in the data-management space, including security requirements and the integration of CBM-generated data with Defence ICT infrastructure. The aspects requiring close attention include bandwidth requirements for data transmission, IT support requirements, and security, ownership and access protocols.

Some of the projected impacts of CBM carry a higher level of uncertainty due to factors such as their longer-term nature, confounding effects of associated processes, and dependence on the specific capability options selected for implementation. The impacts that generated conflicts of opinion during SME discussions included impacts on overall maintenance burden, impacts on associated inventory holdings and impacts on traditional diagnostic and maintenance skills. The longer term, indirect and confounded effects include impacts on workforce, resource consumption effects associated with operation of the equipment and platforms, use of data over longer-term for higher-level decision support functions, effects on associated logistic processes, and the effects on operator confidence and morale.

7. Recommendations for Further Work

The study outlined in this report focused on the development of a broad picture of costs, benefits and risks associated with CBM implementation, based on the current level of knowledge and experience with this technology. In considering implementation of CBM in the military Land domain, four focused studies are recommended flowing on from the significant impacts, risks and opportunities identified by the study participants:

1. Historical analysis of equipment/platform failures and incidents with the view of identifying areas that can be addressed through CBM and generation of potential capability acquisition options
2. Detailed enumeration and quantitative modelling of the financial costs and savings for CBM capability options with the aim of producing a clear business case for this technology
3. Modelling of the required changes to associated maintenance and supply processes in order to assess impacts on the related logistic functions
4. Development of a detailed data-management strategy, including elicitation of technical and legal requirements for effective use of data generated by CBM.

These focused activities would be fundamental for CBM requirement definition and development of implementation strategies in support of the overall capability acquisition process.

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8. References

1. Banks, J. C., Crow, E., Reichard, K. ,Ruark, R. (2003) A Cost-Benefits Analysis of the Effect of Condition-Based Maintenance Strategies for Military Ground Vehicles. In: *IEEE Aerospace Conference,* Big Sky, MT, USA: 8-15 March 2003, IEEE, pp. 3227-3237.
2. Rabeno, E. and Bounds, M. (2009) Condition Based Maintenance of Military Ground Vehicles. In: *IEEE Aerospace Conference,* Big Sky, MT, USA: 7-14 March, 2009, 6 pages.
3. Alkin, D. (2011) *System Health and Usage Data in the Land Environment; Costs, Benefits and Issues (Masters Dissertation)*. The Royal Military College of Science, Cranfield University, September 2011.
4. Butcher, S. W. (2000) *Assessment of Condition-Based Maintenance in the Department of Defense*. Logistics Management Institute, McLean, VA, USA, August 2000, 76 pages.
5. TTCP LND AG-5 (2012) *Condition Based Maintenance of Land Systems*. TTCP Technical Report, TR-LND-AG5-01-2012, September 2012, 60 pages.
6. Rajesh, S. and Francis, B. (2012) *A Study of Condition Based Maintenance for Land Force Vehicles*. Land Operations Division, Defence Science and Technology Organisation, DSTO-GD-0664, March 2012, 31 pages.
7. Gallasch, G. E., Ivanova, K., Rajesh, S. ,Manning, C. (2013) *Condition Based Maintenance Technology Impact Study: Assessment Methods, Study Design and Interim Results*. Land Division, Defence Science and Technology Organisation, draft Technical Report, 2013.
8. Boyatzis, R. E. (1998) *Transforming Qualitative Information: Thematic Analysis and Code Development*, Sage Publications.
9. Lee, A. M. and Bereano, P. L. (1981) Developing technology assessment methodology: Some insights and experiences. *Technological Forecasting and Social Change* **19** 15-31.
10. Fidock, J. J. T. (2011) *Understanding Information Technology Appropriation in Organisations*. [PhD Thesis], RMIT University, February 2011.
11. Carroll, J. (2004) Completing Design in Use: Closing the Appropriation Cycle. In: *12th European Conference on Information Systems (ECIS 2004),* Turku, Finland: 14-16 June 2004, 11 pages.
12. Jeyaraj, A., Rottman, J. W. and Lacity, M. C. (2006) A review of the predictors, linkages and biases in IT innovation adoption research. *Journal of Information Technology* **21** (1) 1-23.
13. Koivisto, R., Wessberg, N., Eerola, A., Ahlquist, T., Kivisaari, S., Myllyoja, J. ,Halonen, M. (2009) Integrating future-oriented technology analysis and risk assessment methodologies. *Technological Forecasting and Social Change* **76** (9) 1163-1176.
14. Kukafka, R., Johnson, S. B., Linfante, A. ,Allegrante, J. P. (2003) Grounding a new information technology implementation framework in behavioural science: a systematic analysis of the literature on IT use. *Journal of Biomedical Informatics* **36** (3) 218-227.
15. Reed, J. H., Jordan, G. and Vine, E. (2007) *Impact evaluation framework for technology deployment programs: An approach for quantifying retrospective energy savings, clean energy advances, and market effects*. US Department of Energy, July 2007, 12 pages.
16. Roessner, J. D. and Frey, J. (1974) Methodology for technology assessment. *Technological Forecasting and Social Change* **6** 163-169.

17. Rogers, E. M. (1995) *Diffusion of innovations*. 4th ed. New York, The Free Press.
18. Tran, T. A. and Daim, T. (2008) A taxonomic review of methods and tools applied in technology assessment. *Technological Forecasting and Social Change* **75** (9) 1396-1405.
19. Knowlege Based Systems Inc. (2010) *IDEF0 Function Modeling Method*. [Accessed 13 June 2013]; Available from: http://www.idef.com/idef0.htm
20. National Institute of Standards and Technology (1993) *Integration Definition for Function Modelling (IDEF0)*. Draft Federal Information Processing Standards, Publication 183, 21 December 1993.
21. Mathieson, G. L. (2004) Benefits analysis - a robust assessment approach. *Journal of the Operational Research Society* **55** (4) 390-402.
22. Pincombe, B., Blunden, S., Pincombe, A. ,Dexter, P. (2013) Ascertaining a hierarchy of dimensions from time-poor experts: Linking tactical Vignettes to strategic scenarios. *Technological Forecasting and Social Change* **80** (4) 584-598.
23. Helmer, O. (1967) *Systematic use of expert opinions*. RAND Corporation, 1967, 13 pages.
24. Rowe, G. and Wright, G. (2001) Expert Opinions in Forecasting: Role of the Delphi Technique. In: Armstrong, J. S. (ed.) *Principles of Forecasting: A Handbook of Researchers and Practitioners*. Boston, Kluwer Academic Publishers 125-144
25. *yEd - Graph Editor*. (2014), [Accessed 28 March 2014]; Available from: http://www.yworks.com/en/products_yed_about.html
26. Gallasch, G. E. (2013) *A survey of Tools for the Cost Benefit Analysis of Condition Based Maintenance in the Land Domain*. Land Division, Defence Science and Technology Organisation, draft Technical Note, 2013.
27. Volti, R. (2006) *Society and Technological Change*. 5th ed. New York, Worth Publishers.
28. Dortmans, P. J. and Curtis, N. J. (2004) *Towards an analytical framework for evaluating the impact of technology on future contexts*. DSTO, DSTO-TR-1554, February 2004, 44 pages.
29. Webb, R. N., Goodman, L., Staples, B. ,Hughes, S. (2006) Identifying potential implications of technologies on military and security operations. In: *CCRTS*, San Diego, USA: 20-22 June 2006, 50 pages.
30. Gordon, T. J. and Helmer, O. (1964) *Report on a long-range forecasting study*. RAND Corporation, 1964, 71 pages.
31. Hockley, C. J., Zagorecki, A. T. and Lacey, L. J. (2011) Enabling Support Solutions in the Defence Environment. In: *Complex Engineering Service Systems: Concepts and Research*. Springer-Verlag
32. Stecki, J. S. (2010) The Rise and Fall of CBM. In: *NATO Research and Technology Organisation Workshop - "Implementation of Condition Based Maintenance"*, Bucharest, Romania: 4-6 October 2010.
33. Bechtel, J. (2007) TARDEC Condition Based Maintenance. In: *Condition Based Maintenance (CBM) Workshop*, TARDEC Auditorium, Warren, MI, USA: 28-29 November 2007, Tank Automotive Research, Development and Engineering Center (TARDEC).
34. Service, N. (2013) Mounted Sustain (RAMD) (presentation). In: *Health and Usage Monitoring and System Information Exploitation (HUMS/SIE) Workshop*, Cranfield, UK: 14 February 2013.
35. Liao, H. and Rausch, M. (2010) Spare Part Inventory Control driven by Condition Based Maintenance. In: *Reliability and Maintainability Symposium (RAMS)*, San Jose, CA, USA: 25-28 January 2010, 6 pages.

36. Xie, J. and Wang, H. (2008) Joint Optimization of Condition-Based Preventive Maintenance and Spare Ordering Policy. In: *Fourth International Conference on Wireless Communications, Networking and Mobile Computing (WiCOM '08),* Dalian, China: 12-14 October 2008, 5 pages.
37. Jardine, A. K. S., Lin, D. and Banjevic, D. (2006) A Review on Machinery Diagnostics and Prognostics Implementing Condition-Based Maintenance. *Mechanical Systems and Signal Processing* **20** (7) 1483-1510.
38. OSIsoft (2010) *Condition-based Maintenance (CBM) Across the Enterprise*. OSIsoft, Inc., 2007.
39. *Defence Standard 25-24: Health and Usage Monitoring Capability for Land Platforms (HUMS)*. (2004) UK Ministry of Defence, Issue 1, 24 December 2004.
40. Starr, A. G. (1997) A Structured Approach to the Selection of Condition Based Maintenance. In: *Fifth International Conference on the Technology Exploitation Process (Factory 2000),* Cambridge, UK: 2-4 April 1997, pp. 131-138.
41. del Rosairo, R. (2007) Prognostics and Diagnostics for Operational Awareness and Condition Based Maintenance (presentation). In: *Condition Based Maintenance (CBM) Workshop,* TARDEC Auditorium, Warren, MI, USA: 28-29 November 2007, Tank Automotive Research, Development and Engineering Center (TARDEC).
42. Banks, J. C., Reichard, K., Crow, E. ,Nickell, K. (2005) How Engineers can conduct Cost-Benefit Analysis for PHM Systems. In: *IEEE Aerospace Conference,* Big Sky, MT, USA: 5-12 March 2005, IEEE, pp. 3958-3967.
43. Jackson, C. (2007) Condition Based Maintenance (CBM) Workshop (presentation). In: *Condition Based Maintenance (CBM) Workshop,* TARDEC Auditorium, Warren, MI, USA: 28-29 November 2007, Tank Automotive Research, Development and Engineering Center (TARDEC).
44. *Joint Service Publication 817: Condition Monitoring and Condition Based Maintenance Policy*. (2007) UK Ministry of Defence, Issue 1, June 2007.
45. Hess, S. M., Biter, W. J. and Hollingsworth, S. D. (2001) An Evaluation Method for Application of Condition-Based Maintenance Technologies. In: *Reliability and Maintainability Symposium (RAMS),* Philadelphia, PA, USA: 22-25 January 2001.
46. Bayoumi, A., Goodman, N., Shah, R., Eisner, L., Grant, L. ,Keller, J. (2008) Condition-Based Maintenance at USC - Part IV: Examination and Cost-Benefit Analysis of the CBM Process. In: *American Helicopter Society Specialists' Meeting on Condition Based Maintenance,* Huntsville, AL, USA: 12-13 February 2008.
47. Haniak, P. (2007) Condition Based Maintenance (presentation). In: *Condition Based Maintenance (CBM) Workshop,* TARDEC Auditorium, Warren, MI, USA: 28-29 November 2007, Tank Automotive Research, Development and Engineering Center (TARDEC).
48. Khalak, A. and Tierno, J. (2006) Influence of Prognostic Health Management on Logistic Supply Chain. In: *American Control Conference,* Minneapolis, MN, USA: June 14-16, 2006, IEEE, 6 pages.
49. Lusardi, R. J. (2008) Evolving CBM+ for USMC Light Armored Vehicles (presentation). In: *DoD Maintenance Symposium and Exhibition,* Denver, Colorado: 27-30 October 2008.
50. DoD (2008) *Condition Based Maintenance Plus DoD Guidebook*. May 2008.

51. DoD *Condition Based Maintenance Plus, a DoD Initiative (presentation)*. [Accessed March 2012]; Available from: http://www.acq.osd.mil/log/mpp/cbm+/CBM101%20briefing_PRINT.PDF
52. Dugan, J. (2007) Condition Based Maintenance (CBM) Workshop Presentation (presentation). In: *Condition Based Maintenance (CBM) Workshop,* TARDEC Auditorium, Warren, MI, USA: 28-29 November 2007, Tank Automotive Research, Development and Engineering Center (TARDEC).
53. Land, J. E. (2001) HUMS - The Benefits -- Past, Present and Future. In: *IEEE Aerospace Conference,* Big Sky, MT, USA: 10-17 March 2001, 12 pages.
54. Bochenek, G. (2007) CBM Workshop Overview (presentation). In: *Condition Based Maintenance (CBM) Workshop,* TARDEC Auditorium, Warren, MI, USA: 28-29 November 2007, Tank Automotive Research, Development and Engineering Center (TARDEC).
55. Tesar, D. (2008) New Wave of Technology Built on the Core of Mechanical Engineering (presentation). In: *DoD Maintenance Symposium and Exhibition,* Denver, Colorado: 27-30 October 2008.
56. Vachtsevanos, G., Lewis, F. L., Roemer, M. J., Hess, A. ,Wu, B. (2006) *Intelligent Fault Diagnosis and Prognosis for Engineering Systems*, Wiley.
57. Akamatsu, M. C. (2007) Condition Based Maintenance Data Warehouse (CBM-DW) (presentation). In: *Condition Based Maintenance (CBM) Workshop,* TARDEC Auditorium, Warren, MI, USA: 28-29 November 2007, Tank Automotive Research, Development and Engineering Center (TARDEC).
58. Dabell, B., Halfpenny, A. and Kirk, J. (2007) VePro - Health and Usage Monitoring for Military Land Systems. In: *Condition Based Maintenance (CBM) Workshop,* TARDEC Auditorium, Warren, MI, USA: 28-29 November 2007, Tank Automotive Research, Development and Engineering Center (TARDEC).
59. MOD (2010) *Programme Initiation Document for the Development and Implementation of the Global Equipment Manager (GEM) - cited in Alkin, D. (2011).* DE&S Director Land Equipment, Abbey Wood, 2010.
60. Spare, J. H. (2001) Building the Business Case for Condition-Based Maintenance. In: *IEEE/PES Transmission and Distribution Conference and Exposition,* Atlanta, GA, USA: 28 October - 2 November 2001, IEEE Power and Energy Society, pp. 954-956.
61. Grall, A., Berenguer, C. and Dieulle, L. (2002) A Condition-Based Maintenance Policy for Stochastically Deteriorating Systems. *Reliability Engineering and System Safety* **76** (2) 167-180.
62. ZenPower International (2005) *An Effective Fast-Track TPM Implementation Approach (brochure)*. Available via http://www.tpmquality.com.
63. Neville, M. J., Organ, P. A., Serle, N., Watters, E. G. ,Wilson, D. R. R. (2006) *A Strategy and Approach to Define HUMS Cost Benefit Analysis for Land Platforms - cited in Alkin, D. (2011)*. Cranfield University, 2006.
64. Webber, G., Smith, J., Anderson, J., Bachkosky, J., Brown, D., Fratarangelo, P., Hogan, R., Johnson, J., Katz, D., Kelly, M., Lister, M., Robinson, D., Rodriguez, J., Rumpf, R., Sinnett, J., Spindel, R. ,Windsor, G. (2002) *Life Cycle Technology Insertion*. Naval Research Advisory Committee Panel on Life Cycle Technology Insertion, NRAC 02-02, July 2002, 68 pages.

Appendix A. First-Round SME Survey Template

A.1. First-Round SME Survey Instructions for Participants

Dear _Participant's Name_,

Thank you for agreeing to participate in our study of the potential impacts of Condition-Based Maintenance (CBM) in the military Land environment. For the purposes of this study, we take CBM to refer to a maintenance practice that is based on assessment of equipment condition using embedded sensors and built-in or portable diagnostic equipment. Equipment maintenance is then ideally performed based on need, rather than schedules or usage.

This study aims to develop a causal map of CBM impacts, based on the general model:

Impacts of CBM technology implementation may include economic, technological, organisational, procedural and social impacts, both positive and negative.

Your responses will help us address important questions such as:

- What resources are necessary to implement CBM in the Land domain?
- What are the likely benefits and costs of CBM, both now and looking out to 20-30 years?
- What factors need to be understood in order for CBM to be effective?

The study outcomes will inform work within the Australian Defence Force (ADF) capability acquisition projects, as well as the international CBM research conducted within The Technical Cooperation Program (TTCP) across Australia, Canada, the United Kingdom and the United States of America.

Survey Structure

We would like to enlist your participation in two survey rounds:

- Round One: This first round should take less than an hour to complete and requires you to answer some free text questions. You are free to add as much or as little text as you feel necessary, before returning the document back by e-mail. We would like to have all responses returned to us by 29 March 2013.

- Round Two: Your responses will be collated together with information from published literature and organised into a 'causal impacts' map. In the second survey round this map will be sent out to all participants for review, comments and adjustments.

Anonymity

Collation and reporting of survey responses will be conducted with de-identified data and particular responses will not be traceable to individual participants. However, we would like to include a list of contributors to the study in the final report. If you would like for your name to be omitted from the report, please let us know by answering Question 6 of the survey.

The study is being conducted at the Unclassified level. It is requested that survey responses do not contain any information with a classification higher than Unclassified.

Ethics Approval

As part of general DSTO requirements for this type of study, we are required to provide an ethics information and consent form (see attached) that is to be read and signed by the participants. (Please note that within the 'DSTO Guidelines for Volunteers' document, the references to military career and medical care apply to ADF members only.) This form should be signed, then scanned and e-mailed back along with your first round survey responses, or faxed back using the fax number +61 8 7389 5624.

Points of Contact

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Best Regards,

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A.2. First-Round SME Survey Questions

The questions included in the first round of SME surveys are listed below. Extra spacing allowed on the original questionnaire for participants to record their responses has been removed here for formatting purposes.

CONDITION-BASED MAINTENANCE IMPACTS STUDY

SURVEY – FIRST ROUND

This survey consists of several open questions that require free-text answers. Please feel free to make the responses as detailed or as brief as you feel necessary, however providing more detail will help us better understand your point of view.

1. **(a) What do you believe are the most appropriate applications for CBM technology within the military Land environment? Please list and describe each application.**[7]

   An example of a CBM application may be the integration of sensors into military vehicles for oil condition monitoring; measuring airflow through an engine air intake; use of accelerometers and gyroscopes for terrain monitoring or to inform structural fatigue monitoring, etc.

   (b) Where possible, please explain the advantages of the applications you listed (e.g. proven technology, value for money, simple to adopt, etc.).

   (c) Can you suggest any CBM applications which may be less appropriate? If so, please list and explain what makes them less attractive (e.g. not cost-effective, subject to technology barriers, etc.).

2. **For a CBM initiative to succeed it requires inputs (resources, technology, personnel, processes) from various domains listed below**[8]**. Please give examples of what you think are the most important inputs to a successful and sustainable CBM system in the military Land environment. Where possible, please identify any potential costs/savings (economic or other) related to your listed inputs.**

   - *Personnel: (e.g. requirement for data analysts for long-term trend analysis)*

   - *Organisation: (e.g. creation and implementation of new standard operating procedures, redesign of maintenance processes)*

   - *Training: (e.g. re-training of operators and maintenance personnel)*

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[7] This question is designed to elicit various capability options for introduction of CBM into the military Land environment.

[8] The groupings suggested here are based on the ADF Fundamental Inputs to Capability (FIC) categories. Similar groupings in US doctrine are described as 'Dimensions of Capability' (Doctrine, Organisations, Training, Leader Development, Materiel, Personnel, Facilities). UK equivalent is termed 'Defence Lines of Development' (Training, Equipment, Personnel, Information, Concepts and Doctrine, Organisation, Infrastructure).

- *Major systems: (e.g. purchase of CBM-enabled equipment and vehicles)*
- *Supplies: (e.g. establishment of supply chain and contracts for CBM technology parts)*
- *Facilities: (e.g. re-design of maintenance workshops, requirement for training facilities)*
- *Support: (e.g. ongoing IT support and upgrades for CBM software)*
- *Command and Management: (e.g. incorporation of equipment condition data into the operational planning process)*
- *Other inputs:*

3. **What impacts (both positive and negative) do you expect to see as a result of CBM implementation in the military Land environment within the areas listed below? Please consider both immediate and longer-term (20-30 year timeframe) impacts. Where possible, please include any comments regarding the potential costs/savings (economic or other) related to these impacts.**

   - *Personnel: (e.g. loss of traditional maintenance skills)*
   - *Organisation: (e.g. better informed capability acquisition process)*
   - *Training: (e.g. simplified maintenance training)*
   - *Major systems: (e.g. prolonged equipment life)*
   - *Supplies: (e.g. more pro-active ordering system for spare parts)*
   - *Facilities: (e.g. reduction of maintenance facility requirements)*
   - *Support: (e.g. more efficient supply system)*
   - *Command and Management: (e.g. better informed operational planning process)*
   - *Other impacts:*

4. **Do you have any other comments regarding the implementation and outcomes of the adoption of CBM technology within the military Land environment?**

5. **Demographics:**

   (a) What is the nature and length of your experience with CBM technology?

   (b) What would you consider your particular area of expertise in the context of CBM technology?

6. **Whilst individual responses will always be anonymous, do you agree to have your name added to the list of contributors in the final study report? Yes/No**

We appreciate your contribution to this study and ask if you could please return the filled-in word document via e-mail to guy.gallasch@dsto.defence.gov.au, before 29 March 2013.

Appendix B. Second-Round SME Survey Template

B.1. Second-Round SME Survey Instructions for Participants

INSTRUCTIONS FOR PARTICIPANTS

LAND MATERIEL CONDITION BASED MAINTENANCE TECHNOLOGY IMPACT STUDY

Dear *Participant's Name*,

Thank you for agreeing to participate in our study of the potential impacts of Condition-Based Maintenance (CBM) in the military Land environment. For the purposes of this study, we take CBM to refer to a maintenance practice that is based on assessment of equipment condition using embedded sensors and built-in or portable diagnostic equipment. Equipment maintenance is then ideally performed based on need, rather than schedules or usage.

This study aims to develop a causal map of CBM impacts, based on the general model:

INPUTS → CBM CAPABILITY → OUTPUTS (IMPACTS)

Impacts of CBM technology implementation may include economic, technological, organisational, procedural and social impacts, both positive and negative.

Your responses will help us address important questions such as:

- What resources are necessary to implement CBM in the Land domain?
- What are the likely costs/benefits of CBM, both now and looking out to 20-30 years?
- What factors need to be understood in order for CBM to be effective?

The study outcomes will inform work within the Australian Defence Force (ADF) capability acquisition projects, as well as the international CBM research conducted within The Technical Cooperation Program (TTCP) across Australia, Canada, the United Kingdom and the United States of America.

Survey Structure

The survey has been structured into two rounds:

Round One: This first round should take less than an hour to complete and requires you to answer some free text questions. You are free to add as much or as little text as you feel necessary, before returning the document back by e-mail.

Following the Round One survey, your responses were collated together with information from published literature and organised into a 'causal impacts' map. Your input has helped to shape and refine the impacts map in two ways:

- Additional impacts have been captured over and above those reported in the literature; and
- Those impacts of particular relevance or importance to the military Land domain have been emphasised by the overlapping of responses from multiple participants.

Round Two: In the second survey round aspects of this map will be sent out to all participants for review, comments and adjustments.

We seek your participation in the **Round Two** survey. At this stage, Round One has nominally been completed, however if you still wish to complete the Round One survey you are more than welcome to do so.

Anonymity

Collation and reporting of survey responses will be conducted with de-identified data and particular responses will not be traceable to individual participants. However, we would like to include a list of contributors to the study in the final report. If you would like your name to be omitted from the report, please let us know by answering the final question of the survey.

The study is being conducted at the Unclassified level. It is requested that survey responses do not contain any information with a classification higher than Unclassified.

Ethics Approval

As part of general DSTO requirements for this type of study, we are required to provide an ethics information and consent form (see attached) that is to be read and signed by the participants. (Please note that within the 'DSTO Guidelines for Volunteers' document, the references to military career and medical care apply to ADF members only.) This study has also been approved by the DRDC Human Research Ethics Committee (Protocol #2013-024) for DRDC participants. **If you have not already returned a signed consent form**, please print, sign, then scan and e-mail the consent form back along with your second round survey responses, or fax it back using the fax number +61 8 7389 5055.

Points of Contact

Any queries and comments regarding the survey structure and content can be addressed to:

Guy Gallasch
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Telephone +61 8 7389 5945
Fax +61 8 7389 5055

Christopher Manning
christopher.manning@dsto.defence.gov.au
Telephone +61 8 7389 4195
Fax +61 8 7389 5055

Best Regards,

Guy Gallasch, Christopher Manning and Sreeja Rajesh

Logistics Projects and Studies
Land Division/Joint and Operations Analysis Division
Defence Science and Technology Organisation

B.2. Second-Round SME Survey Questions and Images

The questions and images included in the second round of SME surveys are listed below. Extra spacing allowed on the original questionnaire for participants to record their responses has been removed here for formatting purposes.

SECOND ROUND SURVEY
LAND MATERIEL CONDITION BASED MAINTENANCE TECHNOLOGY IMPACT STUDY

This survey presents aspects of a 'causal impacts' map related to the impact of the introduction of Condition Based Maintenance (CBM) to Land materiel maintenance. Questions are then asked about the content and structure of the impacts map.

This survey is divided into two parts. The first part deals with the impacts identified as inputs, or enablers, to the introduction of CBM. The second part deals with output impacts, or results, of the introduction of CBM.

A number of questions are optional, given realistic time constraints. However, we would appreciate responses to as many of the optional questions as time permits.

For any of the below questions, you are welcome to provide free text responses, or annotate the Impacts maps directly (either by hand or by electronic means). If you annotate the maps by hand, please scan and email the annotated maps back to us, fax them to +61 8 7389 5055, or send them via snail-mail to:

Guy Edward Gallasch
Land Division 81 Labs
PO Box 1500
Edinburgh SA 5117

Please advise us if you choose the 'snail mail' option so that we will know to expect mail.

Please feel free to make the responses as detailed or as brief as you feel necessary, however providing more detail will help us better understand your point of view. While you are encouraged to respond to all questions, you are welcome to provide blank responses where unavoidable.

Part 1: Input Impacts

Input impacts have been gathered and arranged into an Input Impacts map. The input impacts have been grouped into seven clusters. An overview of these clusters and their causal links is shown in Figure 1, leading into the "CBM Capability" on the right of the figure. The detail of each cluster is shown in Figure 2. Note that each impact has been labelled with a unique letter/number identifier. These maps have been provided for your information and reference. Figure 2 has also been provided in a Microsoft PowerPoint file, to ease electronic annotation.

Scores have been assigned to each impact based on the number of times this impact is mentioned in the literature (blue circle score) or by First Round survey respondents (red circle score). 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.

There are some impacts that were suggested in an internal DSTO workshop that were not found in the literature or mentioned in First Round survey responses. These are marked with a "W" inside a black circle.

In answering the below questions, you are welcome to browse the Input Impacts map.

1. **The scores given to each impact provide a rough indication of the importance of each. Considering the input impacts in Figure 2:**

   a. The following impacts have either the highest blue or red score from each cluster, or have a high combined blue and red score. The sum of blue and red scores is given in brackets for each of these impacts:
      - 4a. Acquisition of HUMS[9]/CBM hardware and software (15)
      - 3a. Development of new logistics and maintenance structures and processes (13)
      - 6. Training and personnel certification (13)
      - 7b. Integration of HUMS/CBM hardware, software and platforms (12)
      - 4b. Design of HUMS/CBM hardware and software maintenance (10)
      - 5g. Data mining, analysis and use for decision-support (8)
      - 5h. Development of algorithms (prognostics and diagnostics) (8)
      - 2f. Inclusion of CBM requirements into acquisition of relevant equipment/platforms (3)

[9] Health and Usage Monitoring System

i. Do you agree that these are the most critical input impacts? If not, please give details.

ii. Do you agree with the rankings of these impacts? If no, please give details.

iii. Would you add any impacts to this list? If yes, please give details.

b. Excluding cluster headings, the following impacts have the lowest score (one) of those given a non-zero score:
- 2c. Allocation of ownership and management responsibility.
- 2d. Assessment of CBM solutions early in the design stage.
- 2e. Allocation of funding for CBM capability.
- 2h. Development of a business case for CBM.
- 3b. Allocation of resources for implementation and facility upgrades.
- 3e. Amendment of existing maintenance contracts with civilian agencies.
- 4e. Increased modularity of equipment/platform design.
- 5a. Data architecture and standards.
- 6a. Modification of maintenance training facilities.

i. Do you agree that these are the least critical input impacts of those given a score? If no, please give details.

ii. Would you add any impacts to this list? If yes, please give details.

c. The impacts shown in the table below are those suggested at an internal DSTO workshop but not mentioned in literature or First Round survey responses.

Using the table provided below, please rate each of these impacts according to your belief of their importance. Where possible, please explain the reasons for your rating.

Impact	**Critical**	**Important**	**Significant**	**Less significant**	**Not significant**	**Reason for given rating**

3c. Promotion of benefits						
3f. Human resource management						
3g. Rollout scheduling and implementation						

2. **Optional. Considering the Input Impacts map in Figure 2 as a whole:**

    a. Are there any input impacts that should be added?

    b. Are there any input impacts that could or should be removed?

    c. Are there any input impacts that could or should be moved into different clusters?

3. **Optional. Causal relationships exist between impacts from different clusters and between impacts within the same cluster.**
   These are represented by arrows in Figure 1 and Figure 2. For example, we have identified a causal link from impact 2f to impact 4a (i.e. 2f occurs before 4a).

    a. Are there any other causal relationships that should be captured by this map?

    b. Are there any causal relationships that you would modify or remove from the map?

   Feel free to capture any causal links by using the number/letter identifiers of the impacts, drawing arrows directly on the map by hand or electronically using the Microsoft PowerPoint file, or recording them in any other way that is convenient.

4. **Do you have any other comments on the Input Impacts map?**

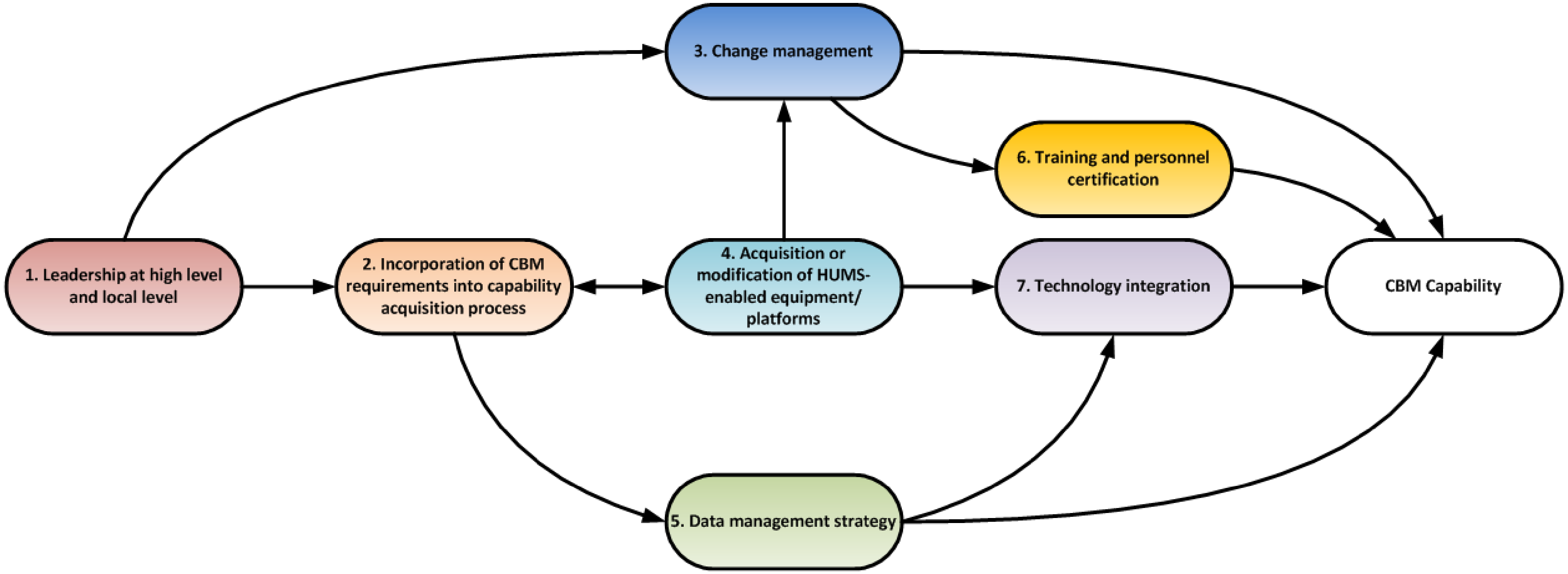
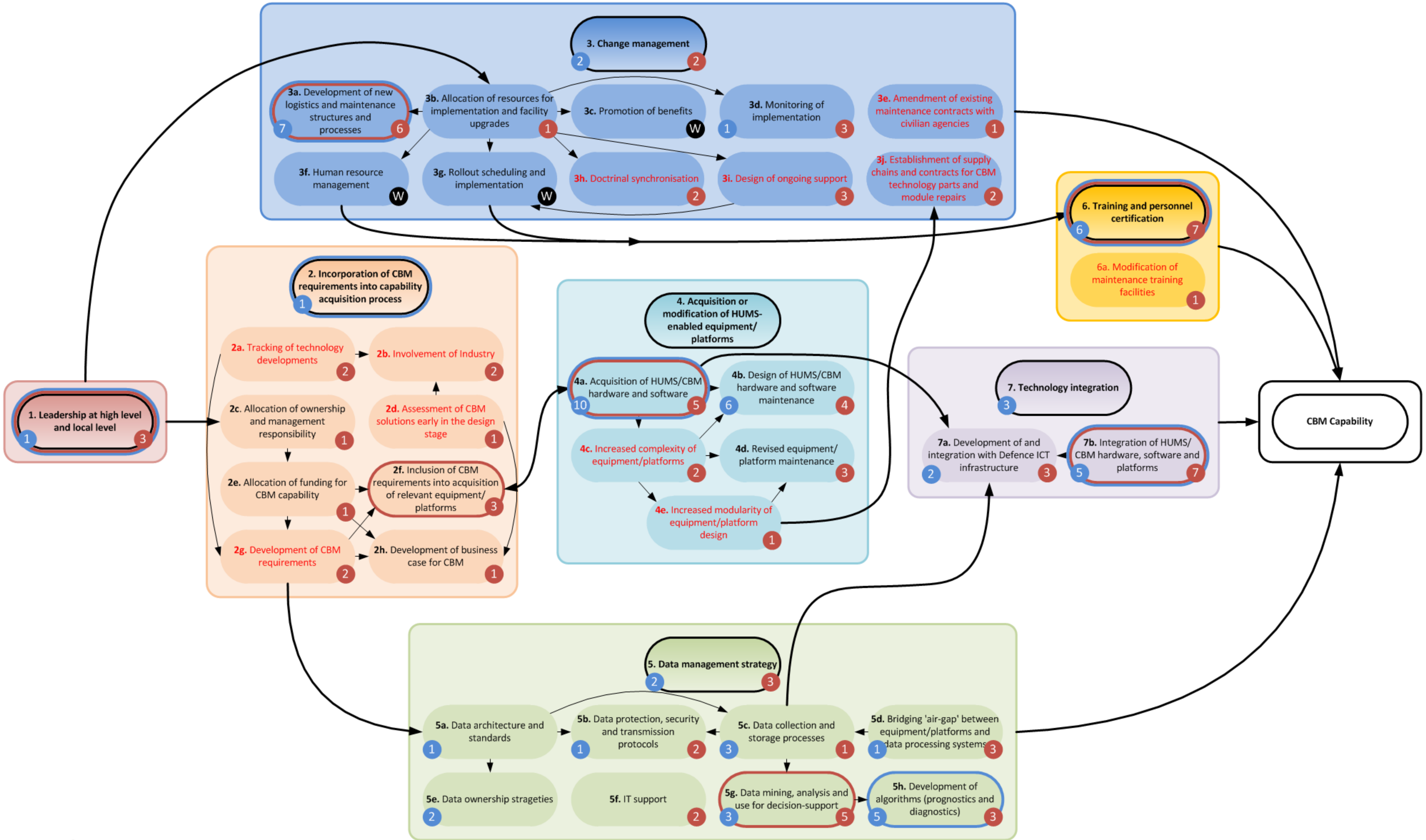


Figure 1: Overview of Input Impact Clusters



Legend:

Text:		Outlines:		Markers:		Arcs:	
Black text:	Impact identified from literature/internal DSTO workshop	Black outline:	Cluster heading	X	Number of items in the literature that identified this impact	→ :	Inter-cluster causal relationship
Bold text:	Cluster heading/high level impact	Blue outline:	Top-ranked impact based on literature	Y	Number of survey respondents that identified this impact	→ :	Intra-cluster causal relationship
Red text:	New impact/cluster heading identified from Round One Survey responses	Red outline:	Top-ranked impact based on Round One survey responses	W	An impact that was identified through an internal DSTO workshop but without support in the literature or Round One survey responses		

Figure 2: Input Impacts Map

Part 2: Output Impacts

Output impacts have been gathered and arranged into an Output Impacts map. The output impacts have been grouped into 12 clusters in a similar way to the input impacts. An overview of these clusters and their causal links is shown in Figure 3, stemming from the "CBM Capability" on the left of the figure. The detail of each cluster is shown in Figure 4. Each impact has been given a unique number/letter identifier. Scores have been given to each output impact in the same way as for the input impacts. These maps have been provided for your information and reference. Figure 4 has also been provided in a Microsoft PowerPoint file for ease of electronic annotation.

In answering the below questions, you are welcome to browse the Output Impacts map.

5. **The scores given to each impact provide a rough indication of the importance of each. Considering the output impacts in Figure 4:**

    a. The following impacts have either the highest blue or red score from each cluster, or have a high combined blue and red score. The sum of blue and red scores is given in brackets for each of these impacts:

    - 10f. Increase in operational availability and capability of equipment/platforms (24).
    - 9a. Improved ability to plan maintenance, e.g. schedule maintenance in a load-balancing way (16).
    - 12b. Improved decision support for mission assignment of equipment/platforms (15).
    - 10a. Improved safety in operation of equipment/platforms (14).
    - 8c. Reduced inventory holdings at supply chain nodes (12).
    - 1a. Diagnostics (11).
    - 8b. More efficient and responsive supply processes (11).
    - 9d. Improved operation and maintenance of the fleet (11).
    - 1c. Automated generation of real-time equipment/platform health information (10).
    - 4a. Reduced preventive maintenance requirements (10).
    - 4c. Improved fault detection (10).
    - 6c. Increase in the quality and quantity of available equipment/platform health and usage data (10).
    - 8g. Change to proactive, CBM-driven supply processes (9).
    - 9e. Reduced overall maintenance burden (9).
    - 6j. Improved ability to estimate equipment/platform condition (8).
    - 11f. Increased confidence in the use of equipment/platforms (8).

i. Do you agree that these are the most critical output impacts? If not, please give details.

ii. Do you agree with the rankings of these impacts? If no, please give details.

iii. Would you add any impacts to this list? If yes, please give details.

b. The following impacts have the lowest combined red and blue scores of one:

- 2b. Tracking of position, status and load of vehicles, critical stores and drivers.
- 3e. Increased demand for IT Support personnel.
- 3f. Increase in personnel capable of implementing and upgrading CBM systems.
- 3h. Decrease the skill/technology gap between Defence and civilian agencies.
- 3i. Reduced scope for innovative operator repair for platform 'revival' to complete a mission.
- 3j. Increased non-technical maintenance role for operators, cf. increased modularity.
- 6e. Improved data availability for accident/incident investigation.
- 6h. Improved monitoring of environmental pollution effects.
- 6i. Greater availability of terrain and environmental data.
- 7c. Increased ability of unauthorised external parties to access generated data.
- 7f. Increase in data security management requirements.
- 8d. Increased Information and Communication Technology (ICT) in workshops.
- 8o. Management of CBM components within the supply chain.
- 9h. Reduction in support equipment in the field and specialised support equipment at the Strategic level.
- 9i. Redesign of maintenance workshops with technical repair/refurbishment pushed rearward.
- 9j. Better utilisation of tradespeople, particularly for preventive maintenance.
- 10i. More difficult to obtain parts and technical knowledge as fleets age.
- 10j. Increased equipment down-time due to spare part obsolescence as fleet life is extended.

- 11d. Reduced accuracy of information underpinning decision-support.
- 11e. Cultivation of culture of equipment ownership/excellence.

i. Do you agree that these are the least critical output impacts of those given a score? If no, please give details.

ii. Would you add any impacts to this list? If yes, please give details.

6. **The First Round Survey has identified a number of diverging views related to the potential impact of CBM.**

   These are highlighted by scores in orange circles in Figure 4. Please provide (additional) thoughts and comments on the diverging views identified below.

   a. **Supply chain costs.**

      The output impacts:

      - 8b. More efficient and responsive supply processes;
      - 8c. Reduced inventory holdings at supply chain nodes;
      - 8h. Reduced logistic footprint; and
      - 8n. Better supply planning.

      suggest that supply chain cost savings are achievable. This is in conflict with the assertion that there will be a "negligible impact on supply chain costs" (8i).

      Please provide your thoughts and comments on this divergence of opinion.

   b. **Maintenance training requirements.**

      A significant diversity of views was expressed when it came to maintenance training requirements (impact 3a):

      - Reduced maintenance training requirements;
      - Reduced maintenance training requirements only for junior maintainers; and
      - Increase in training requirements for senior maintainers for data analysis.

      Please provide your thoughts and comments on this divergence of opinion.

   c. **Traditional diagnostic and maintenance skills.**

      A significant diversity of views was expressed when it came to traditional diagnostic and maintenance skills (impact 3b):

- A reduction in traditional diagnostic and maintenance skills, associated with an increase in the complexity and digitalisation of technology in general and not necessarily as a direct result of CBM;
- No loss of traditional maintenance skills, as the requirement to conduct traditional preventive maintenance will still exist within fleet variants not fitted with CBM technology; and
- Better retention and utilisation of wear characteristic type training skills.

Please provide your thoughts and comments on this divergence of opinion.

d. Regularity of preventive maintenance.

Survey participants have asserted that (impact 4b):

- CBM is associated with a move from fixed toward more 'ad-hoc' scheduling of preventive maintenance;
- CBM allows longer maintenance cycles; and
- Service interval should remain constant to allow for scheduling of equipment to fit in with unit commitments, especially for field units.

Please provide your thoughts and comments on this divergence of opinion.

e. Number of maintainers.

Within survey responses were the assertions that there could be a "potential reduction" in the number of maintainers or that a reduction in the number of maintainers was "unlikely" (impact 3g).

Please provide your thoughts and comments on this divergence of opinion.

7. Optional. Considering the Output Impacts map in Figure 4 as a whole:

a. Are there any output impacts that should be added?

b. Are there any output impacts that could or should be deleted?

c. Are there any output impacts that could or should be moved into different clusters?

8. Optional. Causal relationships exist between impacts from different clusters and between impacts within the same cluster.

These are represented by arrows in Figure 3 and Figure 4. For example, we have identified a causal link from impact 6c to impact 7a.

a. Are there any other causal relationships that should be captured by this map?

b. Are there any causal relationships that you would modify or remove from the map?

Feel free to capture any causal links by using the number/letter identifiers of the impacts, drawing arrows directly on the map by hand or electronically using the Microsoft PowerPoint file, or recording them in any other way that is convenient for you.

9. Do you have any other comments on the Output Impacts map?

Final questions:

10. If you have not responded to the First Round survey:

a. What is the nature and length of your experience with CBM technology?

b. What would you consider to be your particular area of expertise in the context of CBM technology?

c. Whilst individual responses will always be anonymous, please indicate whether you agree to have your name added to the list of contributors in the final study report.

Yes, include my name / No, do not include my name

We appreciate your contribution to this study and ask if you could please return the filled-in word document via e-mail to guy.gallasch@dsto.defence.gov.au, before 31 August 2013.

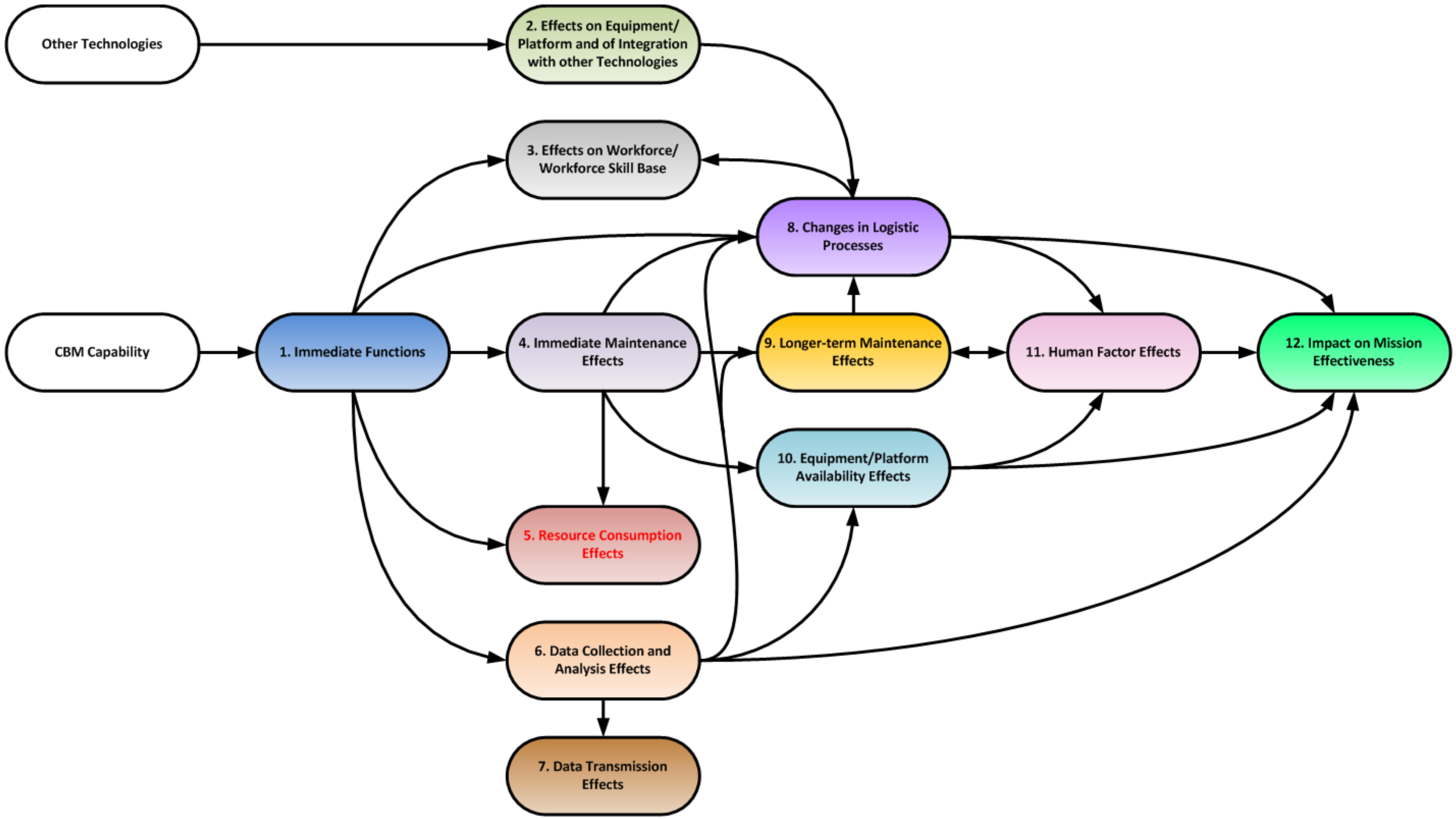


Figure 3: Overview of Output Impact Clusters

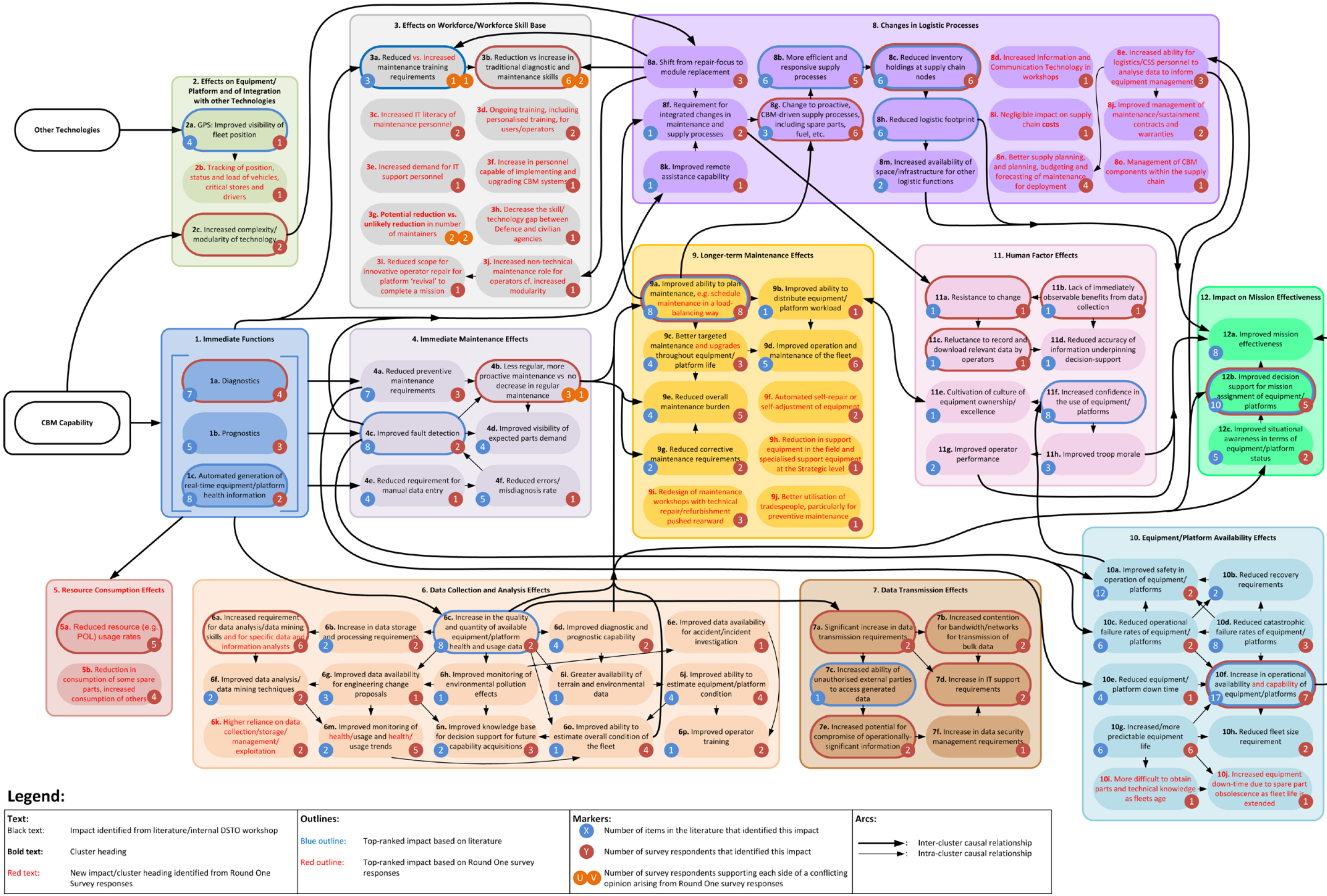


Figure 4: Output Impacts Map

Appendix C. Literature Survey Results

Below is our initial construction of the impacts map based on a survey of the literature and an internal DSTO workshop. In addition to the cited literature, (W) is used to denote impacts that were identified during an internal DSTO workshop.

For brevity, in the following spreadsheets we refer to the eight FIC categories by number:

1. Command and Management
2. Organisation
3. Major Systems
4. Personnel
5. Supply
6. Support
7. Facilities
8. Collective Training.

C.1. Input Impacts Spreadsheet

ID	Title	Description	Indicative $$$ COSTS	Indicative $$$ SAVINGS	Stakeholders	Assumptions	FIC
I-1	**Leadership at high level and local level [31] (W)**	**Personnel at decision-making level and at user-level who actively promote implementation of the capability**	**Labour costs, administrative costs**	**Reduced administrative costs associated with delays in implementation**	**ADF planners, end-users**		**1,2,4**
I-2	**Incorporation of CBM requirements into capability acquisition process [31] (W)**		**Labour costs, administrative costs, travel costs, documentation costs, research costs (TRAs, BOPs, market surveys, etc.)**	**Reduced administrative costs associated with delays in implementation**	**Suppliers, ADF planners, CDG, DMO, DSTO**		**1,2,3,5**
I-2a	Development of business case for CBM [32]						
I-2b	Allocation of funding for CBM capability (W)						
I-2c	Allocation of ownership and management responsibility (W)						
I-2d	Inclusion of CBM requirements into acquisition of relevant equipment/platforms (W)						
I-3	**Change management [33, 34] (W)**	**System integration at organisational level**	**Labour costs, administrative costs, travel costs, costs of developing and distributing documentat-ion (e.g. SOPs); IT/tech support cost increases during roll-out; loss of productivity during roll-out; central management costs; costs of pilot trials; cost of research and optimisation studies**	**Reduced administrative costs associated with delays in implementation; reduced productivity losses during implementation; reduced losses due to resistance to implementation**	**ADF planners, CDG, DSTO, end-users (equipment operators, maintenance personnel), analysts**		**All**
I-3a	Allocation of resources for implementation (W)						
I-3b	Rollout scheduling and implementation (W)						
I-3c	Development of new maintenance & logistics processes [31, 33-38]	Includes CBM-drive spare parts inventory strategy [35, 36]				Without simultaneous optimisation of logistic and maintenance processes with implementation of CBM, a lot of benefits from CBM will be eroded [31]	
I-3d	Human resource management (W)	Analysis of changes in human resource requirements and appropriate actions to satisfy these requirements					
I-3e	Promotion of benefits (W)						
I-3f	Monitoring of implementation [32] (W)						
I-4	**Acquisition of HUMS-enabled equipment/platforms or modification of existing platforms (W)**		**Cost of platform purchase; for modification, includes cost of engineering, research, testing, certification and trials platform maintenance costs (labour, spare parts)**	**Increased disposal value [39]**	**Suppliers, ADF planners, CDG, DMO**	Cost of HUMS-enabled platform purchase is comparable to purchase of platforms without HUMS, as it is becoming standard technology	**2,3,5,6**
I-4a	Equipment/platform maintenance (W)					Cost of maintaining HUMS-enabled platforms is similar to cost of maintaining platforms without HUMS	

ID	Title	Description	Indicative $$$ COSTS	Indicative $$$ SAVINGS	Stakeholders	Assumptions	FIC
I-5	**Acquisition of HUMS/CBM hardware and software [1, 6, 31-33, 38-42] (W)**	**Includes sensors, displays, data acquisition and processing software and hardware [1, 41, 43]**	**Cost of purchase/ development/ modification [1, 6, 38, 41, 42, 44]; cost of initial spare parts supply [1, 6]; transportation costs; assembly/installation costs [1, 6, 39, 42]; testing/certification costs [6, 44]**		**CDG, DMO, end-users**	HUMS/CBM equipment requires minimal corrective costs [1]	2-7
I-5a	HUMS/CBM hardware and software maintenance [1, 6, 31, 32, 39, 42] (W)	Set-up of supply/maintenance contracts; testing, repair and replacement of components; software upgrades, patches and licensing	Labour, spare parts, technical support, upgrades [1, 6, 42]; cost of specialised tools and equipment [38]; administrative costs in contract management; cost of inventory management; cost of transportation; cost of software support, updates and licensing [6])				
I-6	**Training and personnel certification [1, 6, 31, 39, 40, 45] (W)**		**Cost of developing training protocols/SOPs [1, 6]; cost of publishing and distributing training manuals, user/repair manuals [1, 6]; cost of implementing training (time, instructors, equipment, facilities, associated support [6]; loss of productivity during training [6]; cost of complying with qualification/certification requirements [6]**	**Reduced costs of inappropriate equipment use; maximising overall CBM-related savings through extensive and appropriate utilisation of the technology**	**Command and management, end-users, trainers**		**1,2,4,6, 7,8**
I-7	**Technology integration [33, 43, 46] (W)**		**cost of advanced engineering [6, 46]; cost of assembly and installation [1, 6, 39, 42]; cost of testing/trials [6]; cost of external system modifications (to MILIS, C2 systems, etc.) [6]; cost of developing and distributing technical data (e.g. operating manuals, troubleshooting manuals) [1]; cost of using and maintaining existing ICT infrastructure [6]; technical support costs; cost of signal/bandwidth management**	**reduced cost of non-HUMS equipment [6]**	**Suppliers of technology and technical support, command and management, end-users, engineers, ADF ICT managers and maintainers**		**1-7**
I-7a	Integration of HUMS/CBM hardware, software and platforms (w)	integration with other systems, e.g. LOGIS (MILIS), BMS, Communications systems, etc (e.g. existing fielded systems) [38]					
I-7b	Integration with external systems	e.g. LOGIS (MILIS), BMS, C2 systems, communications systems [38] (W)					
I-7c	Defence ICT infrastructure [38] (W)	DLAN, SATCOMS, signal/bandwidth management; various communication links [33]					
I-8	**Data management strategy [31, 42]**		**Research and documentation costs for algorithm development [42]; cost of research and optimisation studies; cost of pilot trials; labour and administrative costs for implementation; cost of using and maintaining ICT infrastructure; labour and administrative costs**		**ADF planners, commercial providers, end-users, security organisations, analysts, operational planners, IT support personnel**		**1-4, 6**
I-8a	Bridging 'air-gap' between equipment/platforms and data processing systems [31]						
I-8b	Data ownership strategies [31, 34]	Includes consideration of data-sharing with commercial organisations/OEMs[31, 34], privacy issues [41]					

ID	Title	Description	Indicative $$$ COSTS	Indicative $$$ SAVINGS	Stakeholders	Assumptions	FIC
I-8c	Data security and transmission protocols [31]						
I-8d	Data architecture and standards [47]						
I-8e	Data collection and storage processes [31, 33, 43]						
I-8f	Data mining, analysis and use for decision-support [31, 33, 43]						
I-8g	IT support (W)						
I-8h	Development of algorithms (prognostics and diagnostics) [31, 32, 41, 42, 48]						

C.2. Output Impacts Spreadsheet

ID	Title	Description	Indicative $$$ COSTS	Indicative $$$ SAVINGS	Stakeholders	Assumptions	FIC	+ / - /?	(S)hort, (M)edium or (L)ong-term	(D)irect/ (I)ndirect
O-1	**Immediate functions**									
O-1a	Diagnostics [5, 6, 31, 38, 46, 47, 49] (W)	Real-time assessment of platform/equipment health [5, 6, 31, 38]	As per costs of inputs to capability; increased cost of minor parts replacement on 'as-required' basis	As per savings from impacts	Operators, maintenance personnel		3,4,6	+	S	D
O-1b	Prognostics [5, 6, 37, 47, 48] (W)	Identifying existence of a fault and impending failure [37, 48, 50]	As per costs of inputs to capability; increased cost of minor parts replacement on 'as-required' basis	Reduced cost of scheduled parts replacement; reduced unplanned maintenance costs	Operators, maintenance personnel	Quality of collected data is sufficient for prognostic purposes and accurate prognostic models are available [31]	3,4,6	+	S	D
O-1c	Automated generation of real-time platform/equipment health information [5, 6, 31, 38, 47, 49, 51, 52] (W)		As per costs of inputs to capability	Reduced costs of reporting and data collation	Operators, maintenance personnel, logistics planners, operational planners	The 'air-gap' between the platform/equipment and data analysis systems is bridged with automatic data transmission [31]	1-4,6	+	S	D
O-2	**Immediate maintenance effects**									
O-2a	Reduced requirement for manual data entry [5, 6, 47, 53] (W)			Reduced labour and administrative costs associated with manual data entry	Operators, maintenance personnel	The 'air-gap' between the platform/ equipment and data analysis is bridged with automatic data transmission [31]; successful integration of relevant software	5,7	+	S	D
O-2b	Reduced errors/misdiagnosis rate [4-6, 54, 55] (W)			Reduced cost of unnecessary maintenance and secondary (maintenance-induced) damage [1, 4, 5, 31, 39]	Operators, maintenance personnel		3,4,6	+	S/M	D
O-2c	Improved fault detection [3, 6, 32, 44, 46, 53, 56, 57] (W)	Quicker and more accurate fault detection		Reduced cost of labour for fault-detection/inspections	Operators, maintenance personnel		3,4,6	+	S	D
O-2d	Reduced preventive maintenance requirements [1, 3, 5, 6, 32, 37, 53] (W)	Associated with reduced No Fault Found (NFF) rate [5, 39]		Reduced cost of preventive maintenance, including labour, parts, plant activity [1, 3, 5, 6, 38, 39]	Operators, maintenance personnel, logistics planners		1,3-6	+	S/M	D
O-2e	Less regular, more proactive maintenance (W)	Associated with a move from scheduled to "ad-hoc" maintenance, condition-triggered maintenance (i.e. CBM) [46, 57, 58] with longer maintenance cycles [55]		Reduced cost of preventive maintenance, including labour, parts, plant activity [1, 3, 5, 6, 38, 39]; reduced cost of unnecessary maintenance [3, 39, 44]	Maintenance personnel, logistic planners		1,3-6	?	S/M/L	D
O-2f	Random failures still occur [31]	It may be possible to provide estimates of failure probability distributions [31]			Operators, maintenance personnel		4,6	-	S/M/L	I
O-2g	Improved visibility of expected parts demand [1, 6, 32, 49]			Reduced reliance on urgent means of transportation for spare parts	Maintenance personnel, supply personnel		4,5,6	+	S/M/L	D

ID	Title	Description	Indicative $$$ COSTS	Indicative $$$ SAVINGS	Stakeholders	Assumptions	FIC	+ / -/?	(S)hort, (M)edium or (L)ong-term	(D)irect/ (I)ndirect
O-3	**Changes in logistic processes**									
O-3a	Requirement for integrated changes in maintenance and supply processes [50] (W)		Change management costs, including training, Standard Operating Procedure development, administration costs, monitoring costs	Productivity/efficiency gains due to maintenance and supply optimisation	ADF policy-makers, logistics planners, maintenance personnel, supply personnel		1,2,4-7	?	S/M	D
O-3b	Improved remote assistance capability [49]		Data-transmission costs	Reduced cost of vehicle and/or SME transportation to the site of equipment failure	Operators, maintenance personnel, SMEs	Equipment/platform status information can be transmitted over long distances	4,6	+	S/M	D
O-3c	Shift from repair-focus to module replacement (W)	Associated with increasing complexity of technology in general	Increased cost of replacement modules	Reduced cost of repairs and training of maintenance personnel	Maintenance personnel, supply personnel		3-Jun	?	M/L	I
O-3d	Change to proactive, CBM-driven spare-parts supply processes [5, 37, 50]	May be associated with automatic re-ordering processes [6, 47, 49]	Change management costs, including training, Standard Operating Procedure development, administration costs, monitoring costs	Reduced labour costs in generation of demands	Maintenance personnel, supply personnel, logistics planners	Combined optimisation of maintenance and supply processes takes place [31, 35]	1,2,4,5, 6	+	M	I
O-3e	More efficient and responsive supply processes [1, 5, 6, 47, 50, 59]	Reduction in administrative and logistics down time [1, 32, 53]; improved spares availability [1]		Reduced reliance on urgent means of transportation for spare parts [1, 5, 6]; reduced inventory holding costs [6, 39]; maximisation of contracting opportunities [3]	Logistics planners, supply personnel, maintenance personnel	Combined optimisation of maintenance and supply processes takes place [31, 35]	1,2,4-7	+	L	I
O-3f	Reduced inventory holdings at supply chain nodes [1, 6, 35, 39, 44, 54] (W)		Potentially increased cost of replacement (vs repair) parts	Reduced inventory holding costs [6, 39], transportation costs (especially for urgent demands [1, 5, 6], overall operating costs [35]	Supply personnel, logistics planners, operational planners	Sufficiently responsive supply of parts from National Support Base (NSB)/OEM nodes. Development of spare parts inventory control strategy driven by CBM [35, 50]	1,5,7	+	M/L	I
O-3g	Reduced logistic footprint [4, 5, 31, 51, 57, 58] (W)	For a given level of logistics capability (the spare space is likely to be taken up by other supplies/functions)		Reduced inventory holding costs [1, 6, 39]; reduced transportation costs (especially for urgent modes) [1, 5, 6], reduced cost of spares [1, 6]; reduced logistic footprint ownership costs [51]	Logistics planners, operational planners; supply personnel, maintenance personnel		1,5,6,7	+	M/L	I
O-3h	Increased availability of space/infrastructure for other logistic functions [1, 6]			Reduced transportation costs for logistics infrastructure [1, 5, 6]	Logistics planners, operational planners	Labour and space savings are significant enough to make a difference overall, not diluted by CBM system maintenance requirements	1,5,6,7	+	M/L	I

ID	Title	Description	Indicative $$$ COSTS	Indicative $$$ SAVINGS	Stakeholders	Assumptions	FIC	+ / -/?	(S)hort, (M)edium or (L)ong-term	(D)irect/ (I)ndirect
O-4	**Longer-term maintenance effects**									
O-4a	Reduced corrective maintenance requirements [6, 40]			Reduced corrective maintenance costs: repair, replacement, spare parts, labour [6, 40]; reduced reliance on urgent transportation of critical parts	Operators, maintenance personnel		3-6	+	M	D
O-4b	Reduced overall maintenance burden [5, 43, 46, 57] (W)			Reduced overall maintenance costs including labour, transportation, spare parts, test equipment [1, 5, 31, 32, 37, 47, 54, 55, 58, 60, 61]	Maintenance personnel, logistics planners	CBM results in an overall decrease in maintenance requirements rather than just a change in the type of maintenance	1,3-6	+	M/L	I
O-4c	Improved ability to plan maintenance [5, 6, 31, 37, 49, 56, 59, 60] (W)	Associated with ability to predict impending parts failure, conduct predictive maintenance [31], track components/major subsystems, analyse maintenance procedures [49], adjust inspection intervals [37]		Reduced reliance on urgent modes of transport for repair parts [6]; reduced losses due to equipment downtime [40]; efficiency gains in maintenance scheduling	Fleet managers, maintenance personnel, operational planners, logistics planners	CBM-generated information is utilised appropriately to plan and optimise maintenance	1-6	+	S/M/L	I
O-4d	Improved ability to distribute equipment/platform workload [59] (W)			Reduced fleet replacement costs via improved through-life management	Fleet managers, maintenance personnel	CBM-generated information is utilised appropriately to distribute equipment/platform workload	3,6	+	M/L	I
O-4e	Better targeted maintenance throughout equipment/platform life [1, 5, 6, 59] (W)			Reduced maintenance costs over equipment life [1, 5, 31, 32, 37, 47, 54, 55, 58, 60, 61]; reduced mid-life upgrade/deep maintenance costs [1]	Fleet managers, maintenance personnel, logistics planners	Appropriate changes are made to maintenance protocols	1,2,3,6	+	M/L	I
O-4f	Improved operation and maintenance of the fleet [1, 5, 38, 39, 58]		change management costs in implementing new processes and training; associated labour and administrative costs; cost of data collation and analysis	Reduced cost of fleet repair, maintenance and replacement; improved fuel economy through more efficiently operating equipment [3, 39]	Fleet managers, maintenance personnel	A concerted effort is made to capitalise on the CBM-generated information for improvement of fleet management processes	3,6	+	L	I
O-5	**Equipment/platform availability effects**									
O-5a	Reduced equipment/platform down time [1, 5, 38, 55]	Improved equipment/component reliability [55, 57, 60]		Reduced productivity losses due to maintenance [40]	Operators, maintenance personnel, operational planners, logistics planners	Effective spares pipeline/supply chain management [1]	1,3,4,6	+	S/M	I
O-5b	Increased Equipment Life [1, 6, 31, 53, 55, 60] (W)			Reduced cost of replacing equipment/platforms [1]; increased return on investment (ROI) [51]	Fleet managers, CDG, DMO		2,3,5,6	+	L	I

ID	Title	Description	Indicative $$$ COSTS	Indicative $$$ SAVINGS	Stakeholders	Assumptions	FIC	+ / -/?	(S)hort, (M)edium or (L)ong-term	(D)irect/ (I)ndirect
O-5c	Increase in operational availability of equipment/platforms [1, 4-6, 31, 32, 39, 46, 47, 50, 51, 54, 55, 57, 58, 60] (W)			Reduced cost of initial spares inventory [1]; reduced costs associated with operational failures [6, 60] (including recovery, repair, injury management, and operational delays)	Operators, maintenance personnel, operational planners, logistics planners		1-4,6	+	S/M	D/I
O-5d	Reduced fleet size requirement (W)			Reduced cost of procurement/replacing equipment/platforms [5, 6, 60]; savings on fuel, maintenance and spares; savings on inventory holding costs	Fleet managers, CDG, DMO, operational planners, strategic planners		1,2,3,5, 6,7	+	L	I
O-5c	Reduced operational failure rates of equipment/platforms [1, 6, 31, 55, 58, 61] (W)			Reduced costs of recovery, repair, replacement, personnel injury management, and indirect costs associated with operational set-backs	Operators, passengers, recovery personnel, maintenance personnel, operational planners, logistics planners		1,3,4,6	+	S/M	D
O-5d	Reduced recovery requirements [5, 6] (W)			Reduced recovery costs [6] and potential injury management costs; reduced indirect costs associated with recovery, e.g. delays	Operators, recovery personnel, maintenance personnel, logistics planners, operational planners		1,3,4,6	+	S/M	I
O-5e	Reduced catastrophic failure rates of equipment/platforms [1, 3, 5, 32, 40, 55, 59, 60] (W)	Associated with reduced impact of equipment failure [59] and reduced collateral damage [5, 60]		Reduced repair and replacement costs [6, 40]; reduced indirect costs of catastrophic failure (delays, etc.); reduced rebuild requirements during depot overhaul [1]; potential reductions in insurance costs [39, 53]	Operators, maintenance personnel, fleet managers		3,4,6	+	M	D
O-5f	Improved safety in operation of equipment/platforms [1, 6, 31, 32, 39, 41, 46, 53, 55, 57, 58, 61] (W)			Reduced injury management costs	Operators, passengers		3,4	+	M/L	I

ID	Title	Description	Indicative $$$ COSTS	Indicative $$$ SAVINGS	Stakeholders	Assumptions	FIC	+ / -/?	(S)hort, (M)edium or (L)ong-term	(D)irect/ (I)ndirect
O-6	**Human factor effects**									
O-6a	Increased confidence in the use of equipment/ platforms [6, 39, 40, 46, 53, 58-60] (W)	Includes increased confidence in use of equipment as well as confidence in use of equipment beyond the expected equipment life [60]		Reduced cost of replacing equipment beyond its expected service life but still in working condition [60]	Operators, passengers	Trust in CBM-generated equipment/platform health information	4	+	M/L	I
O-6b	Cultivation of culture of equipment ownership/ excellence [62]			Reduced costs associated with inadequate care and inappropriate use of equipment/platforms	Operators, maintenance personnel	Trust in CBM-generated equipment/platform health information	4,6	+	M/L	I
O-6c	Improved troop morale [6, 46, 62] (W)				Operators, passengers, maintenance personnel		4,6	+	M/L	I
O-6d	Improved operator performance [39, 46] (W)			Reduction in costs associated with inappropriate/inefficient equipment use	Operators		4	+	M/L	I
O-6e	Resistance to change [34]	Resistance to changes in associated maintenance and logistics processes [34]	Costs of delays in implementation of new technologies and processes; inefficient use of technologies		Operators, maintenance personnel, supply personnel, command and management		1,2,4,5,6	-	S	D
O-6f	Lack of immediately observable benefits from data collection [31]				Operators, maintenance personnel		4,6	-	S	D
O-6g	Reluctance to record and download relevant data by operators [31]		Loss of potential long-term efficiency gains		Operators, maintenance personnel		3,4,6	-	S	I
O-6h	Reduced accuracy of information underpinning decision-support [31]		Loss of expected efficiency gains with operational decision-support applications		Logistics planners, operational planners		1,4	-	S/M	I
O-7	**Data-transmission effects**									
O-7a	Significant increase in data transmission requirements (W)		Cost of ICT infrastructure and network/bandwidth management; cost of IT support		ADF organisation, IT/signals staff		1,2,3,6,7	-	S/M/L	D
O-7b	Increase in requirement for bandwidth/networks for transmission of bulk data (W)		Cost of ICT infrastructure and network/bandwidth management; cost of IT support		ADF organisation, IT/signals staff		1,2,3,6,7	-	S/M/L	D
O-7c	Increased ability of unauthorised external parties to access generated data [31]				Commercial organisations, enemy force, operational planners, IT/signals staff					

ID	Title	Description	Indicative $$$ COSTS	Indicative $$$ SAVINGS	Stakeholders	Assumptions	FIC	+ / -/?	(S)hort, (M)edium or (L)ong-term	(D)irect/ (I)ndirect
O-7d	Increased potential for compromise of operationally-significant information (W)	e.g. data downloads can alert external parties to location of vehicles [31]	potential costs of data security breaches and leaking of operationally important information		Commercial organisations, enemy force, operational planners, IT/signals staff					
O-7e	Increase in data security management requirements (W)	e.g. security issues around transmitting large bulk of data from the AO [31]	increased data protection costs		Operational planners, IT/signals staff		1,6	-	S/M/L	I
O-7f	Increase in IT support requirements (W)		IT support costs		Operational planners, IT/signals staff			-	S/M/L	D
O-8	**Data collection and analysis effects**									
O-8a	Increase in the quality and quantity of available equipment/ platform health and usage data [1, 5, 6, 33, 38, 49, 52, 56]	Includes system RUL and fleet LOT information (total fleet intelligence)	cost of data transmission, storage and processing [6, 40]; associated administration and labour costs; cost of ICT infrastructure and it's maintenance		Analysts, IT/signals staff, fleet managers, operational planners, logistics planners, CDG, DMO, DSTO	Data download and recording is not neglected by maintainers (e.g. due to inadequate implementation, over-sensitivity, and not using the data for real-time analysis with observable benefits) [31]	1-7	+	M/L	D
O-8b	Increase in data processing requirements [40, 45] (W)		including labour and administration costs, IT support costs, software acquisition and processing costs, cost of collecting and analysing data [40]		Analysts, DSTO, IT support staff		2,4,6	-	S/M/L	D
O-8c	Increased requirement for data analysis/data mining skills (W)		HR costs in recruiting and training relevant personnel; contracting and software licensing costs in outsourcing this function		Analysts, ADF organisation, commercial providers		2,4,6	?	S/M/L	D
O-8d	Improved monitoring of usage and usage trends [31, 49]	This is especially useful for military equipment with varying pattern of use [31]			Fleet managers, maintenance personnel		1-6	+	M	D
O-8e	Improved ability to estimate equipment/platform condition [5, 6, 31, 49]				Maintenance personnel, operational planners		1,3,6	+	M	D
O-8f	Improved ability to estimate overall condition of the fleet [31]				Fleet managers, operational planners, strategic planners, CDG, DMO		1,2,3,5, 6	+	M/L	D
O-8g	Improved monitoring of environmental pollution effects [60]	Monitoring of emissions such as gases (18)	Potentially costs of additional sensors and their integration; cost of collating and analysing information	Potentially reduced cost of compliance with environmental legislation [60]	ADF as a public entity, legislative bodies, data analysts, Australian public	Emission monitoring may become more prominent in future legislation [60]	2	+	M/L	D

ID	Title	Description	Indicative $$$ COSTS	Indicative $$$ SAVINGS	Stakeholders	Assumptions	FIC	+ / -/?	(S)hort, (M)edium or (L)ong-term	(D)irect/ (I)ndirect
O-8h	Improved data availability for incident investigation (W)	Physics of failure analysis [33]	Costs in setting up the legal framework for use of the data for this purpose	Potential reduction in costs associated with accidents including claim payouts	Operators, maintenance personnel, investigators, legal personnel, trainers	Processes are in place to deal with legal/HR management implications of the collected data (e.g. for cases of equipment misuse) [31]	2,4	+	M/L	I
O-8i	Improved operator training [31] (W)		cost of data collation and analysis; cost of amending training protocols	Potential reduction in costs associated with accidents, recovery, repairs and injury management	Operators, training personnel, policy-makers (ADF), analysts	A concerted effort is made to analyse and use collected accident/usage data to amend training protocls	1,2,4,8	+	L	I
O-8j	Improved data availability for engineering change proposals [31, 37, 49]		Data analysis costs, including labour and administrative costs	Efficiency gains in development of engineering change proposals	CDG, DMO, engineers		3	+	L	I
O-8k	Improved diagnostic and prognostic capability [2, 37, 46, 52] (W)	associated with development of new algorithms for diagnostics, prognostics and decision-support	Cost of research, trials, documentation, including associated labour, administration and travel costs [39]; data collation and analysis costs; cost of maintaining relevant ICT infrastructure; cost of licensing relevant business analytics software	Flow-through of cost savings associated with more efficient maintenance and increased equipment life	Analysts, DSTO, commercial organisations, research and academic organisations	Funding and contractual arrangements are in place for long-term research	2,3,6	+	L	I
O-8l	Improved knowledge base for decision support for future capability acquisitions [37, 59] (W)	Facilitates improvements in construction of FPS/RFT documents	Research and documentation costs [39]; administrative, labour and travel costs [39]; data collation and analysis costs		DSTO, CDG, DMO, analysts, commercial providers	A concerted effort is made to analyse information and incorporate findings into capability acquisition process	1,2,3	+	L	I
O-8m	Improved data analysis/data mining techniques [31, 49]		Cost of data collation and analysis; cost of research and documentation [39]; cost of relevant ICT infrastructure; cost of software licensing	Efficiency gains in equipment maintenance and usage with more accurate algorithms	DSTO, analysts, research and academic organisations	Funding and contractual arrangements are in place for long-term research	2,3,6	+	L	I
O-8n	Greater availability of terrain and environmental data [33]		Cost of data collation and analysis; cost of research and documentation [39]; cost of relevant ICT infrastructure; cost of software licensing	Efficiency gains in equipment maintenance and usage with more accurate algorithms	DSTO, analysts, operators, maintenance personnel		3,4,6,8	+	L	I
O-9	**Effects of integration with other technologies**									
O-9a	GPS: Improved visibility of fleet position [1, 5, 6, 49]		cost of maintaining networks and infrastructure, including IT support; technology integration costs	efficiency gains in asset utilisation	Operational planners, logistic planners	Integration of GPS tracking technology with CBM and C2 systems	1,3	+	S/M	D

ID	Title	Description	Indicative $$$ COSTS	Indicative $$$ SAVINGS	Stakeholders	Assumptions	FIC	+ / -/?	(S)hort, (M)edium or (L)ong-term	(D)irect/ (I)ndirect
O-10	**Effects on maintenance skill base**									
O-10a	Reduced maintenance training requirements [6, 55, 56] (W)			Reduced cost of training and maintaining qualification	Operators, maintenance personnel		2,4,6,7, 8	+	M/L	I
O-10b	Reduction in traditional diagnostic and maintenance skills (W)	Associated with increase in complexity of technology in general	Cost of outsourcing repairs; cost of replacement modules	Reduced costs of training and maintaining a range of qualifications	Operators, maintenance personnel	Significant decrease in requirement for traditional diagnostic and maintenance skills	2,4,6,8	?	M/L	I
O-11	**Impact on mission effectiveness**									
O-11a	Improved situational awareness in terms of equipment/platform status [47, 50, 52, 55, 63]		Cost of integration of CBM-generated information with C2 systems	Reduced labour and administrative costs involved in manual collection and collation of required information	Operational planners, logistics planners	Relevant, effective and accurate information is available to facilitate situational awareness [31]	1,3	+	S/M	I
O-11b	Improved decision support for mission assignment of equipment/platforms [1, 5, 6, 31, 39, 44, 50, 52, 57, 58] (W)		Cost of integration of CBM-generated information with C2 systems; cost of specific decision-support modules	Potentially reduced overall operational costs; avoidance of operational failure costs [61]	Operational planners, logistics planners	CBM-generated equipment health information is utilised within mission planning processes; Relevant, effective and accurate information is available to support the decision-making process [31]	1,3	+	S/M	I
O-11c	Improved mission effectiveness [5, 6, 39, 44, 46, 51, 52, 58]			Reduced costs associated with mission failures (e.g. delays, recovery, injury management); more efficient use of resources	operational planners, operators, ADF organisation		1-7	+	M/L	I

Appendix D. Contextual Factors for CBM in the Military Land Domain

Contextual factors can be considered in terms of four broad categories, as outlined in Table 21. The technological environment looks at the current and emerging set of technologies and overall trends with which CBM would need to interface. The military strategic environment refers to the set of normative guidelines determined by the strategic guidance, specific policies, budgetary constraints, and capability acquisition processes. Socio-cultural factors consider characteristics of users at local, intermediate and high levels, their normative beliefs and requirements, prior practices, culture and norms. Finally, the physical environment encompasses the range of physical settings for technology use.

Table 21: Contextual factors in technology impacts assessments

Type of context	Contextual factor
Technological environment	Different rates in development of computer/sensor vs platform/equipment technologies and associated obsolescence rates
	Advances in prognostic technologies (embedded diagnostics, distributed architectures, etc.) and lower hardware costs (sensors, computing, interfacing) [6] together with rapid development of computer and advanced sensor technologies, and data acquisition facilities [31, 37]
	Modularisation of vehicles and equipment with associated outsourcing of support to OEMs and shift from repair to replacement maintenance
	Global nature of science and technology, which affects availability and sustainability of IP, knowledge, skill and manufacturing base in times of competing interests [28]
	Existing Defence ICT infrastructure including operational bandwidth availability [31]
	Focus on data ownership by the OEMs [31]
	Security and sensitivity of information [28]
	Expectation of enemy initiatives to counter technological advances [63]
Military strategic environment	Requirement for Land force with a joint, expeditionary capability that can act independently or as part of a coalition force [63]
	Desire of allied nations to integrate military capabilities into joint, combined and network-enabled force structures [21, 63]
	Nature of operations, ranging from combat and sustainment operations to short-notice missions, to tailored missions, support to civil efforts, counter-terrorism support, security support for major events, assistance with CBRN defence, emergency/HA and disaster relief assistance [63]
	Length of capability procurement cycle and associated legacy systems [28, 63]
	Cost of capability in the context of Defence budget [28]
	Use of measures of effectiveness (MOEs) relating to impacts on campaigns and policy-level MOEs [21]
	Difficulty in measuring complex effects produced by military action [21]
Sociocultural military environment	Perceptions of new technologies by operators
	High level of public scrutiny and associated requirement for transparency and adherence to ethical values [63]
	Strongly hierarchical nature of Defence organisations [10]
	Extensive use of doctrine and training support for introduction of capabilities [10]
	Psychological parameters associated with military operations: operational tempo, level of threat, users' cognitive state

Physical environment	Direct physical parameters for use of technology on operations (temperature, humidity, noise, vibrations, dust, dirt, impact) affect requirements for reliability, safety, availability and maintainability [32]
	Equipment usage profiles and differences in use between in-barracks environment and during operations: based on US experience, operational equipment usage rates are up to nine times higher that peacetimes rates [6]; short periods of intensive and potentially unpredictable activity may affect maintenance and usage profiles [31]
	Length of deployments and length of deployment notice [63]
	Requirement for flexibility (configurability of force), agility, resilience, responsiveness, and robustness of force and supporting technologies [63]

Appendix E. Potential Stakeholders for CBM in the Military Land Domain

Analysis detailed in the interim study report [7] suggests the following stakeholder groupings with specific examples from an Australian Defence context detailed in

Table 22: Potential CBM Stakeholders in the Military Land Domain

Stakeholder Group	Examples
End-users	Equipment and platform operators, crew, passengers
Maintenance personnel	Maintainers, maintenance planners, recovery personnel, workshop manages, equipment/maintenance SMEs, OEMs, Defence contractors
Support personnel	IT/signals personnel, logistics personnel, data analysts, trainers
Planning and management personnel	Fleet managers (DMO through System Program Offices (SPOs), Forces Command (FORCOMD), OEMs, Defence contractors); Operational planners, strategic planners; ICT managers
Materiel suppliers	OEMs, Defence contractors
Capability development and acquisition organisation	CDG, DMO, DSTO, OEMs
Research and academic organisations	DSTO, universities
Security organisations	Defence organisations (Australian Signals Directorate (ASD), Defence Intelligence Organisation (DIO)), external organisations (OEMs, Defence contractors)
Legal organisations	ADF and civilian legal personnel, accident/incident investigators, external legislative bodies
Policy-makers	ADF policy makers (e.g. Army Headquarters (AHQ))
Potential adversaries	Enemy forces, external commercial organisations
Other	Australian public, ADF as a public entity

Appendix F. Re-evaluation of Impact Significance Following Second Round of SME Surveys

F.1. Re-evaluation of the Most Significant Capability Input Impacts

Of the seven survey respondents, five suggested only minor revisions to the list of the most important input impacts, as summarised in Table 23.

Table 23: Suggested minor revisions to the list of the most significant Capability Input impacts

ID	Capability Input Impact	Suggested Changes
2f	Inclusion of CBM requirements into acquisition of relevant equipment/platforms	Moving this impact up the list (various placements suggested, including that of the most significant impact)
7b	Integration of HUMS/CBM hardware, software and platforms	Move up to be the second-most important impact
5h	Development of algorithms for prognostic and diagnostic functions	Move down below impact 2f
4a	Acquisition of HUMS/CBM hardware and software	Move down to be the least important impact
5d	Bridging the 'air gap' between equipment/platforms and data processing systems	Add to list of most important impacts
3g	Rollout scheduling and implementation	Add to list of most important impacts
New#1	Configuration management	Add to list of most important impacts
New#2	Design of CBM hardware and software	Add to list of most important impacts
New#3	Good systems engineering practices/processes to cover all aspects of the CBM life-cycle	Add to list of most important impacts

The two remaining respondents proposed substantial revisions to the list of the most important input impacts. The first suggestion is summarised below (underlined text indicates modifications to the existing input impacts):

- New #4. Identification of common failures/incidents (from past fleet usage or maintenance records) that result in vehicle breakdown or mission failure and that can be addressed by monitoring systems;
- 5h. Development or selection of algorithms (prognostic and diagnostic) that can effectively monitor the identified failure modes;
- 2f. Inclusion of CBM requirements that were derived from the identified failure modes into acquisition of relevant equipment/platforms;
- 4a. Acquisition of HUMS/CBM hardware and software;
- 7b. Integration of HUMS/CBM hardware, software and platforms;
- Remove 4b. Design of HUMS/CBM hardware and software maintenance;
- New #5. Perform Independent Verification and Validation (IV&V) procedures to the integrated HUMS/CBM systems to ensure the compliance of these systems;
- 5g. Data mining, analysis and use for decision-support;

- 3a. Development of new maintenance and logistics processes; and
- 6. Training and personnel certification.

The focus of the recommended additions is the evidence-based development of sensible HUMS/CBM solutions. The rationale for removal of 4b from this list was given thusly:

> *It's unlikely that Defence will develop and build its own HUMS/CBM systems for its own vehicle fleet. The HUMS/CBM systems (hardware and software) will be sourced from a HUMS/CBM OEM. The procedure or requirement for maintenance will be designed or given by the OEM.*

The second suggestion for a new prioritised list of the most important input impacts was as follows:

- Add 1. Leadership at high level and local level.
- 3a. Development of new logistics and maintenance structures and processes including documentation of SOPs, TTPs, etc.;
- 2g. Development of CBM requirements;
- New #6. Design of requirements and specifications for hardware and software;
- 2f. Inclusion of CBM requirements into acquisition of the relevant equipment/platforms;
- 4a. Acquisition of HUMS/CBM hardware and software;
- 6. Training and personnel certification;
- 7b. Integration of HUMS/CBM hardware, software and platforms;
- 5g. Data mining, analysis and use for decision-support; and
- Add 2a. Tracking of technology developments.

The rationale behind adding input impact 1 was:

> *Leadership should be highly ranked as it is critical … once the Generals are on-side then everything else becomes easier.*

Input impacts 4b and 5h were not mentioned by this respondent.

F.2. Re-evaluation of the Least Significant Capability Input Impacts

Review of the least cited capability input impacts by the second-round survey respondents resulted in the removal of six impacts from that list. It can be speculated that the deliberate lack of guidance in the first survey meant that some impacts simply didn't come to the participants' attention before the second round of SME surveys.

Input impacts 2c (allocation of ownership and management responsibility) and 2e (allocation of funding for CBM capability) were flagged as important by two respondents. It was suggested that the issue of ownership was critical during the acquisition phase, as it cut across many functional areas. Further:

> *…in practice the ownership of the CBM capability is a source of tension during acquisition and can make or break the final capability. A strong champion for the CBM capability is often required to persistently tackle these issues.*

On the issue of funding, survey responses included:

> *Allocation of Funding is the key to this whole process.*

And

> *…as the platform's project faces cost cuts, a natural focus on protecting platform numbers may see CBM functionality axed for a cheaper acquisition cost, without appropriate importance attributed to through life support costs or operational availability.*

These responses illustrate the perceived importance of funding, providing solid justification for removal of input impacts 2c and 2e from the list of least critical input impacts.

Two respondents also suggested that impact 2d (assessment of CBM solutions early in the design stage) was important for specifying needs and functional/physical performance requirements, and as part of a pilot process for justifying further expense.

In a near-universal response, five of the seven respondents indicated that impact 2h (development of a business case) was very significant. One respondent summed up the responses of many by stating the following:

> *Introducing HUMS/CBM to the military platform usually faces enormous resistance from the operator, maintainer, and owner. From the operator point of view the common reason is worrying being spied with the monitoring systems onboard. The maintainers generally hate it because* [of] *the fear of extra work burden and "it's not how we normally do it (fear of learning new things)". For the owner* [it] *is usually the capital investment for the HUMS/CBM and extra money they need to pay for the implementation. As Defence works in a hierarchy structure, what we found … is once top of the chain of the command can be convinced to embrace HUMS/CBM you don't have to worry about the rest of the people. Therefore, the success of HUMS/CBM implementation generally relies on whether you can sell your business case to the top of the command.*

Respondents further suggested that impact 2h ties in closely with 2g (development of CBM requirements) and 3c (promotion of benefits):

The CBM capability is the first one to get removed when funding becomes tight during acquisition. CBM can often be seen as having high technology risk and dubious benefit – it is therefore an easy target for reduction in scope or removal.

One respondent provided an argument for the importance of input impact 3b (allocation of resources for implementation and facility upgrades) by suggesting that in the past, the Services have escaped full costing for facilities implications for some projects. The participant noted that although the situation has improved, without funding for facilities CBM would be 'confined/denuded'.

Five of the seven respondents also suggested that impact 5a (data architecture and standards) is important as it is a key enabler for data management over the full system life cycle. Furthermore, it is critical for information exchange and integration and would drive logistic information systems, bandwidth requirements and uniformity across fleets.

Further, a respondent pointed out that:

… standards based designs are really important to ensure the longevity and extensibility of these CBM systems into the future (especially in the embedded systems integrated with the vehicle).

No comments were made on the remaining impacts on this list.

F.3. Re-evaluation of the Previously Unreported Input Impacts

Analysis of literature survey and first-round SME survey results identified seven capability input impacts that were only mentioned within internal DSTO workshops. Second-round SME survey participants were asked to review these impacts, with the results presented in histogram form in Figure 9.

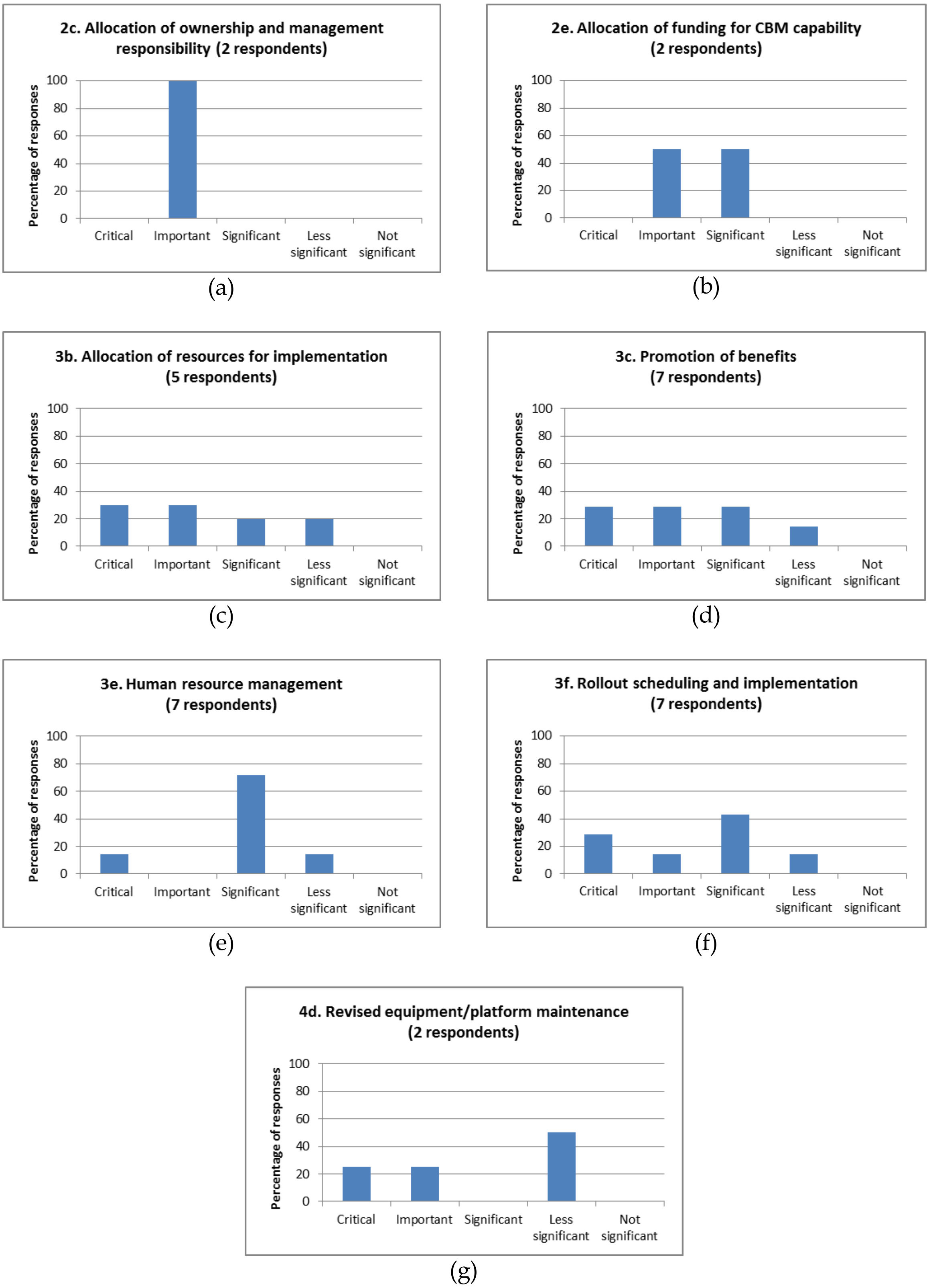


Figure 9: Survey Responses to the Question of Importance of Previously Unmentioned Impacts

Figure 9(a) shows that all corresponding respondents believe input impact 2c (allocation of ownership and management responsibility) to be important, hence the opinions of respondents are convergent. Likewise, Figure 9(b) illustrates that opinions on input impact 2e (allocation of finding for CBM capability) are either important or significant, demonstrating a high level of convergence.

Input impact 3b (allocation of resources for implementation) depicted in Figure 9(c) shows a divergence of opinions. It is useful to examine the reasoning given by participants in choosing these particular ratings. Taking the extremes of opinion, the participant who believed that allocation of resources for implementation was 'critical' gave the following reasoning:

> *Without adequate financial and personnel resources* [CBM] *will not get off the ground or be firmly taken up by maintenance personnel.*

At the other extreme, the reasoning given for believing this input impact to be 'less critical' was:

> *If the commander in charge of the vehicle type is convinced of CBM the resource for implementation shouldn't be a problem. Especially if return of benefits due to HUMS/CBM implementation can be clearly shown, funding allocation will be even less of a worry.*

These two views are not in conflict. The former opinion states that getting resources for implementation of CBM is critical. The latter suggests that getting these resources should not be difficult if personnel in positions of influence are convinced of the need for CBM.

Impact 3c (promotion of benefits) depicted in Figure 9(d) presented another cause for divergence of opinions. Despite differences in rankings, however, there was a general consensus on the significance of key personnel understanding the benefits of CBM:

> *Without strategic capability decision makers understanding the benefits, and valuing them above other opportunities for capability enhancement, CBM doesn't get out of the start-gates.*

And:

> *All new practises require promotion so people see the benefits, and are not under belief* [that this] *will mean either extra work OR that they may no longer be important to the maintenance process.*

Furthermore:

> *… benefits do need to be promoted more, rather than relying on people to accept it themselves. There needs to be justifiable benefits to promote – particularly to cynics and bean-counters to justify the up-front cost that may not produce a Return on Investment for many years.*

Figure 9(e) depicts responses to the question of the importance of input impact 3e (human resource management). The majority of responses indicate a belief that this is 'significant'. Notably, one response flagged it as 'critical' and with the following argument:

> *Critical when it comes to transition, retraining, redeployment of personnel. There needs to be some input of the people themselves into their own destinies. An example of an issue that may need to be resolved is if the introduction of CBM means that there is more work with OEMs and contractors and less work for RAEME people.*

This opinion reflects the general sensitivities around the potential reduction in personnel numbers. One comment explaining the rating of 'less significant' indicates that mechanisms for human resource management issues are already in place.

The issue of rollout scheduling and implementation (impact 3f, Figure 9(f)) again shows a spread of opinion. Those that believe this input impact to be critical stated:

> *This can affect the morale of both believers and critics, and relates to how you phase your funding etc.*

And

> *The ability to deliver against the potential benefits will be closely linked to the schedule and implementation. SDSS and MILIS have had varying degrees of success at rollout which has impacted the long term perception of their utility.*

One respondent believed this to be a less critical issue, indicating that rollout and implementation could be done in conjunction with the existing maintenance cycles if it is:

> *…brought into regions during RESET or Low Tempo periods, giving people the time to learn and value the process.*

This is noteworthy, as the implication is a belief that it should be relatively easy to rollout CBM with a minimum of disruption to existing activities and processes.

Impact 4d (revised equipment/platform maintenance, Figure 9(g)) resulted in polarisation of opinion, with one respondent considering this to be somewhere between critical and important, and the other ranking it as 'less significant'. The former respondent stated:

> *To some degree it is understood that this is something that will have to happen. It is important though to have an understanding of why the changes are needed, what the value is in these changes, particularly for the people affected. For example, a fixed interval maintenance paradigm makes allocation of assets and staff easier, so planning may be easier (predictability, or at least enough advance warning), and hence there may be a push to keep things how they are. It is important to consider the stakeholders that will be involved in the revised processes. People may need to "let go" of old procedures.*

The latter respondent gave no reason for the opinion that this impact is 'less significant'.

F.4. Additional Comments on Capability Input Impacts

In addition to the numerous suggestions on refining the impacts map, three particularly insightful comments relating past experiences in the Air domain were received from the respondents. These comments listed below provide a glimpse at some of the practical issues that the military Land domain may face when implementing CBM.

On the CBM technology life-cycle:

> *CBM technology life-cycles are predicted to be very short. New technologies appear and existing technologies are updated. This includes both hardware (e.g.: new or improved sensors) and software (new thresholds, better fault isolation algorithms etc…). CBM relies on feedback from data on failures and accompanying usage/maintenance context to mature – therefore there needs to be a plan to resource and enable continuous improvements efforts.* [Figure 10] *highlights the short life-cycle of CBM technologies compared to others on a typical Defence system. CBM systems and components may therefore be subject to obsolescence and support issues over their life-cycle.*

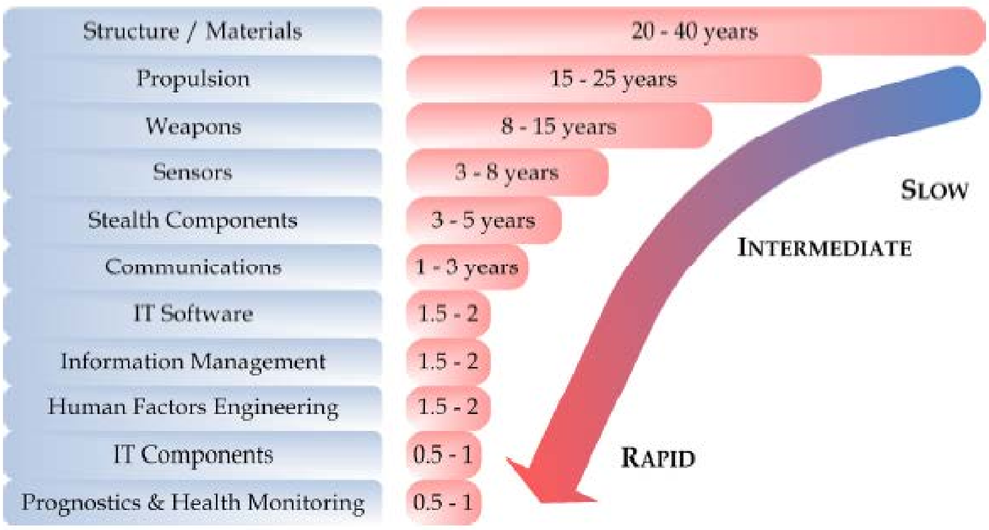


Figure 10: Comparative life-cycle length of components of a typical Defence system (reproduced from [64])

On data ownership:

HUMS/CBM data ownership and management should be clearly defined during the contract negotiation with the HUMS/CBM OEM or if the vehicle type comes with integrated HUMS/CBM then the negotiation should be with the vehicle OEM. From past experience in the Air domain, ambiguous ownership of HUMS/CBM data usually resulted in contract dispute and legal challenges with the OEM. Defence is usually on the losing side due to operational urgencies. Unclear data management responsibility generally cost Defence more money when requesting OEM to perform jobs that are not clearly stated in the contract. Defence should always retain the ownership of the HUMS/CBM data, which is essential during any accident/incident investigations where there is a dispute with OEM.

On data management strategy:

This strategy needs to consider short, medium and long–term use of data. Each of these has separate uses and may apply at different times during the system life-cycle. For example, structural CBM on aircraft may become critically useful after 15 years of use as fatigue and corrosion issues start to arise. Other types of failure data may have more short and medium-term use. The need to effectively archive CBM data needs to be addressed. The restrictions enforced by 'proprietary' data formats and access to all the data that is generated by the CBM system needs to be considered and agreed during early acquisition. This can also be impacted by 'proprietary' data architectures which can limit the choice of solutions that comprises the final CBM capability.

These additional insights were incorporated into the finalised CBM impacts map.

F.5. Re-evaluation of the Most Significant Capability Output Impacts

On review of the most important capability output impacts, three respondents agreed with the list and the broad ordering within it. Suggestions by other respondents included the changes summarised in Table 24.

Table 24: Suggested revisions to the list of the most significant capability output impacts

ID	Capability Output Impact	Suggested Changes
9a	Improved ability to plan maintenance	Move up to potentially the most important impact
6j	Improved ability to estimate equipment/platform condition	Move up in ranking of significance to sit between 12b and 8b
9e	Reduced overall maintenance burden	Move up in ranking of significance to sit between 12b and 8b
11f	Increased confidence in the use of equipment/platforms	Move up in ranking of significance to sit between 12b and 8b
6c	Increase in the quality and quantity of available equipment/platform health and usage data	Move up in ranking of significance
1c	Automated generation of real-time equipment/platform health information	Move up in ranking of significance
1a	Diagnostics	Move up in ranking of significance
11f	Increased confidence in the use of equipment/platforms	Move up in ranking of significance
10f	Increase in operational availability and	Move down in ranking of significance

	capability of equipment/platforms	
8b	More efficient and responsive supply processes	Move down in ranking of significance
8g	Change to proactive, CBM-driven supply processes	Move down in ranking of significance
9j	Improved utilisation of tradespeople, particularly for preventive maintenance	Add to the list of most significant impacts
8o	Management of CBM components within the supply chain	Add to the list of most significant impacts
11e	Cultivation of culture of equipment ownership/excellence	Add to the list of most significant impacts
1b	Prognostics	Add to the list of most significant impacts
8h	Reduced logistic footprint	Add to the list of most significant impacts

There was a suggestion to add an impact on the increase in Space, Weight and Power (SWaP) demands placed on the vehicle due to integration of HUMS/CBM. This suggestion relates closely to the input impact 2f (inclusion of CBM requirements into acquisition of relevant equipment/platforms) than to any output impact. Although an increase in SWaP demands will be an outcome, this should be considered when considering the acquisition of relevant equipment/platforms. Consequently, a comment was added to the input impact 2f to emphasise the need to consider SWaP demands during the requirements/acquisition phases.

No suggestions were made to remove any capability output impacts from this list.

F.6. Re-evaluation of the Least Significant Capability Output Impacts

On review of the least cited output impacts list, a number of justifications were offered for allocation of greater significance to some impacts and therefore their removal from the 'least important' list.

One respondent suggested removal of the following three output impacts:

- 9j. Improved utilisation of tradespeople, particularly for preventive maintenance
- 8o. Management of CBM components within the supply chain
- 11e. Cultivation of culture of equipment ownership/excellence.

The removal of 11e was also supported by another respondent, who suggested that:

> *Perhaps as a result of "Big Brother" watching, people will take more care with their equipment. There is anecdotal evidence to support this, at least.*

Two respondents recommended the removal of 2b (tracking of position, status and load of vehicles, critical stores and drivers), citing that this impact is critical to mission and maintenance planning, and without it, many other impacts would not be realised.

Two respondents also suggested the removal of 6e (improved data availability for accident/incident investigation) as the availability of such data would be critical, especially if fatality was involved. Further, such data could be useful for improving operator training.

Although not directly related to CBM, output impact 6i (greater availability of terrain and environmental data) was flagged as important with the following reason given:

> *With the war in Afghanistan many commanders from both US and UK had indicated that in many incidences their troops travelling in armoured vehicles became combat ineffective after arriving in combat theatre, due to the rough terrain and the environment (temperature related). Many of them stressed that terrain and environment data would have been very helpful during troop training, route planning, and vehicle design. Ineffective combat troops equals mission failure, therefore greater availability of terrain and environmental data should be an important output impact for HUMS/CBM.*

Output impacts 7c (increased ability of unauthorised external parties to access generated data) and 7f (increase in data security management requirements) were also identified as important issues to be managed, especially for tactical operations vehicles, surveillance vehicles, and A-vehicle fleets in general.

No suggestions were given for output impacts to be added to this list.

F.7. Additional Comments on Output Impacts

In addition to numerous suggestions made on refining the output impacts map, a number of insightful comments on specific output impacts were provided.

On reduction in accuracy of information underpinning decision-support (due to reluctance to use CBM from operators):

> *I disagree with this one. Supposedly, the IT system has the intrinsic value of being more accurate, or at least being more consistent, whereas human paper-based handrolic processes will always be more variable – these can't really be standardised in the same way as an automated electronic IT system, as there will always be a degree of human interpretation involved. So, the accuracy would actually probably be better, even without full-blown automation, or complete uptake by everyone.*

On experiences from the Air domain related to the effects on the overall maintenance burden:

> *In the air domain there were cases where inclusion of HUMS actually significantly increased the maintenance burden, but at the same time drastically reduced the mission abort rate for the platform. In other words, the increase in maintenance actually made the platform more reliable, and this situation could also happen to the land based vehicle. In some circumstances HUMS/CBM implementation will increase the maintenance burden and actually not generate any benefits. This is why it is very important in the early stage of HUMS/CBM consideration to identify problems or*

incidents where monitoring systems can actually resolve these issues. Accordingly, this becomes the business case for the utilisation of the HUMS/CBM.

Appendix G. Second Round Interim Impacts Map

G.1. Capability Inputs Portion of the Second Round Impacts Map

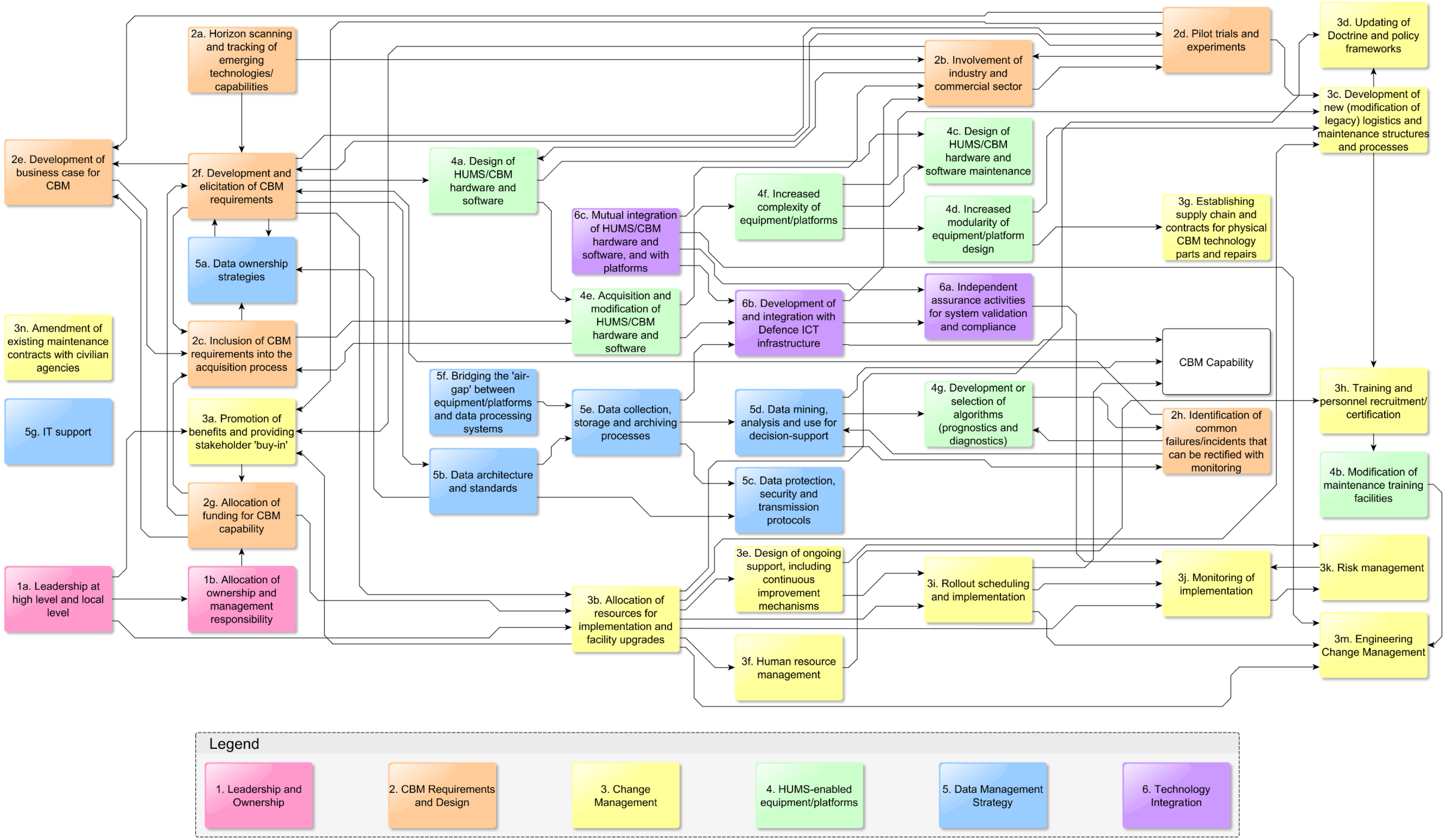


Figure 11: Capability input portion of the second round impacts map

G.2. Capability Outputs Portion of the Second Round Impacts Map

Figure 12: Capability output portion of the second round impacts map

Appendix H. Graph Analysis of the Second-Round Interim Impacts Map

Java code was written to perform graph analysis on the input and output impacts maps. The details of the Java code used for this and the finalised map analysis are provided in Appendix J.

H.1. Capability Input Impacts

H.1.1 Immediate and High-Level Capability Input Impacts

The input impacts map can be considered a directed graph with 41 nodes and 82 edges (causal links). The impacts linking directly to 'CBM Capability' represent immediate input impacts. There are three such impacts, highlighted in pink in Figure 13:

- 3i. Rollout scheduling and implementation
- 5d. Data mining, analysis and use for decision-support
- 6b. Development of and integration with Defence ICT infrastructure.

An internal DSTO workshop assessed these impacts to be reasonable (although not necessarily complete) set of immediate impacts.

Likewise, it was logically assumed that input impacts without predecessors represented high-level input impacts, highlighted in blue in Figure 13:

- 1a. Leadership at high level and local level
- 2a. Horizon scanning and tracking of emerging technologies/capabilities
- 5f. Bridging the 'air-gap' between equipment/platforms and data processing systems
- 6c. Mutual integration of HUMS/CBM hardware and software, and with platforms.

During an internal DSTO workshop 1a and 2a were assessed as reasonable high-level impacts, but 5f and 6c were determined to be intermediate nodes. It was further suggested that input impacts 1b (allocation of ownership and management responsibility) and 3a (promotion of benefits and providing stakeholder 'buy-in') were also high-level input impacts.

During workshop discussions, it was determined that some causal relationships were likely to be missing from the impacts map, due to two reasons:

- Complexity and size of the map make a detailed examination and critique by participants more difficult

- It is generally harder to think about what is required to implement a capability than it is to think about what that capability will do, as the former involves working backwards through causal relationships.

Consequently, workshop participants suggested additional causal relationships involving input impacts 5f and 6c.

H.1.2 Isolated Capability Input Impacts

There were two isolated input impacts without causal links, highlighted in orange in Figure 13:

- 3n. Amendment of existing maintenance contracts with civilian agencies
- 5g. IT support.

Relevance of these impacts was reviewed during the workshop and causal relationships were allocated to rectify the above situation.

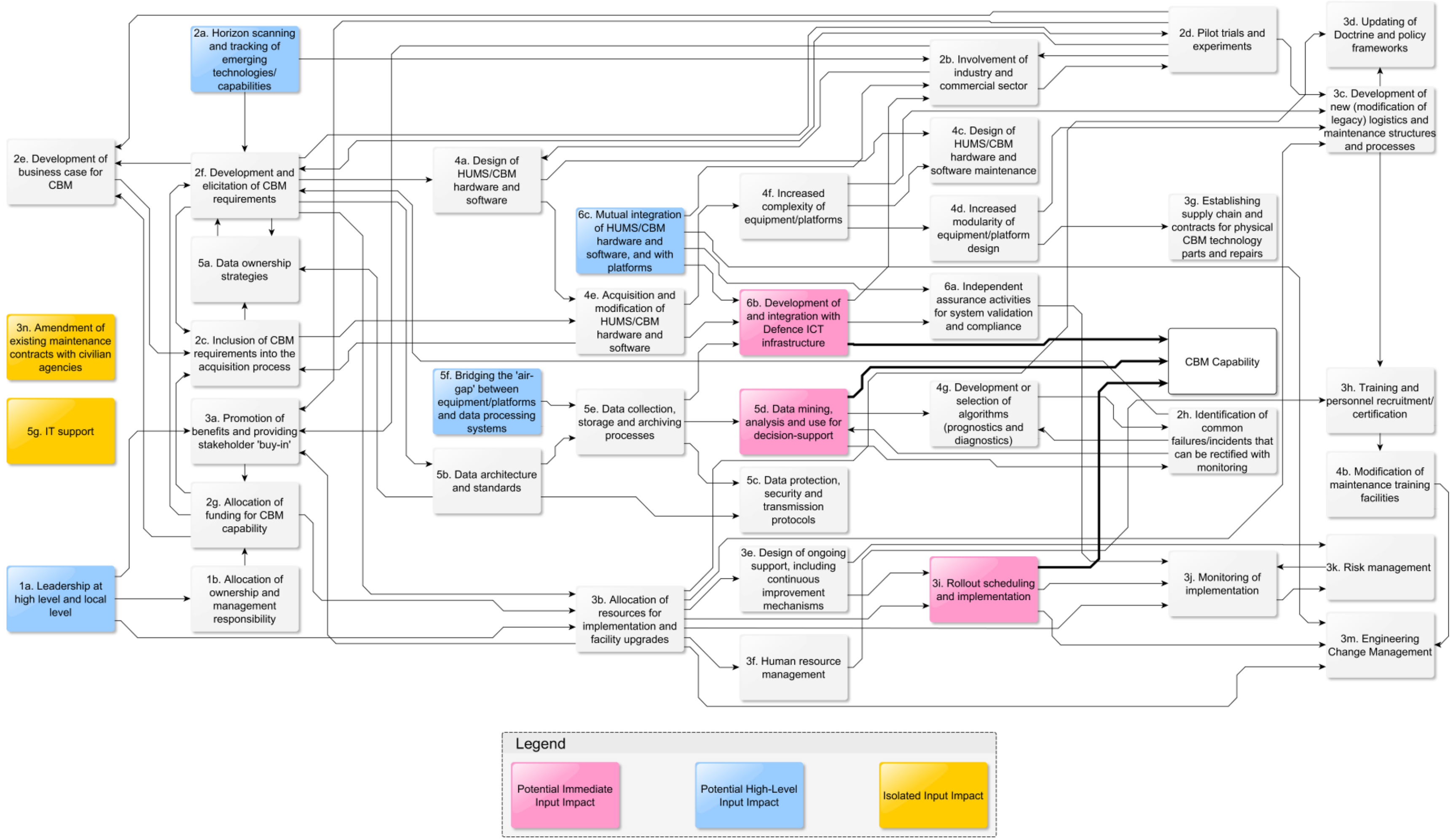


Figure 13: Potential immediate (pink), high-level (blue) and isolated (orange) capability input impacts from the second round impacts map graph structure

H.1.3 Causally-Disconnected Capability Input Impacts

In examining the structure of the graph, it became evident that a number of nodes could not reach the 'CBM Capability' node via the existing causal links:

- 3d. Updating of doctrine and policy frameworks
- 3g. Establishment of supply chain and contracts for physical CBM technology parts and repairs
- 3m. Engineering change management
- 3n. Amendment of existing maintenance contracts with civilian agencies
- 4c. Design of HUMS/CBM hardware and software maintenance
- 5c. Data protection, security and transmission protocols
- 5g. IT support.

Similarly, the predecessors to the above nodes also could not reach the 'CBM Capability' node:

- 3c. Development of new (and modification of legacy) logistics and maintenance structures and processes
- 3f. Human resource management
- 3h. Training and personnel recruitment/certification
- 3j. Monitoring of implementation
- 3k. Risk management
- 4b. Modification of maintenance training facilities
- 4d. Increased modularity of equipment/platform design
- 4f. Increased complexity of equipment/platforms
- 6a. Independent assurance activities for system validation and compliance.

These 16 input impacts constitute 39% of the input impacts, and are highlighted in orange in Figure 14. Similarly to the treatment of the isolated impacts above, workshop participants reviewed the relevance of these impacts and suggested additional causal links.

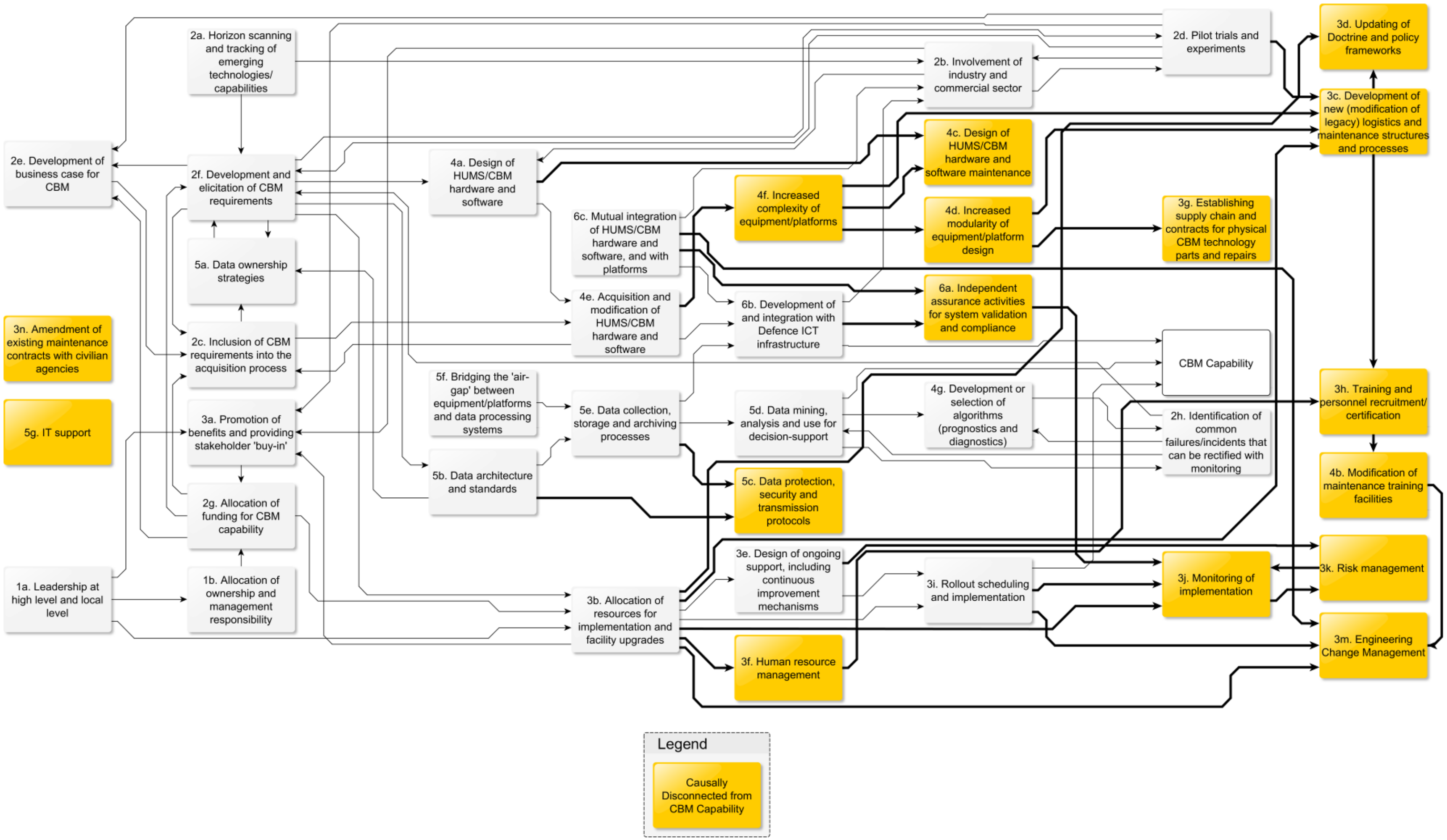


Figure 14: Input impacts that are causally disconnected from the 'CBM Capability' node in the second round impacts map

H.1.4 Capability Input Impact Cycles

Having a directed graph representation allowed identification of cycles within the causal relationships. To do this, custom-written Java code was used to derive the *Strongly Connected Components (SCCs)*, - subsets of impacts that are mutually reachable. In an acyclic graph each node comprises a SCC in its own right (or in other words, each SCC comprises a single node and the number of nodes equals the number of SCCs). Such an SCC is called a *trivial* SCC. When cycles exist, one or more SCCs will be *non-trivial* with more than one node.

The capability input impacts map contains two such sets of impacts, highlighted in green and red in Figure 15. These sets comprise impacts that are mutually causally linked, indicating cyclic behaviour in the realisation/manifestation of the corresponding input impacts.

The first set (green) comprises 17 (or over 41%) of the input impacts:

- 2b. Involvement of industry and commercial sector
- 2c. Inclusion of CBM requirements into acquisition of relevant equipment/ platforms
- 2d. Pilot trials and experiments
- 2e. Development of business case for CBM
- 2f. Development and elicitation of CBM requirements
- 2g. Allocation of funding for CBM capability
- 2h. Identification of common failures/incidents that can be rectified with monitoring
- 3a. Promotion of benefits and providing stakeholder 'buy-in'
- 3b. Allocation of resources for implementation and facility upgrades
- 4a. Design of HUMS/CBM hardware and software
- 4e. Acquisition and modification of HUMS/CBM hardware and software
- 4g. Development or selection of algorithms (prognostics and diagnostics)
- 5a. Data ownership strategies;
- 5b. Data architecture and standards
- 5d. Data mining, analysis and use for decision-support
- 5e. Data collection, storage and archiving processes
- 6b. Development of and integration with Defence ICT infrastructure.

This set corresponds to a *non-terminal* SCC, meaning that although there are cycles in the causal relationships between these impacts, there is always the possibility to move on from this set to impacts outside of this set. It is reasonable that such cyclic behaviour exists, as it indicates the presence of feedback loops and iteration in development and implementation of CBM in the military Land domain.

The second set (red) comprises two input impacts:

- 3j. Monitoring of implementation
- 3k. Risk management.

This set corresponds to a *terminal* SCC, meaning that this cycle, once entered, can never be broken. This is undesirable, as it means that neither of these two input impacts contribute to the establishment of a CBM capability. The workshop participants assessed that this was not the case and additional causal relationships were assigned.

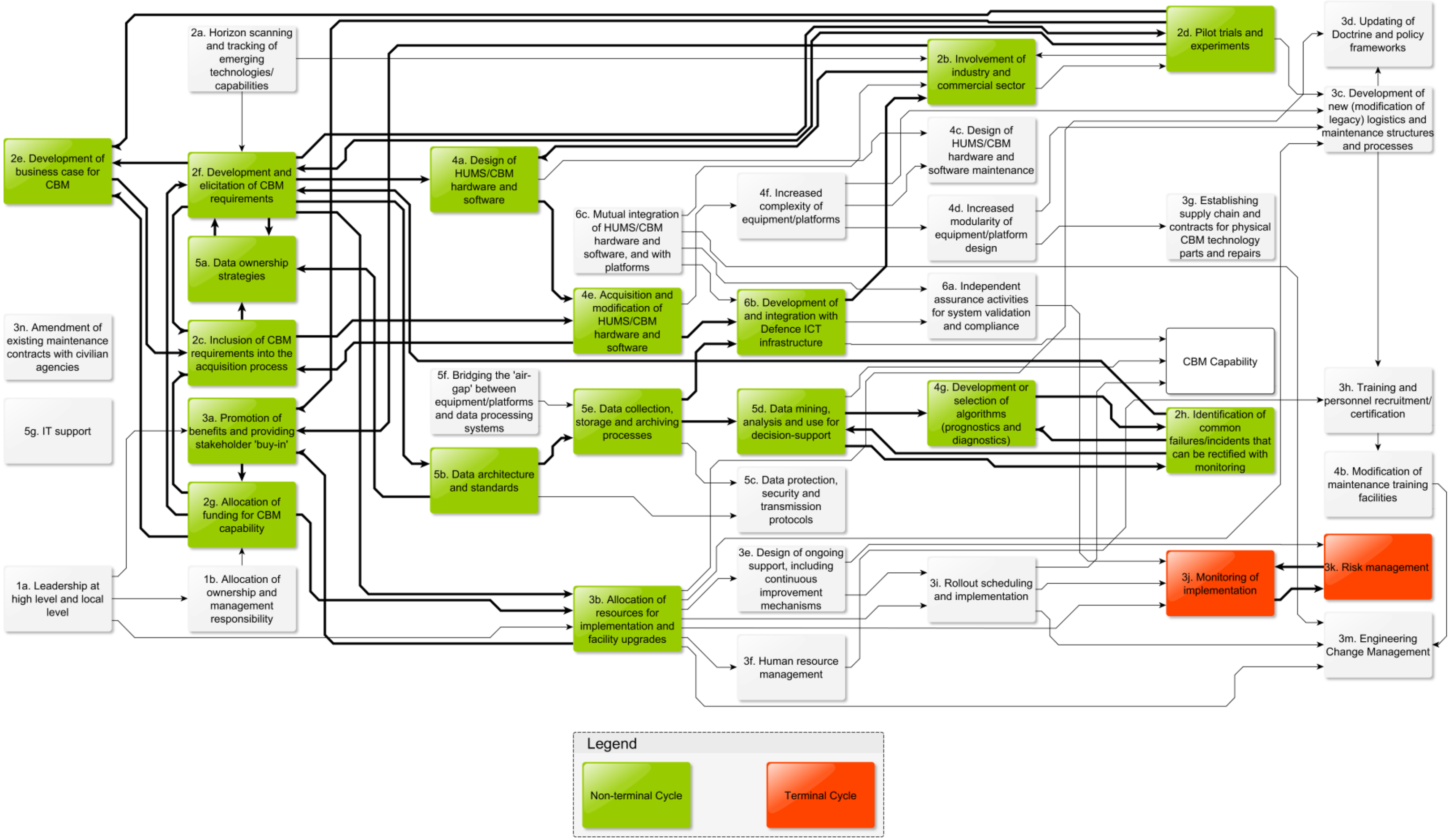


Figure 15: Impact cycles in the second round impacts map: one non-terminal set (green) and one terminal set (red)

H.2. Capability Output Impacts

The capability outputs portion of the impacts map can be considered a directed graph with 77 nodes and 138 edges (causal links).

H.2.1 Immediate and High-Level Capability Output Impacts

Impacts flowing directly from the 'CBM Capability' node were taken to represent immediate output impacts. There were five impacts, highlighted in pink in Figure 16:

- 1a. Diagnostics
- 1b. Prognostics
- 1c. Automated generation of (near) real-time equipment/platform health information
- 3a. Potential impact on maintenance training requirements
- 7h. Increased complexity/modularity of technology.

DSTO workshop participants assessed these impacts to be reasonable immediate impacts, with one caveat: prognostics would generally result from data collection, modelling and analysis effort. Prognostics function developed or adopted as part of the HUMS/CBM acquisition process would be a reasonable 'immediate' output impact, however the continued development and improvement of prognostics in general would be a higher-level impact.

Output impacts without successors were taken to represent high-level output impacts. There were 17 output impacts without successors, highlighted in blue in Figure 16:

- 3g. Potential impact on the number of maintainers
- 3h. Decrease the skill/technology gap between Defence and civilian agencies
- 4a. Reduced resource (e.g. Petrol, Oil and Lubricant (POL)) usage rate
- 4b. Reduction in consumption of some spare parts, increased consumption of others
- 5j. Improved knowledge base for decision support for future capability acquisitions
- 6a. Increase in requirement for bandwidth/networks for transmission of bulk data, including contention for bandwidth
- 6c. Increase in IT support requirements
- 6e. Increase in data security management requirements
- 7a. Reduced scope for innovative operator repair for platform 'revival' to complete a mission
- 7f. Automated self-repair or self-adjustment of equipment
- 7i. Increased ICT in workshops

- 7j. Improved utilisation of tradespeople, particularly for preventive maintenance
- 8c. Improved management of maintenance/sustainment contracts, and of warranties for components/platforms
- 8h. Potential impact on supply chain costs
- 9i. Reduced fleet size requirement
- 10d. Potential change in the accuracy of information underpinning decision-support
- 11a. Improved mission effectiveness.

During the internal DSTO workshop it was assessed that 3h, 7a and 7i were probably not high-level impacts. However, additional causal relationships that would address this could not be identified.

There were no isolated capability output impacts in the graph.

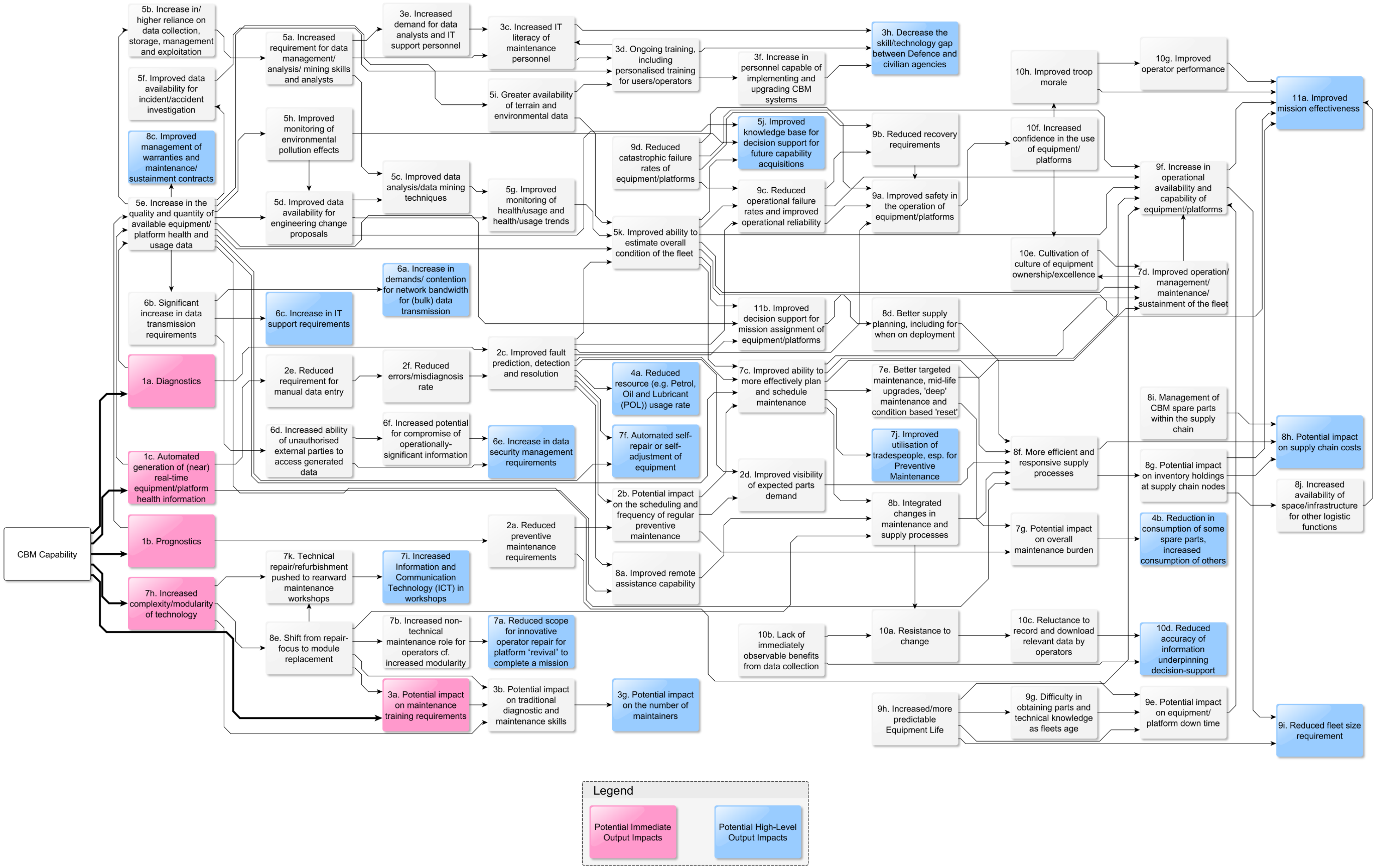


Figure 16: Potential immediate (pink) and high-level (blue) output impacts from the second round impacts map graph structure

H.2.2 Causally-Disconnected Capability Output Impacts

The following five impacts had no path via causal links from the 'CBM capability' node (highlighted in orange in Figure 17):

- 9d. Reduced catastrophic failure rates of equipment/platforms
- 10b. Lack of immediately observable benefits from data collection
- 9g. Difficulty in obtaining parts and technical knowledge as fleets age
- 9h. Increased/more predictable equipment life
- 8i. Management of CBM spare parts within the supply chain.

The internal DSTO workshop determined that these output impacts could be expected with the introduction of CBM capability and suggested additional causal links.

H.2.3 Capability Output Impact Cycles

As with the input impacts map, sets of mutually reachable nodes were identified by examining the SCCs. The two identified sets comprised of two nodes each, and were non-terminal cycles:

- 3c. Increased IT literacy of maintenance personnel
- 3d. Ongoing training, including personalised training for users/operators

And

- 7d. Improved operation/management/maintenance/sustainment of the fleet
- 10e. Cultivation of culture of equipment ownership/excellence.

These cycles are marked in green in Figure 17.

The internal DSTO workshop confirmed that these two cycles made sense in their own right, but noted that many more cycles should exist in the output impacts map due to iteration and mutual reinforcement of the output impacts. This suggested that not all causal relationships had yet been identified.

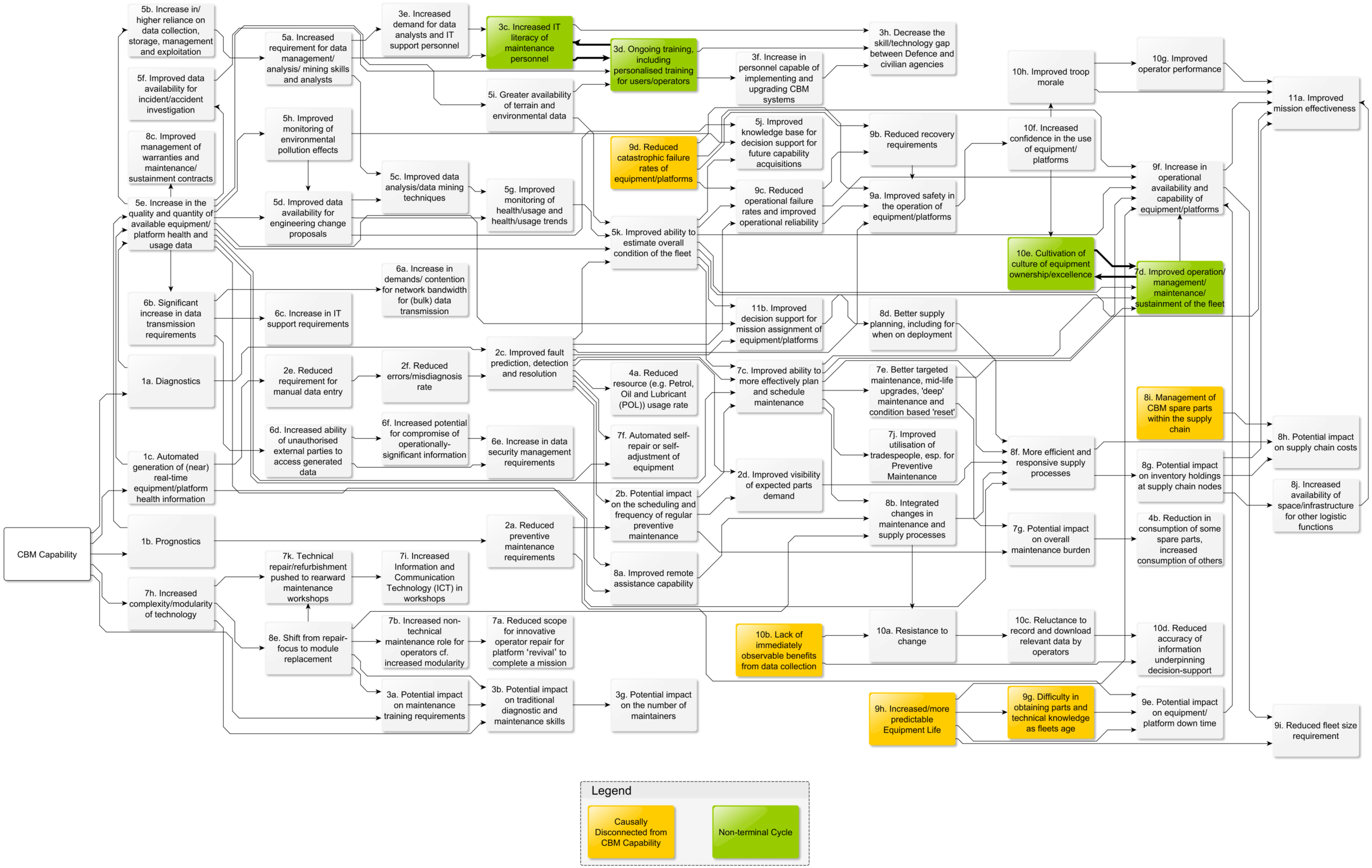


Figure 17: Causally disconnected (orange) and mutually reachable (green) capability output impacts in the second round impacts map

Appendix I. Finalised Impacts Map Impacts Spreadsheet

For brevity, in the following spreadsheets we refer to the eight FIC categories by number:

1. Command and Management
2. Organisation
3. Major Systems
4. Personnel
5. Supply
6. Support
7. Facilities
8. Collective Training.

I.1. Input Impacts Spreadsheet

ID	Title	Description	Indicative $$$ COSTS	Indicative $$$ SAVINGS	Stakeholders	Assumptions	FIC
	Leadership and Ownership	**Identifying who will lead the push for adoption of HUMS and CBM, and who will take ownership of the adoption/implementation process**					
1a	Leadership at high level and local level	Personnel at decision-making level and at user-level who actively promote implementation of the capability	Labour costs, administrative costs	Reduced administrative costs associated with reduced delays in implementation	ADF policy-makers, capability development/acquisition organisations, equipment operators, logistics personnel, maintenance personnel		1,2,4
1b	Allocation of ownership and management responsibility		administrative costs	Reduced administrative costs associated with reduced delays in implementation	ADF policy-makers, capability development/acquisition organisations		1,4
	Incorporation of CBM requirements into the capability acquisition process	**This may be through a Systems Engineering approach to the full life-cycle management of CBM requirements.**					
2a	Horizon scanning and tracking of emerging technologies/capabilities	This involves keeping abreast of the latest technologies on offer from OEMs and after-market technology providers, both in terms of hardware and software (e.g. data housing, archiving, analysis). It also involves being aware of emerging technologies and capabilities that will need to be taken into account either now or later.	labour costs, research costs (e.g. access to information sources, e.g. journal subscriptions), travel costs (e.g. to attend conferences as part of research)	A greater chance of getting a CBM solution that 'works' and getting such a solution after fewer iterations. Reduced costs through a more effective HUMS/CBM implementation.	Materiel suppliers, capability development/acquisition organisations, research and academic organisations		3,6
2b	Involvement of industry and commercial sector	This is to take advantage of the benefits of CBM throughout the existing logistics system and supply chain, to develop maintenance processes and paradigms that do not conflict with original OEM guidance, and to take advantage of that which has already been developed in industry (e.g. libraries of diagnostic and prognostic algorithms, characterisations of failure patterns, etc).	administrative costs (e.g. establishing NDAs), labour costs (interaction with industry and commercial sector)	Reduced research/development and labour costs through leveraging industry and commercial sector knowledge and experience.	Materiel suppliers, capability development/acquisition organisations, research and academic organisations, legal personnel		3,7
2c	Inclusion of CBM requirements into acquisition of relevant equipment/platforms	A natural consequence of a structured, well managed HUMS/CBM acquisition and adoption process. Including these requirements into the capability acquisition process for new equipment/platforms will hopefully avoid many of the additional costs that result from having to engineer retrofitted solutions later on. Space, weight and power (SWaP) are important considerations to take into account here, as HUMS sensors and data processing capabilities will have an impact on SWaP demands.	labour costs, administrative costs, increased document preparation costs	Reduced engineering costs for retrofitting/re-engineering	Materiel suppliers, capability development/acquisition organisations		3
2d	Pilot trials and experiments	This includes assessment of CBM solutions early in the design stage.	Cost of experiments and pilot trials (labour costs, administrative costs, travel costs, hardware/software development and acquisition costs)	A greater chance of getting a CBM solution that 'works' and getting such a solution after fewer iterations. Reduced costs through a more effective HUMS/CBM implementation.	Materiel suppliers, capability development/acquisition organisations, end-users, research and academic organisations		3,6,7
2e	Development of business case for CBM	Business cases for CBM have been identified as a major weakness from an acquisition manager's point of view and often mean that promising technologies are not adopted during design and development.	Administrative costs (potential interaction with industry and commercial partners), document preparation costs, additional labour costs, research costs (hardware/software acquisition costs for pilot studies etc.)	savings associated with adoption of promising technologies in targeted and well justified areas, increasing the potential return on investment.	Materiel suppliers, capability development/acquisition organisations		2,3,6,7

ID	Title	Description	Indicative $$$ COSTS	Indicative $$$ SAVINGS	Stakeholders	Assumptions	FIC
2f	Development and elicitation of CBM requirements	This includes developing key performance parameters, specific monitoring and sensing limits, appropriate system actions etc. Part of this involves identifying who needs the data, when/how soon they need it, and where they need it, as well as who owns it. It was suggested that analysis should be kept to the lowest level possible, e.g. Unit level to facilitate timely decision support for maintainers. Further, this covers specific requirements and specifications of hardware and software.	labour costs, research costs (consultation with stakeholders, surveys, workshops)	Increased effectiveness of the HUMS/CBM solution, through more effective operation and more effective use by stakeholders	All		All
2g	Allocation of funding for CBM capability	Including for ongoing support (e.g. a full through-life support funding allocation), with a commitment not to barter away this funding during project development/reviews etc.	costs associated with acquiring and maintaining a HUMS/CBM capability (e.g. Initial hardware and software development/ acquisition costs, ongoing HUMS/CBM hardware and software maintenance/upgrade costs, personnel training costs)	Reduced costs through having implemented a HUMS/CBM capability (e.g. reduced data collection costs, potentially reduced maintenance costs)	ADF Policy-makers, Materiel suppliers, capability development/acquisition organisations		1,3,6,7
2h	Identification of common failures/incidents that can be rectified with monitoring	Includes examination of historical records, outcomes from pilot studies, etc.	Research costs (extraction/compilation of historical records, potentially from disparate sources; analysis of historical failure modes; research into monitoring techniques), labour costs	Savings as a result of a better-targeted HUMS and CBM capability	Materiel suppliers, capability development/ acquisition organisations, research organisations		3,6
	Change management	**System integration at the organisational level - a rethinking of relationships between individual organisational 'pieces' to enable the advantages of CBM to be realised.**					
3a	Promotion of benefits and providing stakeholder 'buy-in'	This includes promotion of benefits to both end users (maintainers and operators) and to fleet managers and commanders. It is important to get 'buy-in' from the stakeholders, as this is vital to the success of CBM. There will be significant resistance to change from numerous stakeholders - demonstrating benefits is one way to overcome this.	administrative costs, labour costs, travel costs	reduced losses due to resistance to implementation	ADF policy-makers, those advocating for adoption of HUMS/CBM (materiel suppliers, capability development/acquisition organisations, ...), end-users, maintenance personnel (maintainers, maintenance planners, workshop managers, ...), fleet managers	Once commanders are supportive, the ability to have CBM supported across all levels is greatly enhanced.	1,8
3b	Allocation of resources for implementation and facility upgrades	Resources may include money, personnel, facilities, or any other resource required for implementation and facility upgrades.	administrative costs	Reduced administrative costs associated with delays in implementation, reduced productivity losses during implementation	ADF policy-makers, capability development/ acquisition personnel, materiel suppliers		1,3-8
3c	Development of new (and modification of legacy) logistics and maintenance structures and processes	This includes developing a CBM-driven spare parts inventory strategy; developing the appropriate maintenance policy/actions to take in response to specific diagnostic/prognostic signals; updated Electrical and Mechanical Engineer Instructions (EMEIs), Standard Operating Procedures (SOPs), Repair Parts Stores, service manuals, and operator manuals; and a redesign of where maintenance activities fall within the Lines of Support, at what nodes within the maintenance network, and by what assets. It may be possible to draw guidance and advice from civilian agencies or other military agencies that use CBM technology. Current processes undergo periodic reviews in any case, so the cost difference should be small between a review that takes CBM into account and one that does not.	Labour costs, administrative costs, costs of developing and distributing documentation (e.g. SOPs); cost of research and optimisation studies	Reduced productivity losses during implementation	materiel suppliers, capability development/acquisition organisations, equipment operators, maintenance personnel (maintainers, maintenance planners, ...), logistics personnel, training personnel, IT personnel	Without simultaneous optimisation of logistic and maintenance processes in conjunction with the implementation of CBM, a lot of the potential benefits of CBM will be eroded. The new logistics and maintenance structures and processes must not be overly complex or burdensome, and must not rely on maintenance staff to expend large amounts of extra time.	1,4,6,7

ID	Title	Description	Indicative $$$ COSTS	Indicative $$$ SAVINGS	Stakeholders	Assumptions	FIC
3d	Updating of Doctrine and policy frameworks	This includes updating policy documents; doctrine; Standard Operating Procedures (SOPs) and Tactics, Techniques and Procedures (TTPs), etc.	administrative costs, documentation costs, training costs, travel costs (for training)	More effective workforce	ADF policy-makers, training personnel, maintainers, logistics personnel, end-users, fleet managers		1
3e	Design of ongoing support, including continuous improve-ment mechanisms	The design of CBM support mechanisms for in-service fleets requires consideration. This also includes mechanisms for continuous improvement.	labour costs, research costs (e.g. cost of optimisation studies), documentation costs	reduced ongoing support costs through a well (or at least better) designed ongoing support programme.	capability development/acquisition organisations, equipment operators, logistics personnel, maintenance personnel, fleet managers		3,6,7
3f	Human resource management	Analysis of the changes to human resource requirements and the appropriate actions required to satisfy these requirements.	administrative costs, HR costs	savings though having positions filled by people with suitable skills (increases in efficiency)	end-users, logistics personnel, maintenance personnel, data analysts, training personnel		2,4
3g	Establishment of supply chain and contracts for physical CBM technology parts and repairs	HUMS encompasses physical components such as sensors, data loggers, and data transfer components. These will need to be supplied to units, most likely through the existing supply chain (i.e. class 9 repair parts) and associated supply chain mechanisms.	minimal additional supply chain administration overheads (new spare parts lines introduced), purchase of initial quantity of spare parts stocks		supply personnel, logistics personnel, maintainers, materiel suppliers		5,6
3h	Training and personnel recruitment/certification	This includes in the use of sophisticated analysis, decision support and scheduling tools, training of maintenance staff and fleet managers, acquisition of personnel capable of assessing CBM solutions, less emphasis on detailed sub-system knowledge and more on being able to effectively manage to meet operational goals. Training for operators will be critical so that monitoring is conducted (e.g. oil-sampling). Some additional training will be required for maintenance personnel, but no significant additional training required for the maintenance processes themselves (e.g. performing the same PM activities but at different times/through different triggers).	Cost of developing training protocols/SOPs; cost of publishing and distributing training manuals and user/repair manuals; cost of implementing training (time, instructors, equipment, facilities, associated support); loss of productivity during training; cost of complying with qualification/certification requirements. Potential for resource-neutral delivery, if integrated with the routine modernisation of training within Corps Schools, but not resource-neutral in terms of development of the new material, courses, etc.	Reduced costs of inappropriate equipment use; maximising overall CBM-related savings through extensive and appropriate utilisation of the technology.	capability development/acquisition organisations, end-users, logistics personnel, maintenance personnel, data analysts, training personnel	There is the potential for resource-neutral delivery of training, if the changes can be integrated with the routine modernisation of training within Corps Schools.	1,2,4,6, 7,8
3i	Rollout scheduling and implementation	Scheduling of the activities required to adopt/implement HUMS/CBM, and actually carrying these out. This includes configuration management, and definition of metrics to measure the effectiveness of CBM once implemented.	Labour costs, administrative costs, travel costs, costs of developing and distributing documentation (e.g. SOPs); IT/tech support cost increases during roll-out; loss of productivity during roll-out; central management costs; hardware and software development/acquisition costs	reduced productivity losses during implementation	materiel suppliers, capability development/acquisition organisations, end-users, logistics personnel, supply personnel, maintenance personnel, training personnel		All
3j	Monitoring of implementation	This includes not only monitoring the progress of the initial implementation of CBM (ensuring that the adoption of CBM is progressing as expected), but also ongoing monitoring, e.g. assessing the CBM system outputs against post failure investigations (failure of the CBM system). It does not cover monitoring of the ongoing 'success' of CBM in terms of achieving the goals of reduced footprint, reduced maintenance burden, increased operational availability/mission effectiveness, as these are functions of the output impacts.	administrative costs, travel costs, documentation costs	Reduced administrative costs associated with delays in implementation, less likelihood for deviations to implementation plan	fleet managers, ADF policy-makers		1,2
3k	Risk management	This is of particular importance for immature technologies and technologies that lack an effective insertion/integration strategy.	administration costs, labour costs, loss of productivity during roll-out	reduced likelihood of expensive remedial solutions being required	capability development/acquisition organisations, fleet managers, logistics personnel, maintenance personnel, data analysts		1

ID	Title	Description	Indicative $$$ COSTS	Indicative $$$ SAVINGS	Stakeholders	Assumptions	FIC
3m	Engineering Change Management	To ensure the engineering changes required to implement/adopt HUMS and CBM are carried out in a coherent, planned fashion.	administration costs, labour costs, loss of productivity during roll-out	reduced likelihood of incurring costs associated with re-engineering or finding engineering solutions on-the-fly	capability development/acquisition organisations, logistics personnel, maintenance personnel		1,2
3n	Amendment of existing maintenance contracts with civilian agencies	This is especially important where e.g. scheduled maintenance is a condition of sale.	legal costs, administrative costs	potential for savings in operating/maintenance costs	legal personnel, materiel suppliers, maintenance personnel		6
	HUMS-enabled equipment/platforms	**Acquiring HUMS-enabled platforms, or retrofitting HUMS to legacy platforms. Developing appropriate HUMS in-house, or using MOTS/COTS HUMS solutions.**					
4a	Design of HUMS/CBM hardware and software	A HUMS/CBM hardware and software design that conforms to the identified requirements. Preferably a design that takes integration issues into account, rather than being designed in isolation (such integration issues should be specified in the requirements). Standards-based design is an important consideration for the longevity and extensibility of CBM systems into the future (especially in the embedded systems integrated within the vehicle).	engineering costs, research costs	reduced re-design on-the-fly during implementation.	materiel suppliers, capability development/acquisition organisations, research and academic organisations		3,6
4b	Modification of maintenance training facilities	Training in the use of CBM and related technologies may require changes to the equipment and facilities used to deliver the training.	capital expenditure for upgrade/modification of facilities		training personnel, maintenance personnel, fleet managers		2,4,7,8
4c	Design of HUMS/CBM hardware and software maintenance	This involves the set-up of supply/maintenance contracts; testing, repair and replacement of components; software upgrades, patches and licensing, sensor calibration. This must also take into account adjustments of the CBM solution as the target platform evolves and ages, and as CBM solutions evolve and mature (particularly software, but also hardware).	Labour, spare parts, technical support, upgrades; cost of specialised tools and equipment; administrative costs in contract management; cost of inventory management; cost of transportation; cost of software support, updates and licensing; configuration management of software on deployed platforms, particularly in early phases.		capability development/acquisition organisations, materiel suppliers, research and academic organisations		2,4,7,8
4d	Increased modularity of equipment/platform design	As with equipment/platform complexity, this is not exclusively a product of the adoption of CBM technologies, as there is an existing trend for modularisation and repair-by-replacement.	training costs	potential reduction in platform maintenance costs through faster turn-around times	maintainers, supply personnel		3,5
4e	Acquisition and modification of HUMS/CBM hardware and software	Includes the relevant sensors, Built-In Test Equipment (BITE), displays, data acquisition and processing software and hardware including off-board systems. At the least, this should be considered now for future purchases, but existing procedures such as oil sampling can be utilised more widely in the interim.	Cost of platform purchase; for modification of legacy platforms this includes the cost of tracking existing and evolving technologies, research, engineering, assembly and installation; cost of acquisition of physical HUMS/CBM hardware and software (e.g. sensors, data loggers), cost of offboard components, such as the data warehousing solution; Cost of labour, technical support, specialised tools and equipment, Note that the cost of HUMS-enabled platform purchase is comparable to purchase of platforms without HUMS, as it is becoming standard technology.	Increased disposal value of assets (although likely to be minimal in a HUMS-ubiquitous future environment)	Materiel suppliers, capability development/acquisition organisations	HUMS/CBM equipment requires minimal corrective costs.	3,5,6
4f	Increased complexity of equipment/platforms	This is not only as a product of the adoption of CBM, as platforms and technology will continue to increase in complexity regardless.	potential for increased platform maintenance costs, requirement for specialist skills to perform maintenance, increased training costs		maintainers, supply personnel		3

ID	Title	Description	Indicative $$$ COSTS	Indicative $$$ SAVINGS	Stakeholders	Assumptions	FIC
4g	Development or selection of algorithms (prognostics and diagnostics)	These should be able to effectively monitor/predict the identified failure modes and Remaining Useful Life.	Research and documentation costs for: algorithm development, research and optimisation studies, pilot trials; labour and administrative costs for implementation, cost of using and maintaining ICT infrastructure	longer-term savings through implementation/adoption of fit-for-purpose algorithms, less modification and fewer iterations to achieve such algorithms	materiel suppliers, capability development/acquisition organisations, research and academic organisations, data analysts		3,6
	Data management strategy						
5a	Data ownership strategies	Includes consideration of data-sharing with Defence contractors/OEMs, and privacy issues. The issue of data ownership issue particularly important for Defence, through experience in the Air domain of ambiguous ownership resulting in contract disputes and legal challenges (of which Defence is often on the losing side due to operational urgencies.)	Development costs, documentation production and distribution costs, legal costs (negotiation with OEMs etc.), cost of using and maintaining ICT infrastructure	potential avoidance of legal costs, avoidance of costs associated with 'buying access' or the 'buying back' of data from materiel suppliers	ADF policy-makers, IT Support personnel, materiel providers, legal personnel		1,2
5b	Data architecture and standards	HUMS, be it manual or automatic, will generate data. The format and architecture of this data must be determined, taking into consideration the inter-relations with other systems, such as Logistics Information Systems. It must also consider the use of standards for interoperability, both between AUS platforms and in international coalitions. (The main standard in terms of HUMS is the UK MoD's Generic Vehicle Architecture, an open standard. Whether we adopt an existing standard or develop our own remains to be determined.)	cost of research, producing documentation and labour	reduced future costs relating to interoperability between platform variants/platforms both within AUS fleets and in coalition fleets	capability development/acquisition organisations, data analysts, IT support personnel		6
5c	Data protection, security and transmission protocols	This includes data encryption.	May create substantial overhead in information processing and handling. Cost of researching or developing encryption algorithms and data transmission protocols, cost of signal/bandwidth management.	Avoidance of potential costs related to leaking of information, particularly operationally sensitive information, to adversaries	capability development/acquisition organisations, security personnel, IT Support personnel, adversaries		3,6
5d	Data mining, analysis and use for decision-support	Having an easy to use, quick response and easy data management system is universally acknowledged within the maintenance area as a vital 'efficiency multiplier'. This may include employing personnel for the specific purpose of CBM knowledge management.	research costs, training costs, HR costs (recruitment of appropriately skilled personnel), cost of using and maintaining ICT infrastructure	efficiency gains through appropriate input to decision support	capability development/ acquisition organisations, fleet managers, operational and strategic planners, data analysts, maintenance and IT support personnel		4,6,8
5e	Data collection, storage and archiving processes	This refers to collection of data onboard a platform, and collection of data within offboard systems (once extracted from platforms) for subsequent storage and archiving.	costs related to acquiring or developing the technology, IT infrastructure and software that facilitate the collection, storage and archiving of data, documentation costs, research costs (technology market surveys), cost of using and maintaining ICT infrastruct-ure, cost of signal/bandwidth management.	savings related to data exploitation (data analytics, so-called 'big data'), reduced data collection costs, improved accuracy of data (reduced effort for data 'cleaning')	capability development/ acquisition organisations, materiel suppliers, data analysts, logistics personnel, security personnel, IT Support personnel, adversaries		3,4,6,8
5f	Bridging the 'air-gap' between equipment/platforms and data processing systems	Extracting data from platforms has been identified as a significant issue. Although technology may exist to facilitate both wired and wireless data transfer (as well as recording technologies such as USB memory sticks and the burning of CDs/DVDs) there remains debate as to the security concerns inherent in wireless data transfer. Any solution must take into account security concerns and other factors such as timeliness and currency.	research and development costs (surveys of existing technologies, adapting existing technologies), cost of using and maintaining ICT infrastructure, cost of signal/bandwidth management.	reduced cost of data collection through reduced 'manual handling' of data	capability development/acquisition organisations, end-users, maintenance personnel, logistics personnel, security personnel		3,6,7
5g	IT support	This may include the need for an increase in IT Support personnel or retraining of existing personnel.	development costs, documentation costs, training costs, HR costs (recruitment of appropriately skilled personnel)	efficiency gains through appropriate IT support	fleet managers, maintenan-ce personnel, data analysts, IT support personnel		2,3,4

ID	Title	Description	Indicative $$$ COSTS	Indicative $$$ SAVINGS	Stakeholders	Assumptions	FIC
6	**Technology integration**						
6a	Independent assurance activities for system validation and compliance		cost of testing, certification and trials; cost of adequate end-user training		Materiel suppliers, capability development/acquisition organisations, legal organisations		3,4,7,8
6b	Development of and integration with Defence ICT infrastructure	This may involve modifications to the Logistics Information System, Battlefield Management System, Communication systems, Defence Local Area Networks, SATCOMS, signal/bandwidth management etc. to facilitate the introduction of CBM.	cost of advanced engineering, cost of assembly and installation, cost of testing/trials, cost of external system modifications (to the Logistics Information System, Enterprise Resource Planning (ERP) systems, Command and Control systems, etc.), cost of using and maintaining existing ICT infrastructure, cost of developing and distributing technical data (e.g. operating manuals, troubleshooting manuals), cost of signal/bandwidth management.		Materiel suppliers, capability development/acquisition organisations, ICT managers, IT Support personnel		1-4,6,7,8
6c	Mutual integration of HUMS/CBM hardware and software, and with platforms.	This will involve integration with other systems, e.g. Logistics Information System, Battlefield Management System, Communication systems, etc (i.e. existing fielded systems). One approach may be a long term programme of progressive introduction, to allow CBM-enabled systems to interoperate and work in parallel with traditional systems.	cost of advanced engineering, cost of assembly and installation, cost of testing/trials, cost of using and maintaining existing ICT infrastructure, cost of developing and distributing technical data (e.g. operating manuals, troubleshooting manuals), cost of signal/bandwidth management.		Materiel suppliers, capability development/acquisition organisations, ICT managers, IT Support personnel	A key to end-user acceptability will be implementation/integration that does not require the use of a 'separate computer', especially not a separate computer for each system/subsystem operating under a CBM regime.	3,4,6,7,8

I.2. Output Impacts Spreadsheet

ID	Title	Description	Indicative $$$ COSTS	Indicative $$$ SAVINGS	Stakeholders	Assumptions	FIC	+ / - /?	(S)hort, (M)edium or (L)ong-term	(D)irect/ (I)ndirect
1	**Immediate functions**									
1a	Diagnostics	Real-time assessment of equipment/platform health, including the use of Built-in Tests/Built-in Test Equipment (BIT/BITE)	increased cost of minor parts replacement on 'as-required' basis	Less time spent finding the cause/location of a fault, less chance of fault propagation to something more serious	Equipment operators, maintenance personnel		3,4,6	+	S	D
1b	Prognostics	Identifying existence of a fault and impending failure	increased cost of minor parts replacement on 'as-required' basis	Reduced cost of scheduled parts replacement; reduced unplanned maintenance costs	Equipment operators, maintenance personnel	That the quality of collected data is sufficient for prognostic purposes and accurate prognostic models are available.	3,4,6	+	S	D
1c	Automated generation of (near) real-time equipment/platform health information	Timeliness of equipment health information is critical in decision-making processes, particularly for Unit-level maintenance. This node includes the tracking of position, status and load of vehicles, critical stores and drivers, in addition to other more 'traditional' health and usage parameters.	data acquisition, collation, processing and analysis costs	Reduced costs of data collection, reporting and collation, efficiency gains in asset utilisation, reduced maintenance burden through correct usage of equipment (e.g. not overloading or exceeding the design envelope), increased visibility of assets/stores throughout the supply chain (for automated monitoring of vehicle loads/stores)	Equipment operators, maintenance personnel, logistics personnel, operational planners, fleet managers, supply personnel	That the 'air-gap' between the equipment/platform and data analysis systems can be bridged to provide automatic data transmission	1-4,6	+	S/M	D
2	**Immediate maintenance effects**									
2a	Reduced preventive maintenance requirements	Associated with a reduced No Fault Found (NFF) rate, and the potential to extend service intervals of some subsystems.	data collection, collation and analysis costs	Reduced cost of preventive maintenance, including labour, parts, plant activity	Equipment operators, maintenance personnel, logistics personnel	HUMS data is analysed and acted upon	1,3-6	+	S/M	D
2b	**Potential impact on the scheduling and frequency of regular preventive maintenance.**	Less regular, more proactive maintenance is associated with a move from usage-based or time-based scheduled maintenance to condition-triggered maintenance (i.e. CBM). Conversely, the service interval may still remain relatively constant to allow for vehicle availability, in particular for scheduling to fit in with unit commitments - something that is particularly relevant to field units. If servicing is conducted purely on condition based triggers, it may be difficult to schedule servicing to meet the Commanders' commitment during the training year. Other views are that HUMS/CBM will allow for 'better' planning. The contextual differences between in-barracks vs. on deployment operation may be worth teasing out here.	Data collection, collation and analysis costs. Increased complexity of maintenance planning/scheduling	Reduced cost of preventive maintenance, including labour, parts, plant activity; reduced cost of unnecessary maintenance	maintenance personnel, logistics personnel		1,3-6	?	S/M/L	D

ID	Title	Description	Indicative $$$ COSTS	Indicative $$$ SAVINGS	Stakeholders	Assumptions	FIC	+ / -/?	(S)hort, (M)edium or (L)ong-term	(D)irect/ (I)ndirect
2c	Improved fault prediction, detection and resolution	Quicker and more accurate fault detection through diagnostics and prognostics. This is associated with the development of new algorithms for diagnostics, prognostics and decision-support, including learn-as-you-go approaches.	Cost of research, trials and documentation, including associated labour, administration and travel costs; data collection, collation and analysis costs; cost of maintaining relevant ICT infrastructure; cost of licensing relevant business analytics software	Reduced cost of labour for fault-detection/inspections. Flow-through of cost savings associated with more efficient maintenance and increased equipment life	Equipment operators, maintenance personnel, materiel suppliers, data analysts, research and academic organisations	Funding and contractual arrangements are in place for long-term research	2,3,4,6	+	S/M/L	D
2d	Improved visibility of expected parts demand	Automated data collection and analysis may provide an indication of upcoming maintenance, which can be used to infer the spare parts that are likely to be required.	data collection, collation and analysis costs. cost of using and maintaining ICT infrastructure	Reduced reliance on urgent means of transportation for spare parts	Maintenance personnel, supply personnel	That the knowledge of spare parts demand is taken into account by the supply chain; that the potential synergies between HUMS/CBM and the supply chain are identified and taken advantage of.	4,5,6	+	S/M/L	D
2e	Reduced requirement for manual data entry	Also reduces the potential for human-induced errors to be introduced into the data.	data collection, collation and analysis costs. cost of using and maintaining ICT infrastructure	Reduced labour and administrative costs associated with manual data entry	Equipment operators, maintenance personnel	That the 'air-gap' between the equipment/platform and data analysis systems can be bridged to provide automatic data transmission; successful integration of relevant software systems	4,6	+	S	D
2f	Reduced errors/misdiagnosis rate	HUMS may engender more precise diagnosis of faults and failures		Reduced cost of unnecessary maintenance and secondary (maintenance-induced) damage	Equipment operators, maintenance personnel		3,4,6	+	S/M	D
3	**Effects on workforce/workforce skill base**									
3a	**Potential impact on maintenance training requirements**	Reduced maintenance training requirements may only be at the 'junior' level, with more senior maintainers requiring an unchanged amount of training. Conversely, there may be a potential increase in training requirements for senior maintainers in the area of data analysis.	Potential increase in training requirements for senior maintainers re. data analysis	Reduced cost of training and maintaining qualification	Equipment operators, maintenance personnel		2,4,6,7,8	?	M/L	I
3b	**Potential impact on traditional diagnostic and maintenance skills.**	A reduction in the traditional maintenance skills can be associated with increase in complexity of technology in general, not necessarily as a direct result of CBM itself, but of digitisation of equipment and reduction in the cost of ICT technologies - it becomes cheaper to replace a whole unit than to put expensive labour into repairing cheap parts. Conversely, there may be no loss of the traditional skills as the requirement to conduct Preventive Maintenance will still exist within a multitude of equipment/platform variants not fitted with CBM technology. There may also be an improvement in best work practices in line with modern industry standards commonly practiced by larger organisations.	Cost of outsourcing repairs; cost of replacement modules	Reduced costs of training and maintaining a range of qualifications	Equipment operators, maintenance personnel	Whether or not there will be a significant decrease in the requirement for traditional diagnostic and maintenance skills	2,4,6,8	?	M/L	I

ID	Title	Description	Indicative $$$ COSTS	Indicative $$$ SAVINGS	Stakeholders	Assumptions	FIC	+ / -/?	(S)hort, (M)edium or (L)ong-term	(D)irect/ (I)ndirect
3c	Increased IT literacy of maintenance personnel			reduced reliance on data analysts/IT support personnel	maintenance personnel, IT support personnel		4,8	+	M/L	I
3d	Ongoing training, including personalised training for users/operators	Personalised training for operators refers to driver-feedback mechanisms that allow tailored training to be delivered. Enhanced or personalised training can be achieved through HUMS feedback. Ongoing training for upskilling of maintenance personnel may be required for them to gain an understanding the holistic system.	cost of data collation and analysis; cost of amending training protocols	Reduced costs of inappropriate equipment use; maximising overall CBM-related savings through extensive and appropriate utilisation of the technology; Potential reduction in costs associated with accidents, recovery, repairs and injury management	Equipment operators, training personnel, ADF policy-makers, data analysts	That a concerted effort is made to analyse and use collected accident/usage data to amend training protocols, and that personnel are employed to tailor training to individual operators	1,2,4,6, 7,8	+	M/L	I
3e	Increased demand for data analysts and IT support personnel	Relates to the increase in IT Support requirements	recruitment costs, training costs, potentially more wages to be paid		IT/signals personnel		4,6	?	M	I
3f	Increase in personnel capable of implementing and upgrading CBM systems		recruitment costs, training costs, potentially more wages to be paid		maintenance personnel		4,6	?	S/M	D
3g	**Potential impact on the number of maintainers.**	If CBM diagnostics and prognostics work well then it may be that maintenance can be scheduled such as to reduce the number of maintainers required to sustain a fleet although this will be in the longer term and reductions may be minor. Conversely, there may be a personnel-neutral solution but with changes in competencies, e.g. a decrease in traditional maintenance activities but an increase in data analysis.	training costs re. changes in competencies	potential savings through reduced workforce	maintenance personnel, training personnel		4,6	?	M	D
3h	Decrease the skill/technology gap between Defence and civilian agencies	CBM technologies will become increasingly similar between Military and commercial/civilian agencies as new technologies from one will diffuse into the other.		reduced barriers for industry interaction	capability development/acquisition organisations, materiel suppliers, maintainers, equipment operators		4,6,7	+	M/L	I
4	**Resource consumption effects**									
4a	Reduced resource (e.g. Petrol, Oil and Lubricant (POL)) usage rate	This could be achieved via adjustment of vehicle configuration parameters. It will also include a reduction in disposal costs due to less consumption. A reduction in POL usage rate is particularly relevant for vehicles with high lubricant/coolant volumes and low usage rates. In such instances the fluids tend to be changed based on calendar time. This is more a function of HUMS more than of CBM itself.		Reduced cost of resources e.g. POL, reduced transport costs, reduced convoy protection costs	Logistics personnel, equipment operators, supply personnel		1,5	+	M/L	I
4b	Reduction in consumption of some spare parts, increased consumption of others	Decreased consumption of 'consumables' such as coolant, engine oil. Potential increased consumption of replacement parts due to earlier Preventive Maintenance intervention.	potential increase in consumption of some types of spare parts	potential reduction in consumption of some types of spare parts	maintenance personnel, logistics personnel, supply personnel		5	+	S/M	D

ID	Title	Description	Indicative $$$ COSTS	Indicative $$$ SAVINGS	Stakeholders	Assumptions	FIC	+ / -/?	(S)hort, (M)edium or (L)ong-term	(D)irect/ (I)ndirect
5	**Data collection and analysis effects**									
5a	Increased requirement for data management/data analysis/data mining skills, and for specific data and information analysts	This includes increased complexity of data-related tools, and specialisation of personnel. The data analyst role could be filled by senior maintenance staff. The data analysis and mining includes reporting to both the end users (maintainers and operators) and to higher level fleet managers.	HR costs in recruiting and training relevant personnel; contracting and software licensing costs in outsourcing this function		data analysts, IT/signals personnel, materiel suppliers		2,4,6	?	S/M/L	D
5b	Increase in, and higher reliance on, data collection, storage, management and exploitation requirements	This includes both off-platform storage and processing and the requirement for on-platform processing, where computing power may be limited compared to e.g. a desktop or laptop PC. The increase in reliance on data collection, storage, management and exploitation is likely to be a result of the use of HUMS data in decision-making at many levels in the organisation.	labour and administration costs, IT support costs, cost of software licensing/acquisition, Cost of data collation and analysis, cost of relevant ICT infrastructure		data analysts, capability development/acquisition organisations, IT/signals personnel, maintenance personnel, logistics personnel, operational planners, fleet managers		2,4,5,6	-	S/M/L	D
5c	Improved data analysis/data mining techniques	It may be that such techniques are developed as a result of the introduction of CBM, but it may be that existing techniques from the commercial sector/academia are adequate.	Cost of data collation and analysis; cost of research and documentation; cost of relevant ICT infrastructure; cost of software licensing	Efficiency gains in equipment maintenance and usage with more accurate algorithms	capability development/acquisition organisations, data analysts, research and academic organisations	Funding and contractual arrangements are in place for long-term research	2,3,6	+	L	I
5d	Improved data availability for engineering change proposals	This includes proposals for changes as part of mid-life upgrades and during 'deep' maintenance/condition-based reset	Data analysis costs, including labour and administrative costs	Efficiency gains in development of engineering change proposals	capability development/acquisition organisations		3	+	L	I
5e	Increase in the quality and quantity of available equipment/platform health and usage data	This includes system Remaining Useful Life (RUL) and fleet Life Of Type (LOT) information, i.e. 'total fleet intelligence'. It is worth noting that an increase in quantity of data is not a benefit if the data is not useful. This data may include information on both running costs and maintenance costs.	cost of data transmission, storage and processing; associated administration and labour costs; cost of ICT infrastructure and maintenance of that infrastructure		Data analysts, IT/signals personnel, fleet managers, operational planners, logistics personnel, capability development/acquisition organisations, research and academic organisations	That data download and recording is not neglected by maintainers (e.g. due to inadequate implementation, over-sensitivity, and/or no demonstration of observable benefits)	1-7	+	M/L	D
5f	Improved data availability for incident/accident investigation	Improved availability will facilitate physics-of-failure analysis, post-failure analysis as well as accident investigation	Costs in setting up the legal framework for use of the data for this purpose	Potential reduction in costs associated with accidents including claim payouts	Equipment operators, maintenance personnel, accident/incident investigators, legal personnel, training personnel	That processes are in place to deal with legal/HR management implications of the collected data (e.g. for cases of equipment misuse)	2,4	+	M/L	I
5g	Improved monitoring of health/usage and health/usage trends	This is especially useful for military equipment with varying patterns of use			Fleet managers, maintenance personnel, data analysts		1-6	+	M	D
5h	Improved monitoring of environmental pollution effects	Including e.g. the monitoring of exhaust emissions and other gases. This also facilitates the monitoring of health effects on living organisms, including humans.	Potentially costs of additional sensors and their integration; cost of collating and analysing information	Potentially reduced cost of compliance with environmental legislation	ADF as a public entity, legislative bodies (external to Defence), data analysts, Australian public	That emission monitoring may become more prominent in future legislation	2	+	M/L	D

ID	Title	Description	Indicative $$$ COSTS	Indicative $$$ SAVINGS	Stakeholders	Assumptions	FIC	+ / -/?	(S)hort, (M)edium or (L)ong-term	(D)irect/ (I)ndirect
5i	Greater availability of terrain and environmental data		Cost of data collation and analysis; cost of research and documentation (8); cost of relevant ICT infrastructure; cost of software licensing	Efficiency gains in equipment maintenance and usage with more accurate algorithms	capability development/acquisition organisations, research and academic organisations, data analysts, equipment operators, maintenance personnel	The HUMS system onboard mobile platforms, such as vehicles, records terrain and environmental data	3,4,6,8	+	L	I
5j	Improved knowledge base for decision support for future capability acquisitions	This facilitates improvements in construction of Functional Performance Specification/Request for Tender (FPS/RFT) documents, and improved decision support at global, sub-fleet and local levels.	Research and documentation costs; administrative, labour and travel costs; data collation and analysis costs		capability development/acquisition organisations, data analysts	A concerted effort is made to analyse information and incorporate findings into capability acquisition process	1,2,3	+	L	I
5k	Improved ability to estimate overall condition of the fleet	This includes assessments/estimations of equipment/platform/fleet health in real-time or near real-time when deployed. This provides improved situational awareness in terms of equipment/platform status and an enhanced ability to estimate equipment/platform condition.	data collection, collation and analysis costs; Cost of integration of CBM-generated information with C2 systems; cost of using and maintaining ICT infrastructure	Reduced labour and administrative costs involved in manual collection and collation of required information	Fleet managers, operational planners, strategic planners, capability development/acquisition organisations, maintenance personnel, logistics personnel	That relevant, effective and accurate information is available to facilitate situational awareness	1,2,3,5, 6	+	M/L	D
6	**Data-transmission effects**									
6a	Increase in requirement for bandwidth/networks for transmission of bulk data, including contention for bandwidth	Transfer of HUMS data in a deployed situation is likely to be in competition with many other data transmission requirements, and is likely to be of a lower priority than other traffic such as situational awareness data, especially if being transmitted over the same bearer.	Cost of ICT infrastructure and network/bandwidth management; cost of IT support		capability development/acquisition organisations, IT/signals personnel		1,2,3,6, 7	-	S/M/L	D
6b	Significant increase in data transmission requirements	This includes increases in both the volume and timeliness/speed requirements of data transmission.	Cost of ICT infrastructure and network/bandwidth management; cost of IT support		capability development/acquisition organisations, IT/signals personnel		1,2,3,6, 7	-	S/M/L	D
6c	Increase in IT support requirements		IT support costs, including additional personnel		Operational planners, IT/signals personnel		1,6	-	S/M/L	D
6d	Increased ability of unauthorised external parties to access generated data	With increased data transmission comes an increase in the potential for unauthorised external parties to gain access to that data.			Materiel suppliers, external commercial organisations, adversaries (including enemy forces), operational planners, IT/Signals personnel		1,2,3,7	-	S/M/L	I
6e	Increase in data security management requirements	For example, this is necessary to address the security issues surrounding the transmission of bulk of data from the area of operations.	increased data protection costs		Operational planners, IT/signals personnel		1,6	-	S/M/L	I
6f	Increased potential for compromise of operationally-significant information	This is true of data transmissions that can alert external parties to the location of vehicles if GPS tracking is integrated into the HUMS; transmission of location and status of an entire fleet is problematic from an operational security perspective.	potential costs of data security breaches and leaking of operationally important information		External commercial organisations, enemy forces, operational planners, IT/signals personnel		1,2,3,6, 7	-	S/M/L	I

ID	Title	Description	Indicative $$$ COSTS	Indicative $$$ SAVINGS	Stakeholders	Assumptions	FIC	+ / -/?	(S)hort, (M)edium or (L)ong-term	(D)irect/ (I)ndirect
7	**Longer-term maintenance effects**									
7a	Reduced scope for innovative operator repair for platform 'revival' to complete a mission	With increased modularity and commensurate decrease in the maintenance skills of equipment operators may come a decrease in the ability to perform temporary repairs "on-the-fly".	increased platform recovery costs, costs associated with reduced mission effectiveness	reduced training costs	equipment operators, maintainers, recovery personnel		3,4	-	M/L	I
7b	Increased non-technical maintenance role for operators cf. increased modularity	With increased modularity may come an increased non-technical maintenance role for operators, for example, swapping out a faulty module for one that is working.	increased training costs for training of operators	reduced maintenance burden for maintainers	equipment operators, maintainers		3,4,6	+	M/L	I
7c	Improved ability to more effectively plan and schedule maintenance.	Planning: determining what maintenance needs to occur. Scheduling: determining when it will occur. This is associated with the ability to predict impending parts failure, conduct "Predictive" maintenance, track components/major subsystems, analyse maintenance procedures , adjust inspection intervals, and to bring maintenance forward or delay maintenance to coincide with other events, such as inspections or regular servicing. This also includes the ability to schedule maintenance in a load-balancing way across workshops. All of this is enabled through improved fault prediction capabilities and more data, which gives the justification for adjusting the schedule. Note that an improved ability to plan doesn't mean planning becomes easier - it is likely to become more complicated.	data collection, collation and analysis costs; cost of using and maintaining ICT infrastructure	Reduced reliance on urgent modes of transport for repair parts; reduced losses due to equipment downtime; efficiency gains in maintenance scheduling	Fleet managers, maintenance personnel, operational planners, logistics personnel, data analysis	That CBM-generated information is utilised appropriately to plan and optimise maintenance. This requires a maintenance and fleet management system that allows for "flexible (health-based) maintenance scheduling" rather than pre-planned scheduled maintenance.	1-6	+	S/M/L	I
7d	Improved operation/management/maintenance/sustainment of the fleet	This could be particularly true for old fleets that are approaching or have exceeded their Life of Type, and through identification of maintenance capability gaps. In terms of improving fleet operation and management, usage monitoring affords the ability to rotate highly utilised vehicles/equipment to units with lower usage rates and vice versa to "even out" the usage of the fleet, hence providing a means to more evenly distribute equipment/platform workload.	change management costs in implementing new processes and training; associated labour and administrative costs; cost of data collation and analysis	Reduced cost of fleet repair, maintenance and replacement; improved fuel economy through more efficiently operating equipment; potential for a more streamlined supply chain, e.g. reduced inventory holdings at supply chain nodes; better informed decisions regarding logistics management	Fleet managers, maintenance personnel, supply personnel, ADF policy-makers	That a concerted effort is made to capitalise on the CBM-generated information for improvement of fleet management processes, including that appropriate changes are made to other parts of the organisation that are affected.	1,3,5,6	+	S/M/L	I
7e	Better targeted maintenance, mid-life upgrades, 'deep' maintenance and condition based 'reset'	For example, this may be achieved through refinements to Preventive Maintenance regimes, better targeted 'deep' maintenance or 'condition-based reset', and better informed mid-life upgrades.	data collection, collation and analysis costs; cost of using and maintaining ICT infrastructure	Reduced maintenance costs over equipment life; reduced mid-life upgrade/deep maintenance costs	Fleet managers, maintenance personnel, logistics personnel	That appropriate changes are made to maintenance protocols.	1,2,3,6	+	M/L	I
7f	Automated self-repair or self-adjustment of equipment	For example, automatic maintenance/adjustment of equipment (e.g. engine valves, calibration of targeting systems) based on data generated from diagnostics.	appropriate hardware and software development, procurement, maintenance etc., appropriate operator/maintainer training	Reduction in maintenance burden, e.g. reduction in repair time particularly for parts of the drive-train that are hard to access by human maintainers, reduction in the need to bring equipment into a workshop for (relatively) minor adjustments	maintenance personnel, equipment operators	That this attains cultural acceptance, i.e. being comfortable with automated adjustments	6	+	M/L	D

ID	Title	Description	Indicative $$$ COSTS	Indicative $$$ SAVINGS	Stakeholders	Assumptions	FIC	+ / -/?	(S)hort, (M)edium or (L)ong-term	(D)irect/ (I)ndirect
7g	**Potential impact on** overall maintenance burden	This includes a potential impact on the amount of "maintenance-induced" (maintainer-generated) maintenance in addition to potential impacts on Preventive and Corrective maintenance. Reductions could be achieved through forewarning of equipment degradation and pending equipment failure, and if less maintenance is conducted, there is less opportunity for maintenance-induced maintenance.	costs associated with an increase in the complexity of maintenance planning/scheduling	Reduced overall maintenance costs including labour, transport-ation, spare parts, test equipment. In particular, reduced corrective maintenance costs: repair, replacement, spare parts, labour; reduced reliance on urgent transportation of critical parts	Maintenance personnel, logistics personnel, equipment operators	That CBM results in an overall decrease in maintenance requirements rather than just a change in the type of maintenance.	1,3-6	?	M/L	I
7h	Increased complexity/modularity of technology	This is not an exclusive result of the introduction of CBM. Could be: positive in the sense that more complex technology will likely have HUMS and self-test functions built in, with reduced turn-around times due to increased modularity and better fault detection and isolation capabilities; negative in the sense that modular replacement may reduce maintenance skills at the 'coalface' and may require more specialised skills for repair of the modules/LRUs themselves.	potential requirement for specialist skills for low-level maintenance, increased training costs	potential reductions in maintenance costs and gains in asset utilisation through faster turn-around times (modular replacement)	maintainers, workshop managers, materiel suppliers		3,6	+/-	S/M/L	I
7i	Increased Information and Communication Technology (ICT) in workshops	This is primarily associated with automated collection and transmission of vehicle health and usage information, and the increased use of this information for decision support. Increased ICT in workshops is a trend that is already happening.	costs involved with procuring and maintaining the appropriate ICT, including hardware and software; training costs.	savings flowing from more efficient and effective workshops	maintenance personnel, logistics personnel		6,7	?	S/M	D
7j	Improved utilisation of tradespeople, particularly for Preventive Maintenance	This follows from better informed, better targeted maintenance.		increased ability to perform maintenance through increased productivity	maintenance personnel, workshop managers		4,6	+	S/M/L	D
7k	Technical repair/refurbishment pushed to rearward maintenance workshops	This refers to having smaller 1st Line and larger 3rd and 4th Line facilities, and includes a reduced technical presence at Unit level, and a reduction in support equipment in the field. (Note that there won't necessarily be a reduction in the amount of support equipment required overall.) This will follow from the trend toward modularisation and repair-by-replacement, and the increase in BIT/BITE, and commonality across embedded diagnostics/prognostics.	establishing the new structure and protocols/procedures	more efficient workshops, reduced test equipment purchase costs, reduced transport costs (following from modularisation - transport the modules, rather than the whole platform)	maintenance personnel (maintainers, workshop managers), fleet managers			+	M/L	I
8	**Changes in logistic processes**									
8a	Improved remote assistance capability	The notion of tele-maintenance or remote maintenance assistance becomes feasible with the collection of (near) real-time health and usage data, where advice can be provided by a small set of Subject Matter Experts (SMEs) without requiring those SMEs to travel to the location of the maintenance support requirement.	Data-transmission costs	Reduced cost of vehicle and/or SME transportation to the site of equipment failure	Equipment operators, maintenance personnel, equipment/maintenance Subject matter experts	That equipment/platform status information can be transmitted over long distances in (near) real-time	4,6	+	S/M	D
8b	Integrated changes in maintenance and supply processes	This refers to the potential to integrate HUMS, CBM and the supply chain in order to take mutual advantage of what each offers. For example, foreknowledge of spare parts demand provided by HUMS may help to preposition the required spare parts appropriately.	Change management costs, including training, Standard Operating Procedure development, administration costs, monitoring costs	Productivity/efficiency gains due to maintenance and supply optimisation	ADF policy-makers, logistics personnel, maintenance personnel, supply personnel		1,2,4-7	?	S/M	D

ID	Title	Description	Indicative $$$ COSTS	Indicative $$$ SAVINGS	Stakeholders	Assumptions	FIC	+ / -/?	(S)hort, (M)edium or (L)ong-term	(D)irect/ (I)ndirect
8c	Improved management of maintenance/sustainment contracts, and of warranties for components/platforms	For example, HUMS data can provide an objective assessment of the fulfilment of contractual obligations, or through assessing the quality of the platform for contractual/payment purposes.		reduction in legal fees, admin related to warranty claims, admin related to evaluating if contractual obligations have been met, improved contractual outcomes, improved warranty outcomes			1,6	+	M/L	I
8d	Better supply planning, including for when on deployment.	A cogent picture of fleet health will aid in the provisioning of supplies, including for when deploying.		ability to position inventory in a more informed manner			1,5	+	M	D
8e	Shift from repair-focus to module replacement	Associated with increasing complexity of technology in general	Increased cost of replacement modules	Reduced cost of repairs and training of maintenance personnel	maintenance personnel, supply personnel		3-6	?	M/L	I
8f	More efficient and responsive supply processes	This may be achieved through a reduction in Administrative and Logistics Down Time (ALDT) delays; improved spares availability, a reduction in stock-outs, correct type and stocking levels of replacement parts and lubricants; better predictive stocking of high usage spare parts based on the work effort being applied to the equipment in a particular unit and not based on recent usage rates as a sole means of determining the stock holding. The latter is particularly advantageous when a Unit increases its work tempo without the recent usage rate data to trigger changes to stock holdings. This may also be associated with automatic re-ordering processes and sense-and-respond actions. However, any efficiency gains depend on the ERP used and design of the supply system in general - supply of spares sits within a broader logistic supply system for other commodities.	reduced labour costs in generation of demands, Change management costs, including training, Standard Operating Procedure development, (documentation costs), administration costs, monitoring costs	Reduced reliance on urgent means of transportation for spare parts; reduced inventory holding costs; maximisation of contracting opportunities, Reduced labour costs in generation of demands	Logistics personnel, supply personnel, maintenance personnel	That combined optimisation of maintenance and supply processes takes place. Any efficiency gains depend on the Enterprise Resource Planning tools used and design of the supply system in general - supply of spares is but one facet within a broader logistic supply system for many other commodities.	1,2,4-7	+	M/L	I
8g	**Potential impact on** inventory holdings at supply chain nodes	It is conceivable that this could be achieved through a reduction in holdings of consumable items like lubricants etc. and potentially a reduction in Repair Parts Stores stock holdings, but is most likely to be achieved in an in-barracks setting rather than when on deployment. Note that for a given level of logistics capability, any spare space is likely to be taken up by other supplies/functions.	Potentially increased cost of replacement (vs repair) parts	Reduced inventory holding costs, reduced transportation costs (especially for urgent demands), reduced cost of spares, reduced logistic footprint ownership costs	Supply personnel, logistics personnel, operational planners, maintenance personnel	That there is sufficiently responsive supply of parts from the National Support Base (NSB)/Original Equipment Manufacturer (OEM) nodes. Requires the development of CBM-driven spare parts inventory control strategy.	1,5,6,7	?	M/L	I
8h	**Potential impact on supply chain costs**	Potentially in conflict with other assertions surrounding reduced footprint and usage, better planning, better management etc..					5,6,7	?		
8i	Management of CBM spare parts within the supply chain	This refers to the physical components that make up a CBM system, e.g. the sensors and data loggers that were not previously managed through the supply chain.	increase in footprint due to new spare parts being inserted	potential reduction in overall total inventory			5	?	S	D
8j	Increased availability of space/infrastructure for other logistic functions	Space freed up through reductions in spare parts footprint may be taken up by other logistic functions.		Reduced transportation costs for logistics infrastructure	Logistics personnel, operational planners	That labour and space savings are significant enough to make a difference overall, and are not diluted by the maintenance requirements of the CBM system itself	1,5,6,7	+	M/L	I

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9	**Effects on Equipment/ Platform**									
9a	Improved safety in the operation of equipment/platforms			Reduced injury management costs	Equipment operators, passengers		3,4	+	M/L	I
9b	Reduced recovery requirements	Fewer operational failures while on deployment will reduce the requirement for equipment recovery, which is especially beneficial if recovery must occur under fire.		Reduced recovery costs and potential injury management costs; reduced indirect costs associated with recovery, e.g. delays	Equipment operators, recovery personnel, maintenance personnel, logistics personnel, operational planners		1,3,4,6	+	S/M	I
9c	Reduced operational failure rates and improved operational reliability of equipment/platforms	Having better insight/knowledge into the condition of individual vehicles/platforms, and of the fleet as a whole, will facilitate better informed decision-making when planning for deployment		Reduced costs of recovery, repair, replacement, personnel injury management, and indirect costs associated with operational set-backs	Equipment operators, passengers, recovery personnel, maintenance personnel, operational planners, logistics personnel		1,3,4,6	+	S/M	D
9d	Reduced catastrophic failure rates of equipment/platforms	This is associated with the reduced impact of equipment failure and reduced collateral damage through better information about equipment health.		Reduced repair and replacement costs; reduced indirect costs of catastrophic failure (delays, etc.); reduced rebuild requirements during depot overhaul; potential reductions in insurance costs	Equipment operators, maintenance personnel, fleet managers	Only if available HUMS data is acted on in a timely manner.	3,4,6	+	M	D
9e	**Potential impact on** equipment/platform down time	A decrease in down time could be achieved through improved diagnostics and a more efficient/effective supply chain. An increase in down-time may occur as spare parts become obsolete, scarce, and consequently harder to source, when fleets are extended beyond their nominal Life-of-Type.	costs related to reduced operational availability	Reduced productivity losses due to maintenance	Equipment operators, maintenance personnel, operational planners, logistics personnel	That an effective spares pipeline and effective supply chain management is in place.	1,3,4,6	?	S/M/L	I
9f	Increase in operational availability and capability of equipment/platforms	Or, at the least, an increase in the confidence of equipment availability, facilitating more confident deployment planning.		Reduced cost of initial spares inventory; reduced costs associated with operational failures (including recovery, repair, injury management, and operational delays)	Equipment operators, maintenance personnel, operational planners, logistics personnel		1-4,6	+	S/M	D/I
9g	Difficulty in obtaining parts and technical knowledge as fleets age		Increased spare part cost, particularly if one-off runs to produce spare parts are required; research into substitutes				3,5,6,7	-	L	I
9h	Increased/more predictable Equipment Life			Reduced cost of replacing equipment/platforms; increased return on investment (ROI)	Fleet managers, end-users, maintenance personnel, capability development/ acquisition organisations		2,3,5,6	+	L	I
9i	Reduced fleet size requirement	This is potentially as a result of improved operational availability/capability.		reduced cost of procurement/ replacing equipment/ platforms; savings on fuel, maintenance and spares; savings on inventory holding costs	Fleet managers, capability development/acquisition organisations, operational planners, strategic planners		1,2,3,5, 6,7	+	L	I

ID	Title	Description	Indicative $$$ COSTS	Indicative $$$ SAVINGS	Stakeholders	Assumptions	FIC	+ / -/?	(S)hort, (M)edium or (L)ong-term	(D)irect/ (I)ndirect
10	**Human factor effects**									
10a	Resistance to change	There may be resistance to changes to associated maintenance and logistics processes, through perceptions of an increased training burden, increased complexity of equipment operation, the potential for job losses, and "spy in the cab" syndrome	Costs of delays in implementation of new technologies and processes; inefficient use of technologies		end-users, logistics personnel, maintenance personnel, operational planners, strategic planners, ADF policy-makers, fleet managers		1,2,4,5, 6	-	S	D
10b	Lack of immediately observable benefits from data collection	If operators/maintainers cannot readily see the benefits of any 'additional' data collection, they are less likely to do it in preference to other work perceived as having greater importance.			Equipment operators, maintenance personnel, fleet managers, data analysts		4,6	-	S	D
10c	Reluctance to record and download relevant data by operators	Can be summed up by "if it is not easy to use, it won't be used".	Loss of potential long-term efficiency gains		Equipment operators, maintenance personnel		3,4,6	-	S	I
10d	Potential change in the accuracy of information underpinning decision-support	A possible effect of the introduction of new technologies of which there is no readily apparent benefit is that the technology won't be utilised effectively. If HUMS data collection is not automated, there is the risk that, through resistance to change and other cultural issues, the quality and quantity of HUMS data recorded will diminish.	Loss of expected efficiency gains with operational decision-support applications		Logistics personnel, operational planners		1,4	?	S/M	I
10e	Cultivation of culture of equipment ownership/excellence			Reduced costs associated with inadequate care and inappropriate use of equipment/platforms	Equipment operators, maintenance personnel	That there is trust in CBM-generated equipment/platform health information	4,6	+	M/L	I
10f	Increased confidence in the use of equipment/platforms	Includes increased confidence in use of equipment as well as confidence in use of equipment beyond the expected equipment life		Reduced cost of replacing equipment beyond its expected service life but still in working condition	Equipment operators, passengers	That there is trust in CBM-generated equipment/platform health information	4	+	M/L	I
10g	Improved operator performance	This may be achieved through e.g. enhanced or personalised training afforded by HUMS feedback		Reduction in costs associated with inappropriate/inefficient equipment use	Equipment operators	That personnel are employed who tailor training to individual operators	4	+	M/L	I
10h	Improved troop morale			improvements in worker efficiency	Equipment operators, passengers, maintenance personnel		4,6	+	M/L	I
11	**Impact on mission effectiveness**									
11a	Improved mission effectiveness			Reduced costs associated with mission failures (e.g. delays, recovery, injury management); more efficient use of resources	strategic planners, operational planners, equipment operators, logistics personnel, fleet managers		1-7	+	M/L	I
11b	Improved decision support for mission assignment of equipment/platforms	A picture of the health of assets can inform the assignment of assets to missions. HUMS has the ability to augment the picture of asset health currently generated by maintainers and maintenance managers.	Cost of integration of CBM-generated information with C2 systems; cost of specific decision-support modules	Potentially reduced overall operational costs; avoidance of operational failure costs	Operational planners, logistics personnel, fleet managers	That CBM-generated equipment health information is utilised in mission planning processes; that relevant, effective and accurate information is available to support the decision-making process	1,3	+	S/M	I

Appendix J. Details of Java Code Used for Graph Analysis of the Impacts Maps

J.1. Java Code

J.1.1 ExamineCausalImpactMap.java

```
import java.util.Vector;

/**
 * The 'main' class for the Causal Impacts Map analysis code.
 * @author Guy Edward Gallasch, 22 May 2014
 *
 */
public class ExamineCausalImpactMap {

  /**
   * Main method.
   * @param args Not used.
   */
  public static void main(String[] args) {
    // TODO Auto-generated method stub

    //Parameters for the Causal Impacts Map analysis.
    //For pragmatic reasons, this information is hard-coded.
    boolean isInputImpacts = true; //true indicates the map is an input impacts map, false
indicates an output impacts map

    String inputFilePath = "D:/Documents and Settings/gallasge/My Documents/DSTO/";
    String inputFileName = "Final Input Impacts automaton.txt";

    String outputFilePath = "D:/Documents and Settings/gallasge/My Documents/DSTO/";
    String outputFileName = "Final Input Impacts Analysis Report.txt";

    //Create the analysis object
    Analysis analysis = new Analysis(isInputImpacts);

    //Read in the Causal Impacts Map for analysis
    analysis.readInput(inputFilePath, inputFileName);

    //Initiate the analysis
    analysis.analyse();

    //Record the analysis results
    analysis.reportResults(outputFilePath,outputFileName);
  }
}
```

J.1.2 Analysis.Java

```
import java.io.BufferedReader;
import java.io.FileReader;
import java.io.FileWriter;
import java.io.IOException;
import java.io.PrintWriter;
import java.util.Enumeration;
import java.util.Iterator;
import java.util.Stack;
import java.util.StringTokenizer;
import java.util.Vector;
```

```
/**
 * Java code for analysing Causal Impacts Maps
 * @author Guy Edward Gallasch, 22 May 2014
 *
 */
public class Analysis {

  //  Variables  for  storing  the  list  of  nodes,  the  'start  nodes'  (nodes  without
predecessors),
  // the 'end nodes' (nodes without successors), and isolated nodes (nodes without either).
  private Vector<Node> listOfNodes = null;
  private Vector<Node> startNodes = null;
  private Vector<Node> endNodes = null;
  private Vector<Node> isolatedNodes = null;


  //Variables for paths, loops and associated results
  private Vector<Path> paths = null;
  private Vector<Path> cycles = null;
  private int minPathLength = 0;
  private int maxPathLength = 0;
  private int minCycleLength = 0;
  private int maxCycleLength = 0;
  private int[] histogramCycleLength = null;
  private int[] histogramPathLength = null;
  private Integer[] pathsFromEachStartingNode = null;
  private Integer[] pathsToEachEndingNode = null;
  Vector<Node> nodesNotLinkedToCBMCapability = null;

  //Variables  for  calculating  and  storing  strongly  connected  components  (SCCs)  using  a
Tarjan-like approach
  private boolean[][] reachabilityMatrix;
  private Vector<Vector<Node>> SCCs = null;

  //Variables for storing sorted node ingress and egress results
  private Vector<Node> decreasingIngress = null;
  private Vector<Node> decreasingEgress = null;
  private Vector<Node> decreasingCombinedIngressEgress = null;

  //Variables to facilitate a recursive depth-first-search of the Causal Impacts Map, and
for storing the results
  private Stack<Node> stack = null;
  private Vector<Node> yetToExplore = null;

  //variables  for  storing  results  about  the  prevalence  of  nodes  in  cycles  and  paths,  and
corresponding path criticalities
  Vector<Node> prevalenceInCycles = null;
  Vector<Node> prevalenceInPaths = null;
  Vector<Path> pathCriticalityBasedOnNodePrevalence = null; //new Vector<Path>();
  Vector<Path> pathCriticalityBasedOnNodeIngressEgress = null;

  //A switch for adjusting the output based on whether the Causal Impacts Map being examined
is an input impacts map or an output impacts map
  private boolean isInputImpacts;


  /** Constructor for the Analysis class.
   *  @param  isInputImpacts  A  switch  that  indicates  whether  the  map  being  analysed  is  an
input impacts map or an output impacts map.
   */
  public Analysis (boolean isInputImpacts) {
    this.isInputImpacts = isInputImpacts;
  }

  /**
   * Method for reading the impacts map from the files indicated by the two arguments.
   * @param inputFilePath The path of the file containing the map to analyse.
   * @param inputFileName The name of the file containing the map to analyse.
   */
  public void readInput(String inputFilePath, String inputFileName) {
```

```
    //Local variable declarations
    BufferedReader inputFile = null;
    String line, newSuccID, newNodeID;
    StringTokenizer tokenizer;
    Node newNode = null, newSucc, test;
    listOfNodes = new Vector<Node>();

    //Read in the impacts map
    try {
      //Open the input file at the specified location
      inputFile = new BufferedReader(new FileReader(inputFilePath + inputFileName));

      //Read and parse each line in the input file
      while(inputFile.ready()) {

        //Read in a line comprising a node (impact) and a list of successor nodes
        line = inputFile.readLine();
        newNode = null;
        tokenizer = new StringTokenizer(line,",");
        newNodeID = tokenizer.nextToken();

        //Check whether this particular node has been seen before
        for(Enumeration<Node>e = listOfNodes.elements(); e.hasMoreElements(); ) {
          test = e.nextElement();
          if(test.getID().equals(newNodeID)) {
            newNode = test;
            break;
          }
        }

        //If it hasn't, then create a new node and add it to the list of nodes
        if(newNode == null) {
          newNode = new Node(newNodeID);
          listOfNodes.add(newNode);
        }

        //Now, process each of the successor nodes to this node
        while(tokenizer.hasMoreTokens()) {
          newSuccID = tokenizer.nextToken();
          newSucc = null;

          //Check whether this particular successor has been seen before
          for(Enumeration<Node> e = listOfNodes.elements(); e.hasMoreElements(); ) {
            test = e.nextElement();
            if(test.getID().equals(newSuccID)) {
              newSucc = test;
              break;
            }
          }

          //If it hasn't, then create a new node and add it to the list of nodes
          if (newSucc == null) {
            newSucc = new Node(newSuccID);
            listOfNodes.add(newSucc);
          }

          //Add this successor node to the list of successors of the node corresponding to
this line of the input file
          newNode.addSuccessor(newSucc);

          //Add  the  node  corresponding  to  this  line  of  the  input  file  to  the  list  of
predecessors of this successor node
          newSucc.addPredecessor(newNode);

        }

      }

      //Close the input file.
      inputFile.close();
    } catch (IOException f) {
```

```
        f.printStackTrace();
        if(inputFile != null)
          try {
            inputFile.close();
          } catch (IOException g) {
            g.printStackTrace();
          }
          System.exit(1);
      }
    }


    /**
     * A method for performing analysis on the impacts map stored within this object.
     */
    public void analyse() {

      //Local variable declarations
      Node node = null;

      //Scan through the nodes and identify those without predecessors (i.e. these are 'start
  nodes')
      startNodes = new Vector<Node>();
      for(Enumeration<Node> e = listOfNodes.elements(); e.hasMoreElements(); ) {
        node = e.nextElement();
        if(node.getPredecessors().size() == 0)  {
          startNodes.add(node);
        }
      }

      //Scan through the nodes and identify those without successors (i.e. these are 'end
  nodes')
      endNodes = new Vector<Node>();
      for(Enumeration<Node> e = listOfNodes.elements(); e.hasMoreElements(); ) {
        node = e.nextElement();
        if(node.getSuccessors().size() == 0)  {
          endNodes.add(node);
        }
      }

      //Scan through the nodes and identify those without successors or predecessors (i.e.
  these are 'isolated nodes')
      isolatedNodes = new Vector<Node>();
      for(Enumeration<Node> e = listOfNodes.elements(); e.hasMoreElements(); ) {
        node = e.nextElement();
        if(node.getSuccessors().size() == 0 && node.getPredecessors().size() == 0)  {
          isolatedNodes.add(node);
        }
      }


      //Order the nodes by decreasing ingress, egress and ingress+egress
      decreasingIngress = new Vector<Node>();
      decreasingEgress = new Vector<Node>();
      decreasingCombinedIngressEgress = new Vector<Node>();

      //For each node...
      for(int index = 0; index < listOfNodes.size(); index++) {
        node = listOfNodes.elementAt(index);

        //...get the ingress, egress and sum of ingress and egress...
        int ingress = node.ingress();
        int egress = node.egress();
        int ingressEgress = node.ingressEgress();

        //... locate the correct place to insert this node into each of the three ordered
  lists...
        int ingressVectorPosition = 0;
        int egressVectorPosition = 0;
        int combinedIngressEgressVectorPosition = 0;
```

```
      while(ingressVectorPosition < decreasingIngress.size() && ingress <=
decreasingIngress.elementAt(ingressVectorPosition).ingress()) {
        ingressVectorPosition++;
      }
      while(egressVectorPosition < decreasingEgress.size() && egress <=
decreasingEgress.elementAt(egressVectorPosition).egress()) {
        egressVectorPosition++;
      }
      while(combinedIngressEgressVectorPosition < decreasingCombinedIngressEgress.size() &&
ingressEgress <=
decreasingCombinedIngressEgress.elementAt(combinedIngressEgressVectorPosition).ingressEgress
()) {
        combinedIngressEgressVectorPosition++;
      }

      //... and then insert the node in the appropriate places in the three sorted lists
      decreasingIngress.insertElementAt(node, ingressVectorPosition);
      decreasingEgress.insertElementAt(node, egressVectorPosition);
      decreasingCombinedIngressEgress.insertElementAt(node,
combinedIngressEgressVectorPosition);
    }


    //Prepare for the recursive depth-first search, which will determine the set of all
paths and cycles within the Causal Impacts Map,
    // as well as the mutual reachability of all nodes within the Causal Impacts Map
    paths = new Vector<Path>();
    cycles = new Vector<Path>();
    stack = new Stack<Node>();
    yetToExplore = new Vector<Node>(startNodes);

    //Initialise (to false) a boolean matrix for storing reachability information, i.e.
which nodes can reach which other nodes
    reachabilityMatrix = new boolean[listOfNodes.size()][listOfNodes.size()];
    for (int row = 0; row < listOfNodes.size(); row++) {
      for (int column = 0; column < listOfNodes.size(); column++) {
        reachabilityMatrix[row][column] = false;
      }
    }

    //Initiate a recursive depth-first search for each starting node.
    while(yetToExplore.size() > 0) {
      stack.push(yetToExplore.remove(0));
      recurse();
    }

    //Using the information in the reachability matrix, which at this point contains the
transitive closure of the causal relationships between nodes,
    // extract the strongly connected components (SCCs), which are maximal subsets of nodes
that are mutually reachable (hence by definition are disjoint).
    SCCs = new Vector<Vector<Node>>();
    for(int row = 0; row < listOfNodes.size(); row++) {
      Vector<Node>scc = new Vector<Node>();
      if(!reachabilityMatrix[row][row]) {
        reachabilityMatrix[row][row] = true;
        scc.add(listOfNodes.elementAt(row));
        for(int column = 0; column < listOfNodes.size(); column++)  {
          if(row != column) {
            if(reachabilityMatrix[row][column] == true && reachabilityMatrix[column][row] ==
true) {
              reachabilityMatrix[column][column] = true;
              scc.add(listOfNodes.elementAt(column));
            }
          }
        }
      }
      if(scc.size() > 0) {
        SCCs.add( (Vector<Node>) scc.clone());
      }
    }
```

```
    //Scan through the cycles detected by the recursive depth-first-search and determine the
longest and shortest lengths therein
    if(cycles.size() > 0) {
      minCycleLength = cycles.elementAt(0).size();
      maxCycleLength = minCycleLength;
    }
    for(int index = 0; index < cycles.size(); index++) {
      if(cycles.elementAt(index).size() < minCycleLength) {
        minCycleLength = cycles.elementAt(index).size();
      }
      if(cycles.elementAt(index).size() > maxCycleLength) {
        maxCycleLength = cycles.elementAt(index).size();
      }
    }

    //Compile a histogram of cycle lengths
    histogramCycleLength = new int[maxCycleLength-minCycleLength+1];
    for(int index = 0; index < cycles.size(); index++) {
      histogramCycleLength[cycles.elementAt(index).size() - minCycleLength]++;
    }

    //Scan through the cycles to determine the prevalence of nodes within cycles, by
incrementing the appropriate counter every
    // time the respective node is encountered in a cycle
    for(int index = 0; index < cycles.size(); index++) {
      for(Iterator<Node> e = cycles.elementAt(index).iterator(); e.hasNext(); ) {
        e.next().incrementPrevalenceInCycles();
      }
    }


    //Scan through the paths detected by the recursive depth-first-search and determine the
longest and shortest lengths therein
    if(paths.size() > 0) {
      minPathLength = paths.elementAt(0).size();
      maxPathLength = minPathLength;
    }
    for(int index = 0; index < paths.size(); index++) {
      if(paths.elementAt(index).size() < minPathLength) {
        minPathLength = paths.elementAt(index).size();
      }
      if(paths.elementAt(index).size() > maxPathLength) {
        maxPathLength = paths.elementAt(index).size();
      }
    }

    //Compile a histogram of path lengths
    histogramPathLength = new int[maxPathLength-minPathLength+1];
    for(int index = 0; index < paths.size(); index++) {
      histogramPathLength[paths.elementAt(index).size() - minPathLength]++;
    }


    //Scan through the paths to determine the prevalence of nodes within paths, by
incrementing the appropriate counter every
    // time the respective node is encountered in a path

    //At the same time, determine which paths start from each of the 'start nodes' and which
lead to each of the 'end nodes'
    pathsFromEachStartingNode = new Integer[startNodes.size()];
    for(int index = 0; index < startNodes.size(); index++) {
      pathsFromEachStartingNode[index] = new Integer(0);
    }
    pathsToEachEndingNode = new Integer[endNodes.size()];
    for(int index = 0; index < endNodes.size(); index++) {
      pathsToEachEndingNode[index] = new Integer(0);
    }

    //Special application-specific case: also determine which of the nodes (if any) are not
covered by a path that leads to/from the 'CBM Capability' node
    nodesNotLinkedToCBMCapability = (Vector<Node>) listOfNodes.clone();
```

```
    for(int index = 0; index < paths.size(); index++) {
      for(Iterator<Node> e = paths.elementAt(index).iterator(); e.hasNext(); ) {
        node = e.next();
        node.incrementPrevalenceInPaths();
        if(isInputImpacts) {
          if(paths.elementAt(index).lastElement().getID().equals("CBM Capability")) {
            nodesNotLinkedToCBMCapability.remove(node);
          }
        }
        else {
          if(paths.elementAt(index).firstElement().getID().equals("CBM Capability")) {
            nodesNotLinkedToCBMCapability.remove(node);
          }
        }
      }

pathsFromEachStartingNode[startNodes.indexOf(paths.elementAt(index).firstElement())]++;
      pathsToEachEndingNode[endNodes.indexOf(paths.elementAt(index).lastElement())]++;
    }

    //Now, sort the nodes in descending order based on the prevalence of node counts in
cycles
    prevalenceInCycles = new Vector<Node>();
    int newIndex = 0;
    for(int index = 0; index < listOfNodes.size(); index++) {
      if(listOfNodes.elementAt(index).getPrevalenceInCycles() > 0) {
        newIndex = 0;
        while(newIndex < prevalenceInCycles.size() &&
listOfNodes.elementAt(index).getPrevalenceInCycles() <
prevalenceInCycles.elementAt(newIndex).getPrevalenceInCycles())
          newIndex++;
        prevalenceInCycles.insertElementAt(listOfNodes.elementAt(index), newIndex);
      }
    }

    //Now, sort the nodes in descending order based on the prevalence of node counts in
paths
    prevalenceInPaths = new Vector<Node>();
    for(int index = 0; index < listOfNodes.size(); index++) {
      if(listOfNodes.elementAt(index).getPrevalenceInPaths() > 0) {
        newIndex = 0;
        while(newIndex < prevalenceInPaths.size() &&
listOfNodes.elementAt(index).getPrevalenceInPaths() <
prevalenceInPaths.elementAt(newIndex).getPrevalenceInPaths())
          newIndex++;
        prevalenceInPaths.insertElementAt(listOfNodes.elementAt(index), newIndex);
      }
    }

    //Now, sort the start nodes based on how many paths start from that node
    Vector<Node> sortedStartNodes = new Vector<Node>();
    Vector<Integer> sortedPathsFromEachStartingNode = new Vector<Integer>();
    for(int index = 0; index < startNodes.size(); index++) {
      newIndex = 0;
      while(newIndex < sortedStartNodes.size() && pathsFromEachStartingNode[index] <
sortedPathsFromEachStartingNode.elementAt(newIndex))
        newIndex++;
      sortedStartNodes.insertElementAt(startNodes.elementAt(index), newIndex);
      sortedPathsFromEachStartingNode.insertElementAt(pathsFromEachStartingNode[index],
newIndex);
    }
    startNodes = sortedStartNodes;
    pathsFromEachStartingNode = sortedPathsFromEachStartingNode.toArray(new
Integer[startNodes.size()]);

    //Now, sort the end nodes based on how many paths end in that node
    Vector<Node> sortedEndNodes = new Vector<Node>();
    Vector<Integer> sortedPathsToEachEndingNode = new Vector<Integer>();
    for(int index = 0; index < endNodes.size(); index++) {
      newIndex = 0;
```

```
      while(newIndex < sortedEndNodes.size() && pathsToEachEndingNode[index] <
sortedPathsToEachEndingNode.elementAt(newIndex))
        newIndex++;
      sortedEndNodes.insertElementAt(endNodes.elementAt(index), newIndex);
      sortedPathsToEachEndingNode.insertElementAt(pathsToEachEndingNode[index], newIndex);
    }
    endNodes = sortedEndNodes;
    pathsToEachEndingNode = sortedPathsToEachEndingNode.toArray(new
Integer[endNodes.size()]);

    //Calculate two measures of path criticality, based on:
    // 1. The combined 'prevalence of nodes' score of all nodes in a path, normalised by the
length of the path
    // 2. The combined sum of ingress and egress of all nodes in a path, normalised by the
length of the path
    float criticalityBasedOnNodePrevalence, criticalityBasedOnNodeIngressEgress;
    for(int index = 0; index < paths.size(); index++) {
      criticalityBasedOnNodePrevalence = 0;
      criticalityBasedOnNodeIngressEgress = 0;
      for(Enumeration<Node> e = paths.elementAt(index).elements(); e.hasMoreElements(); ) {
        node = e.nextElement();
        criticalityBasedOnNodePrevalence = criticalityBasedOnNodePrevalence +
node.getPrevalenceInPaths();
        criticalityBasedOnNodeIngressEgress = criticalityBasedOnNodeIngressEgress +
node.ingressEgress();
      }

paths.elementAt(index).setCriticalityByNodePrevalence(Math.round(100*criticalityBasedOnNodeP
revalence/paths.elementAt(index).size())/100.0f);

paths.elementAt(index).setCriticalityByNodeIngressEgress(Math.round(100*criticalityBasedOnNo
deIngressEgress/paths.elementAt(index).size())/100.0f);
    }

    //Sort the paths in descending order based on criticality as determined by prevalence of
nodes scores
    pathCriticalityBasedOnNodePrevalence = new Vector<Path>();
    for(int index = 0; index < paths.size(); index++) {
      newIndex = 0;
      while(newIndex < pathCriticalityBasedOnNodePrevalence.size() &&
paths.elementAt(index).getCriticalityByNodePrevalence() <
pathCriticalityBasedOnNodePrevalence.elementAt(newIndex).getCriticalityByNodePrevalence() )
        newIndex++;
      pathCriticalityBasedOnNodePrevalence.insertElementAt(paths.elementAt(index),
newIndex);
    }

    //Sort the paths in descending order based on criticality as determined by node ingress
and egress
    pathCriticalityBasedOnNodeIngressEgress = new Vector<Path>();
    for(int index = 0; index < paths.size(); index++) {
      newIndex = 0;
      while(newIndex < pathCriticalityBasedOnNodeIngressEgress.size() &&
paths.elementAt(index).getCriticalityByNodeIngressEgress() <
pathCriticalityBasedOnNodeIngressEgress.elementAt(newIndex).getCriticalityByNodeIngressEgres
s() )
        newIndex++;
      pathCriticalityBasedOnNodeIngressEgress.insertElementAt(paths.elementAt(index),
newIndex);
    }
  }


  /**
   * A method for writing the results to the report file specified by the two input
arguments.
   * @param outputFilePath The path of the report file to contain the results.
   * @param outputFileName The name of the report file to contain the results.
   */
  public void reportResults(String outputFilePath, String outputFileName) {
```

```
    //Local variable declarations
    PrintWriter out = null;

    //Write the results file
    try {
      //Open the results file for writing
      out = new PrintWriter(new FileWriter(outputFilePath + outputFileName));


      //Write the report header
      out.println("Report on the " + (isInputImpacts ? "Input" : "Output") + " Impacts
Map");
      out.println("-------------------------------" + (isInputImpacts ? "\n" : "-\n"));

      //Write the results on starting, ending and isolated nodes
      out.println("Starting and Ending (Terminating) Nodes:");
      out.println("----------------------------------------\n");

      //First, the start nodes...
      out.println("Start Nodes (nodes without predecessors):");
      if(startNodes.size() == 0) {
        out.println("There are no nodes without predecessors.");
      }
      else {
        out.println("There are " + startNodes.size() + " start nodes, comprising:");
        for(Enumeration<Node>e = startNodes.elements(); e.hasMoreElements(); )
          out.println(e.nextElement());
      }
      out.println();


      //... then the end nodes...
      out.println("End Nodes (nodes without successors):");
      if(endNodes.size() == 0) {
        out.println("There are no nodes without successors.");
      }
      else {
        out.println("There are " + endNodes.size() + " end nodes, comprising:");
        for(Enumeration<Node>e = endNodes.elements(); e.hasMoreElements(); )
          out.println(e.nextElement());
      }
      out.println();


      //....and then the isolated nodes
      out.println("Isolated Nodes (nodes without successors AND without predecessors):");
      if(isolatedNodes.size() == 0) {
        out.println("There are no nodes without either successors or predecessors.");
      }
      else {
        out.println("There are " + isolatedNodes.size() + " isolated nodes, comprising:");
        for(Enumeration<Node>e = isolatedNodes.elements(); e.hasMoreElements(); )
          out.println(e.nextElement());
      }
      out.println();


      //Write the results on node Ingress and Egress
      out.println("Node Ingress and Egress:");
      out.println("------------------------\n");

      //Firstly, node ingress...
      out.println("Nodes, ordered by ingress:");
      for(int index = 0; index < decreasingIngress.size(); index++) {
        out.print("Ingress of " + decreasingIngress.elementAt(index).ingress() + ": " +
decreasingIngress.elementAt(index) + " <- ");

        //Also record the identities of the predecessor nodes
        for(Enumeration<Node>e                                                          =
decreasingIngress.elementAt(index).getPredecessors().elements(); e.hasMoreElements(); ) {
          out.print(e.nextElement()+ " ");
```

```
          }
          out.println();
        }
        out.println();

        //... then node egress...
        out.println("Nodes, ordered by egress:");
        for(int index = 0; index < decreasingEgress.size(); index++) {
          out.print("Egress  of  "  +  decreasingEgress.elementAt(index).egress()  +  ":  "  +
decreasingEgress.elementAt(index) + " -> ");

          //Also record the identities of the successor nodes
          for(Enumeration<Node>e                                                              =
decreasingEgress.elementAt(index).getSuccessors().elements(); e.hasMoreElements(); )  {
            out.print(e.nextElement()+ " ");
          }
          out.println();
        }
        out.println();

        //... then the combined node ingress and egress
        out.println("Nodes, ordered by ingress+egress:");
        for(int index = 0; index < decreasingCombinedIngressEgress.size(); index++) {
          out.print("Ingress+Egress                  of                   "                  +
decreasingCombinedIngressEgress.elementAt(index).ingressEgress() + ": ");

          //Also record the identities of the predecessor nodes...
          for(Enumeration<Node>e                                                              =
decreasingCombinedIngressEgress.elementAt(index).getPredecessors().elements();
e.hasMoreElements(); )  {
            out.print(e.nextElement()+ " ");
          }
          out.print("-> " + decreasingCombinedIngressEgress.elementAt(index) + " -> ");

          //... and the successor nodes
          for(Enumeration<Node>e                                                              =
decreasingCombinedIngressEgress.elementAt(index).getSuccessors().elements();
e.hasMoreElements(); )  {
            out.print(e.nextElement()+ " ");
          }
          out.println();
        }
        out.println();


        //Write the results on mutual dependencies, i.e. the strongly connected components
        out.println("Mutual Dependencies:");
        out.println("--------------------");
        out.println();

        //Count the number of non-trivial SCCs (SCCs comprising more than one node)
        int nontrivial=0;
        for(int index = 0; index < SCCs.size(); index++) {
          if(SCCs.elementAt(index).size() > 1)
            nontrivial++;
        }

        //Record the total number of SCCs, and the number that are non-trivial
        out.println("Number of SCCs is " + SCCs.size());
        out.println("Number of non-trivial SCCs is " + nontrivial);
        out.println();

        //Record the identities of the nodes comprising each non-trivial SCC
        for(int index = 0; index < SCCs.size(); index++) {
          if(SCCs.elementAt(index).size() > 1) {
            out.println("Non-trivial SCC:");
            for(Enumeration<Node> e = SCCs.elementAt(index).elements(); e.hasMoreElements(); )
{
              out.print(e.nextElement() + " ");
            }
            out.println();
```

```
          out.println();
        }
      }


      //Record the results on Cycles and Paths
      out.println("Cycles and Paths:");
      out.println("-----------------");
      out.println();

      //Record  the  basic  statistics  on  number  of  elementary  cycles,  maximum  and  minimum
cycle length
      out.println("Number of elementary cycles: " + cycles.size());
      out.println("Maximum cycle length: " + maxCycleLength);
      out.println("Minimum cycle length: " + minCycleLength);
      out.println();

      //Record the cycle length histogram
      out.println("Histogram  of  Cycle  Lengths  (cycle  length,  instances  of  cycles  of  that
length):");
      for(int index = 0; index < maxCycleLength-minCycleLength+1; index++) {
        out.println("("  +  (index  +  minCycleLength)  +  ","  +  histogramCycleLength[index]  +
")");
      }
      out.println();

      //Record the results on the prevalence of nodes within cycles
      Node node = null;
      out.println("Prevalence of nodes in cycles:");
      for(Enumeration<Node> e = prevalenceInCycles.elements(); e.hasMoreElements(); ) {
        node = e.nextElement();
        out.println("Node  "  +  node  +  "  appears  in  "  +  node.getPrevalenceInCycles()  +  "
cycles      out      of      "      +      cycles.size()      +      "      ("      +
Math.round(10000*((float)node.getPrevalenceInCycles())/cycles.size())/100.0f      +"%    of
cycles)");
      }
      out.println();

      //Record the actual cycles
      out.println("The cycles are:");
      for(int index = 0; index < cycles.size(); index++) {
        out.print((index+1) + ". ");
        for(Iterator<Node> e = cycles.elementAt(index).iterator(); e.hasNext(); ) {
          out.print(e.next() + " ");
        }
        out.println();
      }
      out.println();

      //Record the basic statistics on number of paths, maximum and minimum path length
      out.println("Number of paths: " + paths.size());
      out.println("Maximum path length: " + maxPathLength);
      out.println("Minimum path length: " + minPathLength);
      out.println();

      //Record the path length histogram
      out.println("Histogram  of  Path  Lengths  (path  length,  instances  of  paths  of  that
length):");
      for(int index = 0; index < maxPathLength-minPathLength+1; index++) {
        out.println("(" + (index + minPathLength) + "," + histogramPathLength[index] + ")");
      }
      out.println();

      //Record the results on the prevalence of nodes within paths
      out.println("Prevalence of nodes in paths:");
      for(Enumeration<Node> e = prevalenceInPaths.elements(); e.hasMoreElements(); ) {
        node = e.nextElement();
        out.println("Node " + node + " appears in " + node.getPrevalenceInPaths() + " paths
out       of       "       +       paths.size()       +       "(       "       +
Math.round(10000*((float)node.getPrevalenceInPaths())/paths.size())/100.0f  +"% of paths)");
      }
```

```
        out.println();

        //Record the nodes not covered by at least one path to/from the 'CBM Capability' node
        out.println("Number of nodes not covered by at least one path " + (isInputImpacts ?
"to" : "from") + " 'CBM Capability': " + nodesNotLinkedToCBMCapability.size() + " (" +
Math.round(10000*((float)nodesNotLinkedToCBMCapability.size())/listOfNodes.size())/100.0f +
"% of nodes)");
        if(nodesNotLinkedToCBMCapability.size() == 0)
          out.println("(All nodes are covered by at least one path " + (isInputImpacts ? "to"
: "from") + " 'CBM Capability')");
        out.println();

        //Record the number of paths that start in each starting node
        out.println("Paths that start at each starting node:");
        for(int index = 0; index < startNodes.size(); index++) {
          out.println(pathsFromEachStartingNode[index] + " paths start from node " +
startNodes.elementAt(index) + " (" +
Math.round(10000*((float)pathsFromEachStartingNode[index])/paths.size())/100.0f + "% of
paths)");
        }
        out.println();

        //Record the number of paths that end in each terminal node (ending node)
        out.println("Number of paths that terminate at each terminating node:");
        for(int index = 0; index < endNodes.size(); index++) {
          out.println(pathsToEachEndingNode[index] + " paths terminate in node " +
endNodes.elementAt(index) + " (" +
Math.round(10000*((float)pathsToEachEndingNode[index])/paths.size())/100.0f + "% of
paths)");
        }
        out.println();

        //Record the top and bottom 25 paths in terms of path criticality based on prevalence
of nodes
        out.println("Top 25 most critical paths based on a combined 'prevalence of nodes in
paths' score are:");

        //assumes at least 25 paths exist
        for(int index = 0; index < 25; index++) {
          out.print("Score of " +
pathCriticalityBasedOnNodePrevalence.elementAt(index).getCriticalityByNodePrevalence() + ":
path is ");
          for(Enumeration<Node> e =
pathCriticalityBasedOnNodePrevalence.elementAt(index).elements(); e.hasMoreElements(); ) {
            out.print(e.nextElement() + " ");
          }
          out.println();
        }
        out.println();

        out.println("Bottom 25 most critical (Top 25 least critical) paths based on a combined
'prevalence of nodes in paths' score are:");
        //assumes at least 25 paths exist

        for(int index = pathCriticalityBasedOnNodePrevalence.size()-25; index <
pathCriticalityBasedOnNodePrevalence.size(); index++) {
          out.print("Score of " +
pathCriticalityBasedOnNodePrevalence.elementAt(index).getCriticalityByNodePrevalence() + ":
path is ");
          for(Enumeration<Node> e =
pathCriticalityBasedOnNodePrevalence.elementAt(index).elements(); e.hasMoreElements(); ) {
            out.print(e.nextElement() + " ");
          }
          out.println();
        }
        out.println();


        //Record the top and bottom 25 paths in terms of path criticality based on node
ingress and egresss
```

```
      out.println("Top 25 most critical paths based on a normalised combined 'node ingress
and egress' score are:");
      //assumes at least 25 paths exist

      for(int index = 0; index < 25; index++) {
        out.print("Score                     of                      "                     +
pathCriticalityBasedOnNodeIngressEgress.elementAt(index).getCriticalityByNodeIngressEgress()
+ ": path is ");
        for(Enumeration<Node>                              e                               =
pathCriticalityBasedOnNodeIngressEgress.elementAt(index).elements();  e.hasMoreElements();  )
{
          out.print(e.nextElement() + " ");
        }
        out.println();
      }
      out.println();

      out.println("Bottom  25  most  critical  (Top  25  least  critical)  paths  based  on  a
normalised combined 'node ingress and egress' score are:");
      //assumes at least 25 paths exist

      for(int    index    =    pathCriticalityBasedOnNodeIngressEgress.size()-25;    index    <
pathCriticalityBasedOnNodeIngressEgress.size(); index++) {
        out.print("Score                     of                      "                     +
pathCriticalityBasedOnNodeIngressEgress.elementAt(index).getCriticalityByNodeIngressEgress()
+ ": path is ");
        for(Enumeration<Node>                              e                               =
pathCriticalityBasedOnNodeIngressEgress.elementAt(index).elements();  e.hasMoreElements();  )
{
          out.print(e.nextElement() + " ");
        }
        out.println();
      }
      out.println();

      //Record all of the paths themselves
      out.println("The paths are:");
      for(int index = 0; index < paths.size(); index++) {
        out.print((index+1) + ". ");
        for(Enumeration<Node> e = paths.elementAt(index).elements(); e.hasMoreElements(); )
{
          out.print(e.nextElement() + " ");
        }
        out.println();
      }

      //Close the output file
      out.flush();
      out.close();
    }
    catch (IOException e) {
      e.printStackTrace();
      System.exit(1);
    }
  }


  /**
   * Recursive method for performing the depth-first search of the Causal Impacts Map,
including extracting paths (from starting nodes to ending nodes)
   * and cycles, as well as recording the transitive closure of the causal relationships
captured by the map.
   */
  private void recurse() {

    //Local variable declarations
    Node node, succ;

    //If there are still nodes on the stack...
    if(stack.size() >  0)
    {
```

```
        //... examine the node on the top of the stack.
        node = stack.peek();

        //For all of its successors...
        for (Enumeration<Node> e = node.getSuccessors().elements(); e.hasMoreElements(); ) {
          succ = e.nextElement();

          //... record that each node on the stack can reach this successor (i.e. transitive
closure of reachability)
          for(int count = 0; count < stack.size(); count++ ) {
            if(listOfNodes.indexOf(stack.elementAt(count)) != listOfNodes.indexOf(succ)){

reachabilityMatrix[listOfNodes.indexOf(stack.elementAt(count))][listOfNodes.indexOf(succ)] =
true;
            }
          }

          //If the set of end nodes contains this successor, then we have found a path from
one of the start nodes to one of the end nodes
          // (this end node)
          if (endNodes.contains(succ)) {

            //Record the path
            stack.push(succ);
            paths.add(new Path(stack));
            stack.pop();
          }

          //Else, if the stack contains the successor, we have found a loop
          else if (stack.contains(succ)) {

            //Extract the loop from the stack
            Path potentialLoop = new Path(stack.subList(stack.indexOf(succ), stack.size()));

            //Check that the equivalent loop hasn't already been recorded previously
            boolean found = false;
            for(int count = 0; count < potentialLoop.size(); count++) {
              if(cycles.contains(potentialLoop)) {
                found = true;
                break;
              }
              potentialLoop.add(potentialLoop.remove(0));
            }

            //If not recorded previously, then record the loop
            if(!found) {
              cycles.add(potentialLoop);
            }

            //record that each node in the loop can reach each other node in the loop
            for(int count = stack.indexOf(succ)+1; count < stack.size(); count++) {
              for(int count2 = stack.indexOf(succ); count2 < count; count2++) {

reachabilityMatrix[listOfNodes.indexOf(stack.elementAt(count))][listOfNodes.indexOf(stack.el
ementAt(count2))] = true;
              }
            }
          }
          //Else, if this successor results in neither a path or a loop, push it on the stack
and recurse.
          else {
            stack.push(succ);
            recurse();
          }
        }

        //Pop this node off the stack, as it has now been fully explored.
        stack.pop();
      }
    }
}
```

J.1.3 Node.java

```java
import java.util.Vector;


/**
 * A class representing the nodes within the Causal Impacts Map, as well as some auxiliary
properties to facilitate analysis.
 * @author Guy Edward Gallasch, 22 May 2014
 *
 */

public class Node {

  //Variables representing node properties
  private String ID;
  private Vector<Node> predecessors;
  private Vector<Node> successors;

  //Variables for storing auxiliary information to aid analysis
  private int prevalenceInCycles = 0;
  private int prevalenceInPaths = 0;


  /**
   * Base Node Constructor.
   * "I'm being swallowed by a Node(String ID) Constructor and I don't like it very much!"
   */
  public Node() {

    //Initialise instance variables
    this.ID = new String();
    this.predecessors = new Vector<Node>();
    this.successors = new Vector<Node>();
  }

  /**
   * Constructor, where a Node ID is provided.
   * @param ID String representation of the Node ID
   */
  public Node(String ID){
    this();
    this.ID = new String(ID);
  }


  //Getter and Setter for Node ID
  public String getID() {
    return ID;
  }
  public void setID(String newID) {
    ID = new String(newID);
  }

  //Getter for the list of predecessors (the corresponding setter is never needed, hence is
omitted)
  public Vector<Node>getPredecessors() {
    return this.predecessors;
  }

  //Getter for the list of successors (the corresponding setter is never needed, hence is
omitted)
  public Vector<Node>getSuccessors() {
    return this.successors;
  }

  //Utility method for adding a predecessor node to this node
  public void addPredecessor(Node toAdd) {
```

```
    this.predecessors.add(toAdd);
  }

  //Utility method for adding a successor node to this node
  public void addSuccessor(Node toAdd) {
    this.successors.add(toAdd);
  }

  //Utility methods for obtaining the ingress, egress and ingress+egress, based on this
node's recorded predecessors and successors
  public int ingress() {
    return predecessors.size();
  }
  public int egress() {
    return successors.size();
  }
  public int ingressEgress() {
    return (successors.size() + predecessors.size());
  }

  //Implementation of the .toString() method, to facilitate recording of results in the log
file.
  //This simply returns the node ID (as a string)
  public String toString() {
    return this.ID;
  }

  //Getter for the statistic of the prevalence of this node in cycles (the corresponding
setter is never needed, hence is omitted)
  public int getPrevalenceInCycles() {
    return prevalenceInCycles;
  }

  //Utility method for incrementing the counter that records the prevalence of this node in
cycles
  public void incrementPrevalenceInCycles() {
    prevalenceInCycles++;
  }

  //Getter for the statistic of the prevalence of this node in paths (the corresponding
setter is never needed, hence is omitted)
  public int getPrevalenceInPaths() {
    return prevalenceInPaths;
  }

  //Utility method for incrementing the counter that records the prevalence of this node in
paths
  public void incrementPrevalenceInPaths() {
    prevalenceInPaths++;
  }
}
```

J.1.4 Path.java

```
import java.util.Collection;


/**
 * A class representing paths of nodes within the Causal Impacts Map, as well as some
auxiliary properties to facilitate analysis.
 * This class extends the java.util.Vector class.
 * @author Guy Edward Gallasch, 22 May 2014
 *
 */
public class Path extends java.util.Vector<Node> {

  //Variables for recording auxiliary statistics
  private float criticalityByNodePrevalence = (float) 0.0;
  private float criticalityByNodeIngressEgress = (float) 0.0;
```

```
  /**
   * Base constructor.
   */
  public Path() {
    super();
  }

  /**
   * Constructor that initialises the underlying java.util.Vector with the content of the
java.util.Collection passed in as the argument.
   * @param c The Collection to be used to populate this Path object.
   */
  public Path(Collection<Node> c) {
    this();
    this.addAll(c);
  }

  //Getter and setter methods for the 'Criticality by node prevalence' measure
  public void setCriticalityByNodePrevalence(float criticalityByNodePrevalence) {
    this.criticalityByNodePrevalence = criticalityByNodePrevalence;
  }

  public float getCriticalityByNodePrevalence() {
    return criticalityByNodePrevalence;
  }

  //Getter and setter methods for the 'Criticality by node ingress and egress' measure
  public void setCriticalityByNodeIngressEgress(
      float criticalityByNodeIngressEgress) {
    this.criticalityByNodeIngressEgress = criticalityByNodeIngressEgress;
  }

  public float getCriticalityByNodeIngressEgress() {
    return criticalityByNodeIngressEgress;
  }
}
```

J.2. Java Code Input

Input to the above Java code is in the form of a list of comma-separated node IDs, where each line in the input corresponds to one node in the impacts map. The first ID on each line refers to the node in question, and any subsequent node IDs on the corresponding line represent the successors of that node. The input in Appendices J.2.1 and J.2.2 below represent the structure of the finalised impacts map.

J.2.1 Finalised Input Impacts Map

```
1a,3a,3b,1b
1b,2g
2a,2b,2f
2b,3a,4a,2d
2c,5a,4e
2d,3c,3a,2e,2b,2f
2e,2c,2g
2f,5a,3b,4a,5b,2c,2e,2d,2a,5g
2g,3b,2e,2c,2f
2h,2f,5d,4g
3a,2g
3b,3m,3j,3e,3d,3f,3a,3c,3i
3c,3d,3h,3n
3d,3h
3e,3k,3i
3f,3h
```

```
3g,3c
3h,4b
3i,3m,3j,CBM Capability
3j,3k
3k,3j,5c
3m,CBM Capability
3n,3h,4b
4a,4c,4e,6c,5g
4b,3m
4c,3g
4d,3g,3c
4e,6b,4f,2c
4f,3c,4c,4d
4g,2h
5a,2f
5b,5e,5c,5a,5f
5c,5d
5d,4g,2h,CBM Capability,5g
5e,6b,5d,5c
5f,5e
5g,CBM Capability
6a,3j
6b,2b,6a,CBM Capability
6c,2b,6a,3m,6b
CBM Capability
```

J.2.2 Finalised Output Impacts Map

```
CBM Capability,1a,1b,1c,7h,3a
1a,5e,2c
1b,5e,2a
1c,5e,2e,8a
2a,9e,2b
2b,7g,7c,2d
2c,7f,4a,5k,11b,9c,9a,7c,8a,2b,2d,9d
2d,8f
2e,2f
2f,2c
3a,3b
3b,3g
3c,3h,3d
3d,3f,3h,3c
3e,3c
3f,3h
3g
3h
4a
4b
5a,3e,3c,5c
5b,5a,10b
5c,5g
5d,5c,5g,5j
5e,7f,11b,7c,6b,8c,8f,5h,5d,5k,5i,5f,5b,10b
5f,3d
5g,5k,9h
5h,5d,5j
5i,3d,5k
5j
5k,11b,9c,9f,7d,7c,8d,5j
6a
6b,6a,6c,6d
6c
6d,6e,6f
6e
6f,6e
7a
7b,7a
7c,9f,8f,8b,7j,7d,7e
7d,9f,10e
```

```
7e,7d,7g,9h
7f,9d
7g,4b
7h,3b,7k,8e,8i
7i
7j
7k,7i
8a,8b
8b,10a,8f
8c
8d,8f
8e,7k,7b,3b,3a,8b
8f,8h,8g
8g,8h,11a,8j
8h
8i,8h,4b
8j,11a
9a,10f
9b,9a
9c,9a,9f,9b
9d,9f,9b,9a,9c
9e,9f
9f,11a,9i
9g,9e
9h,9g,9e,9i,9f,7g
9i
10a,10c
10b,10d,10a
10c,10d
10d
10e,7d
10f,10e,10h
10g,11a
10h,11a,10g
11a
11b,11a
```

J.3. Analysis Results for the Finalised Impacts Map

The report files produced by the above Java code are reproduced below for the input and output portions of the finalised impacts map.

J.3.1 Input Impacts Map

```
Report on the Input Impacts Map
-------------------------------

Starting and Ending (Terminating) Nodes:
----------------------------------------

Start Nodes (nodes without predecessors):
There are 1 start nodes, comprising:
1a

End Nodes (nodes without successors):
There are 1 end nodes, comprising:
CBM Capability

Isolated Nodes (nodes without successors AND without predecessors):
There are no nodes without either successors or predecessors.

Node Ingress and Egress:
------------------------

Nodes, ordered by ingress:
Ingress of 5: 2f <- 2a 2d 2g 2h 5a
Ingress of 5: 3c <- 2d 3b 3g 4d 4f
```

```
Ingress of 5: CBM Capability <- 3i 3m 5d 5g 6b
Ingress of 4: 3a <- 1a 2b 2d 3b
Ingress of 4: 2b <- 2a 2d 6b 6c
Ingress of 4: 2c <- 2e 2f 2g 4e
Ingress of 4: 3m <- 3b 3i 4b 6c
Ingress of 4: 3j <- 3b 3i 3k 6a
Ingress of 4: 3h <- 3c 3d 3f 3n
Ingress of 3: 3b <- 1a 2f 2g
Ingress of 3: 2g <- 1b 2e 3a
Ingress of 3: 5a <- 2c 2f 5b
Ingress of 3: 2e <- 2d 2f 2g
Ingress of 3: 5g <- 2f 4a 5d
Ingress of 3: 5d <- 2h 5c 5e
Ingress of 3: 5c <- 3k 5b 5e
Ingress of 3: 6b <- 4e 5e 6c
Ingress of 2: 4a <- 2b 2f
Ingress of 2: 2d <- 2b 2f
Ingress of 2: 4e <- 2c 4a
Ingress of 2: 2h <- 4g 5d
Ingress of 2: 4g <- 2h 5d
Ingress of 2: 3d <- 3b 3c
Ingress of 2: 3i <- 3b 3e
Ingress of 2: 3k <- 3e 3j
Ingress of 2: 3g <- 4c 4d
Ingress of 2: 4b <- 3h 3n
Ingress of 2: 4c <- 4a 4f
Ingress of 2: 5e <- 5b 5f
Ingress of 2: 6a <- 6b 6c
Ingress of 1: 1b <- 1a
Ingress of 1: 2a <- 2f
Ingress of 1: 5b <- 2f
Ingress of 1: 3e <- 3b
Ingress of 1: 3f <- 3b
Ingress of 1: 3n <- 3c
Ingress of 1: 6c <- 4a
Ingress of 1: 4d <- 4f
Ingress of 1: 4f <- 4e
Ingress of 1: 5f <- 5b
Ingress of 0: 1a <-

Nodes, ordered by egress:
Egress of 9: 2f -> 5a 3b 4a 5b 2c 2e 2d 2a 5g
Egress of 8: 3b -> 3m 3j 3e 3d 3f 3a 3c 3i
Egress of 5: 2d -> 3c 3a 2e 2b 2f
Egress of 4: 2g -> 3b 2e 2c 2f
Egress of 4: 4a -> 4c 4e 6c 5g
Egress of 4: 5b -> 5e 5c 5a 5f
Egress of 4: 5d -> 4g 2h CBM Capability 5g
Egress of 4: 6c -> 2b 6a 3m 6b
Egress of 3: 1a -> 3a 3b 1b
Egress of 3: 2b -> 3a 4a 2d
Egress of 3: 4e -> 6b 4f 2c
Egress of 3: 3c -> 3d 3h 3n
Egress of 3: 2h -> 2f 5d 4g
Egress of 3: 3i -> 3m 3j CBM Capability
Egress of 3: 6b -> 2b 6a CBM Capability
Egress of 3: 4f -> 3c 4c 4d
Egress of 3: 5e -> 6b 5d 5c
Egress of 2: 2a -> 2b 2f
Egress of 2: 2c -> 5a 4e
Egress of 2: 2e -> 2c 2g
Egress of 2: 3e -> 3k 3i
Egress of 2: 3n -> 3h 4b
Egress of 2: 3k -> 3j 5c
Egress of 2: 4d -> 3g 3c
Egress of 1: 3a -> 2g
Egress of 1: 1b -> 2g
Egress of 1: 5a -> 2f
Egress of 1: 5g -> CBM Capability
Egress of 1: 4g -> 2h
Egress of 1: 3m -> CBM Capability
```

```
Egress of 1: 3j -> 3k
Egress of 1: 3d -> 3h
Egress of 1: 3f -> 3h
Egress of 1: 3h -> 4b
Egress of 1: 3g -> 3c
Egress of 1: 4b -> 3m
Egress of 1: 5c -> 5d
Egress of 1: 4c -> 3g
Egress of 1: 5f -> 5e
Egress of 1: 6a -> 3j
Egress of 0: CBM Capability ->

Nodes, ordered by ingress+egress:
Ingress+Egress of 14: 2a 2d 2g 2h 5a -> 2f -> 5a 3b 4a 5b 2c 2e 2d 2a 5g
Ingress+Egress of 11: 1a 2f 2g -> 3b -> 3m 3j 3e 3d 3f 3a 3c 3i
Ingress+Egress of 8: 2d 3b 3g 4d 4f -> 3c -> 3d 3h 3n
Ingress+Egress of 7: 1b 2e 3a -> 2g -> 3b 2e 2c 2f
Ingress+Egress of 7: 2a 2d 6b 6c -> 2b -> 3a 4a 2d
Ingress+Egress of 7: 2b 2f -> 2d -> 3c 3a 2e 2b 2f
Ingress+Egress of 7: 2h 5c 5e -> 5d -> 4g 2h CBM Capability 5g
Ingress+Egress of 6: 2b 2f -> 4a -> 4c 4e 6c 5g
Ingress+Egress of 6: 2e 2f 2g 4e -> 2c -> 5a 4e
Ingress+Egress of 6: 4e 5e 6c -> 6b -> 2b 6a CBM Capability
Ingress+Egress of 5: 1a 2b 2d 3b -> 3a -> 2g
Ingress+Egress of 5: 2c 4a -> 4e -> 6b 4f 2c
Ingress+Egress of 5: 2d 2f 2g -> 2e -> 2c 2g
Ingress+Egress of 5: 2f -> 5b -> 5e 5c 5a 5f
Ingress+Egress of 5: 4g 5d -> 2h -> 2f 5d 4g
Ingress+Egress of 5: 3b 3i 4b 6c -> 3m -> CBM Capability
Ingress+Egress of 5: 3b 3i 3k 6a -> 3j -> 3k
Ingress+Egress of 5: 3b 3e -> 3i -> 3m 3j CBM Capability
Ingress+Egress of 5: 3c 3d 3f 3n -> 3h -> 4b
Ingress+Egress of 5: 3i 3m 5d 5g 6b -> CBM Capability ->
Ingress+Egress of 5: 4a -> 6c -> 2b 6a 3m 6b
Ingress+Egress of 5: 5b 5f -> 5e -> 6b 5d 5c
Ingress+Egress of 4: 2c 2f 5b -> 5a -> 2f
Ingress+Egress of 4: 2f 4a 5d -> 5g -> CBM Capability
Ingress+Egress of 4: 3e 3j -> 3k -> 3j 5c
Ingress+Egress of 4: 3k 5b 5e -> 5c -> 5d
Ingress+Egress of 4: 4e -> 4f -> 3c 4c 4d
Ingress+Egress of 3: -> 1a -> 3a 3b 1b
Ingress+Egress of 3: 2f -> 2a -> 2b 2f
Ingress+Egress of 3: 2h 5d -> 4g -> 2h
Ingress+Egress of 3: 3b -> 3e -> 3k 3i
Ingress+Egress of 3: 3b 3c -> 3d -> 3h
Ingress+Egress of 3: 3c -> 3n -> 3h 4b
Ingress+Egress of 3: 4c 4d -> 3g -> 3c
Ingress+Egress of 3: 3h 3n -> 4b -> 3m
Ingress+Egress of 3: 4a 4f -> 4c -> 3g
Ingress+Egress of 3: 4f -> 4d -> 3g 3c
Ingress+Egress of 3: 6b 6c -> 6a -> 3j
Ingress+Egress of 2: 1a -> 1b -> 2g
Ingress+Egress of 2: 3b -> 3f -> 3h
Ingress+Egress of 2: 5b -> 5f -> 5e

Mutual Dependencies:
--------------------

Number of SCCs is 16
Number of non-trivial SCCs is 1

Non-trivial SCC:
3a 3b 2g 2a 2b 2f 4a 2d 2c 5a 4e 2e 5b 2h 5d 4g 3j 3e 3i 3k 5c 6c 6b 5e 5f 6a

Cycles and Paths:
-----------------

Number of elementary cycles: 445
Maximum cycle length: 18
Minimum cycle length: 2
```

```
Histogram of Cycle Lengths (cycle length, instances of cycles of that length):
(2,9)
(3,6)
(4,7)
(5,8)
(6,16)
(7,23)
(8,22)
(9,21)
(10,27)
(11,26)
(12,28)
(13,38)
(14,58)
(15,68)
(16,53)
(17,28)
(18,7)

Prevalence of nodes in cycles:
Node 2f appears in 428 cycles out of 445 (96.18% of cycles)
Node 2b appears in 350 cycles out of 445 (78.65% of cycles)
Node 2g appears in 349 cycles out of 445 (78.43% of cycles)
Node 2h appears in 335 cycles out of 445 (75.28% of cycles)
Node 5d appears in 334 cycles out of 445 (75.06% of cycles)
Node 5c appears in 328 cycles out of 445 (73.71% of cycles)
Node 3k appears in 323 cycles out of 445 (72.58% of cycles)
Node 6b appears in 289 cycles out of 445 (64.94% of cycles)
Node 3j appears in 265 cycles out of 445 (59.55% of cycles)
Node 2d appears in 261 cycles out of 445 (58.65% of cycles)
Node 3b appears in 246 cycles out of 445 (55.28% of cycles)
Node 3a appears in 245 cycles out of 445 (55.06% of cycles)
Node 2e appears in 189 cycles out of 445 (42.47% of cycles)
Node 2c appears in 182 cycles out of 445 (40.9% of cycles)
Node 4e appears in 176 cycles out of 445 (39.55% of cycles)
Node 4g appears in 168 cycles out of 445 (37.75% of cycles)
Node 4a appears in 162 cycles out of 445 (36.4% of cycles)
Node 6c appears in 116 cycles out of 445 (26.07% of cycles)
Node 3i appears in 116 cycles out of 445 (26.07% of cycles)
Node 3e appears in 116 cycles out of 445 (26.07% of cycles)
Node 6a appears in 90 cycles out of 445 (20.22% of cycles)
Node 5b appears in 89 cycles out of 445 (20.0% of cycles)
Node 5e appears in 86 cycles out of 445 (19.33% of cycles)
Node 5a appears in 54 cycles out of 445 (12.13% of cycles)
Node 2a appears in 54 cycles out of 445 (12.13% of cycles)
Node 5f appears in 43 cycles out of 445 (9.66% of cycles)

The cycles are:
1. 3j 3k
2. 2f 5a
3. 3b 3j 3k 5c 5d 4g 2h 2f
4. 3a 2g 3b 3j 3k 5c 5d 4g 2h 2f 4a 4e 6b 2b
5. 4a 4e 6b 2b
<snip>
441. 2g 2f 2d 2e
442. 3a 2g 2f 2d 2b
443. 3a 2g 2f 2a 2b
444. 3a 2g 2f 2a 2b 2d
445. 2g 2f 2a 2b 2d 2e

Number of paths: 14991
Maximum path length: 31
Minimum path length: 4

Histogram of Path Lengths (path length, instances of paths of that length):
(4,2)
(5,2)
(6,7)
(7,19)
(8,31)
```

```
(9,49)
(10,83)
(11,91)
(12,150)
(13,226)
(14,311)
(15,391)
(16,470)
(17,555)
(18,657)
(19,811)
(20,987)
(21,1163)
(22,1281)
(23,1407)
(24,1504)
(25,1502)
(26,1342)
(27,1002)
(28,596)
(29,262)
(30,78)
(31,12)

Prevalence of nodes in paths:
Node CBM Capability appears in 14991 paths out of 14991( 100.0% of paths)
Node 1a appears in 14991 paths out of 14991( 100.0% of paths)
Node 2f appears in 14748 paths out of 14991( 98.38% of paths)
Node 3m appears in 13439 paths out of 14991( 89.65% of paths)
Node 3b appears in 13055 paths out of 14991( 87.09% of paths)
Node 4b appears in 13026 paths out of 14991( 86.89% of paths)
Node 3c appears in 12968 paths out of 14991( 86.51% of paths)
Node 5d appears in 12844 paths out of 14991( 85.68% of paths)
Node 5c appears in 12784 paths out of 14991( 85.28% of paths)
Node 3k appears in 12694 paths out of 14991( 84.68% of paths)
Node 4e appears in 12570 paths out of 14991( 83.85% of paths)
Node 2g appears in 12524 paths out of 14991( 83.54% of paths)
Node 2h appears in 12272 paths out of 14991( 81.86% of paths)
Node 2b appears in 11344 paths out of 14991( 75.67% of paths)
Node 2c appears in 10819 paths out of 14991( 72.17% of paths)
Node 4f appears in 10160 paths out of 14991( 67.77% of paths)
Node 3h appears in 9784 paths out of 14991( 65.27% of paths)
Node 3j appears in 9752 paths out of 14991( 65.05% of paths)
Node 2d appears in 8147 paths out of 14991( 54.35% of paths)
Node 3a appears in 7850 paths out of 14991( 52.36% of paths)
Node 4a appears in 7843 paths out of 14991( 52.32% of paths)
Node 6b appears in 7765 paths out of 14991( 51.8% of paths)
Node 2e appears in 7367 paths out of 14991( 49.14% of paths)
Node 3n appears in 6484 paths out of 14991( 43.25% of paths)
Node 3g appears in 6384 paths out of 14991( 42.59% of paths)
Node 4g appears in 6136 paths out of 14991( 40.93% of paths)
Node 3i appears in 6000 paths out of 14991( 40.02% of paths)
Node 3e appears in 5942 paths out of 14991( 39.64% of paths)
Node 4d appears in 5080 paths out of 14991( 33.89% of paths)
Node 5b appears in 4148 paths out of 14991( 27.67% of paths)
Node 5e appears in 4118 paths out of 14991( 27.47% of paths)
Node 4c appears in 3844 paths out of 14991( 25.64% of paths)
Node 1b appears in 3618 paths out of 14991( 24.13% of paths)
Node 6c appears in 3288 paths out of 14991( 21.93% of paths)
Node 3d appears in 3271 paths out of 14991( 21.82% of paths)
Node 2a appears in 2243 paths out of 14991( 14.96% of paths)
Node 5f appears in 2059 paths out of 14991( 13.73% of paths)
Node 5a appears in 1174 paths out of 14991( 7.83% of paths)
Node 6a appears in 926 paths out of 14991( 6.18% of paths)
Node 5g appears in 675 paths out of 14991( 4.5% of paths)
Node 3f appears in 29 paths out of 14991( 0.19% of paths)

Number of nodes not covered by at least one path to 'CBM Capability': 0 (0.0% of nodes)
(All nodes are covered by at least one path to 'CBM Capability')

Paths that start at each starting node:
```

```
14991 paths start from node 1a (100.0% of paths)

Number of paths that terminate at each terminating node:
14991 paths terminate in node CBM Capability (100.0% of paths)

Top 25 most critical paths based on a combined 'prevalence of nodes in paths' score are:
Score of 14119.0: path is 1a 3b 3m CBM Capability
Score of 13179.14: path is 1a 3b 3c 3h 4b 3m CBM Capability
Score of 13085.43: path is 1a 3a 2g 2f 3b 3m CBM Capability
Score of 13015.86: path is 1a 3b 3j 3k 5c 5d CBM Capability
Score of 12808.33: path is 1a 3a 2g 3b 3m CBM Capability
Score of 12737.6: path is 1a 3a 2g 2f 3b 3c 3h 4b 3m CBM Capability
Score of 12707.71: path is 1a 3b 3c 3n 4b 3m CBM Capability
Score of 12623.3: path is 1a 3a 2g 2f 3b 3j 3k 5c 5d CBM Capability
Score of 12556.06: path is 1a 3b 3j 3k 5c 5d 2h 2f 2c 4e 4f 3c 3h 4b 3m CBM Capability
Score of 12535.36: path is 1a 3b 3j 3k 5c 5d 2h 2f 2d 3c 3h 4b 3m CBM Capability
Score of 12514.22: path is 1a 3a 2g 3b 3c 3h 4b 3m CBM Capability
Score of 12495.2: path is 1a 3b 3i 3m CBM Capability
Score of 12480.86: path is 1a 1b 2g 2f 3b 3m CBM Capability
Score of 12471.57: path is 1a 3b 3e 3k 5c 5d CBM Capability
Score of 12440.42: path is 1a 3b 3j 3k 5c 5d 2h 2f 2c 4e 6b CBM Capability
Score of 12407.6: path is 1a 3a 2g 2f 3b 3c 3n 4b 3m CBM Capability
Score of 12387.22: path is 1a 3a 2g 3b 3j 3k 5c 5d CBM Capability
Score of 12378.85: path is 1a 3b 3a 2g 2f 2c 4e 4f 3c 3h 4b 3m CBM Capability
Score of 12370.06: path is 1a 3b 3j 3k 5c 5d 2h 2f 4a 4e 4f 3c 3h 4b 3m CBM Capability
Score of 12349.81: path is 1a 3b 3j 3k 5c 5d 2h 2f 2c 4e 4f 3c 3n 4b 3m CBM Capability
Score of 12342.25: path is 1a 3b 3c 3n 3h 4b 3m CBM Capability
Score of 12322.5: path is 1a 3a 2g 2f 2c 4e 4f 3c 3h 4b 3m CBM Capability
Score of 12320.27: path is 1a 3b 3a 2g 2f 2d 3c 3h 4b 3m CBM Capability
Score of 12317.94: path is 1a 3b 3e 3k 5c 5d 2h 2f 2c 4e 4f 3c 3h 4b 3m CBM Capability
Score of 12314.4: path is 1a 1b 2g 2f 3b 3c 3h 4b 3m CBM Capability

Bottom 25 most critical (Top 25 least critical) paths based on a combined 'prevalence of
nodes in paths' score are:
Score of 8457.17: path is 1a 3a 2g 2e 2c 5a 2f 5b 5f 5e 6b 6a 3j 3k 5c 5d 5g CBM Capability
Score of 8422.54: path is 1a 1b 2g 2c 5a 2f 5b 5f 5e 5c 5d 5g CBM Capability
Score of 8420.65: path is 1a 1b 2g 2e 2c 5a 2f 5b 5e 6b 2b 4a 6c 6a 3j 3k 5c 5d 5g CBM
Capability
Score of 8411.75: path is 1a 3a 2g 2c 5a 2f 5b 5f 5e 5d 5g CBM Capability
Score of 8395.11: path is 1a 1b 2g 2f 5b 5f 5e 6b 2b 4a 6c 6a 3j 3k 5c 5d 5g CBM Capability
Score of 8389.75: path is 1a 1b 2g 2e 2c 5a 2f 5b 5f 5e 6b 2b 4a 6c 3m CBM Capability
Score of 8366.85: path is 1a 3a 2g 2c 5a 2f 5b 5f 5e 6b 2b 4a 6c 6a 3j 3k 5c 5d 5g CBM
Capability
Score of 8366.0: path is 1a 1b 2g 2c 5a 2f 5b 5e 6b 2b 4a 5g CBM Capability
Score of 8347.14: path is 1a 1b 2g 2e 2c 5a 2f 5b 5f 5e 5c 5d 5g CBM Capability
Score of 8331.38: path is 1a 3a 2g 2e 2c 5a 2f 5b 5f 5e 5d 5g CBM Capability
Score of 8319.24: path is 1a 3a 2g 2e 2c 5a 2f 5b 5f 5e 6b 2b 4a 6c 6a 3j 3k 5c 5d 5g CBM
Capability
Score of 8294.64: path is 1a 1b 2g 2e 2c 5a 2f 5b 5e 6b 2b 4a 5g CBM Capability
Score of 8272.35: path is 1a 1b 2g 2c 5a 2f 5b 5f 5e 6b 6a 3j 3k 5c 5d 5g CBM Capability
Score of 8268.64: path is 1a 1b 2g 2c 5a 2f 5b 5f 5e 6b CBM Capability
Score of 8235.33: path is 1a 1b 2g 2f 5b 5f 5e 6b 2b 4a 5g CBM Capability
Score of 8222.06: path is 1a 1b 2g 2e 2c 5a 2f 5b 5f 5e 6b 6a 3j 3k 5c 5d 5g CBM Capability
Score of 8217.79: path is 1a 3a 2g 2c 5a 2f 5b 5f 5e 6b 2b 4a 5g CBM Capability
Score of 8193.5: path is 1a 1b 2g 2e 2c 5a 2f 5b 5f 5e 6b CBM Capability
Score of 8161.07: path is 1a 3a 2g 2e 2c 5a 2f 5b 5f 5e 6b 2b 4a 5g CBM Capability
Score of 8155.25: path is 1a 1b 2g 2c 5a 2f 5b 5f 5e 6b 2b 4a 6c 6a 3j 3k 5c 5d 5g CBM
Capability
Score of 8117.71: path is 1a 1b 2g 2e 2c 5a 2f 5b 5f 5e 6b 2b 4a 6c 6a 3j 3k 5c 5d 5g CBM
Capability
Score of 8059.08: path is 1a 1b 2g 2c 5a 2f 5b 5f 5e 5d 5g CBM Capability
Score of 8005.85: path is 1a 1b 2g 2e 2c 5a 2f 5b 5f 5e 5d 5g CBM Capability
Score of 7915.5: path is 1a 1b 2g 2c 5a 2f 5b 5f 5e 6b 2b 4a 5g CBM Capability
Score of 7878.93: path is 1a 1b 2g 2e 2c 5a 2f 5b 5f 5e 6b 2b 4a 5g CBM Capability

Top 25 most critical paths based on a normalised combined 'node ingress and egress' score
are:
Score of 7.14: path is 1a 3a 2g 2f 3b 3i CBM Capability
Score of 7.14: path is 1a 3a 2g 2f 3b 3m CBM Capability
Score of 7.0: path is 1a 3b 3a 2g 2f 5g CBM Capability
Score of 6.91: path is 1a 3b 3a 2g 2f 2d 2b 4a 6c 6b CBM Capability
```

```
Score of 6.91: path is 1a 3b 3a 2g 2f 2d 2b 4a 4e 6b CBM Capability
Score of 6.9: path is 1a 3b 3a 2g 2f 2d 2b 4a 5g CBM Capability
Score of 6.89: path is 1a 3b 3a 2g 2f 2c 4e 6b CBM Capability
Score of 6.89: path is 1a 3b 3a 2g 2f 5b 5e 5d CBM Capability
Score of 6.89: path is 1a 3b 3a 2g 2f 4a 6c 6b CBM Capability
Score of 6.89: path is 1a 3b 3a 2g 2f 4a 4e 6b CBM Capability
Score of 6.88: path is 1a 3b 3a 2g 2f 4a 5g CBM Capability
Score of 6.88: path is 1a 3a 2g 2f 3b 3i 3m CBM Capability
Score of 6.82: path is 1a 3b 3a 2g 2f 2d 2b 4a 6c 3m CBM Capability
Score of 6.78: path is 1a 3b 3a 2g 2f 5b 5c 5d CBM Capability
Score of 6.78: path is 1a 3b 3a 2g 2f 5b 5e 6b CBM Capability
Score of 6.78: path is 1a 3b 3a 2g 2f 4a 6c 3m CBM Capability
Score of 6.75: path is 1a 3a 2g 2c 4e 6b 2b 2d 2f 3b 3i CBM Capability
Score of 6.75: path is 1a 3a 2g 2c 4e 6b 2b 2d 2f 3b 3m CBM Capability
Score of 6.73: path is 1a 3b 3a 2g 2f 2d 2e 2c 4e 6b CBM Capability
Score of 6.71: path is 1a 1b 2g 2f 3b 3i CBM Capability
Score of 6.71: path is 1a 1b 2g 2f 3b 3m CBM Capability
Score of 6.7: path is 1a 3b 3a 2g 2f 2e 2c 4e 6b CBM Capability
Score of 6.67: path is 1a 3b 3a 2g 2c 4e 6b 2b 2d 2f 5g CBM Capability
Score of 6.67: path is 1a 3a 2g 2c 5a 2f 3b 3i CBM Capability
Score of 6.67: path is 1a 3a 2g 2c 5a 2f 3b 3m CBM Capability

Bottom 25 most critical (Top 25 least critical) paths based on a normalised combined 'node
ingress and egress' score are:
Score of 4.64: path is 1a 3a 2g 2e 2c 4e 4f 4c 3g 3c 3n 4b 3m CBM Capability
Score of 4.62: path is 1a 3a 2g 2c 4e 4f 4d 3g 3c 3n 4b 3m CBM Capability
Score of 4.62: path is 1a 3a 2g 2c 4e 4f 4c 3g 3c 3n 4b 3m CBM Capability
Score of 4.57: path is 1a 1b 2g 2e 2c 4e 4f 4d 3c 3n 3h 4b 3m CBM Capability
Score of 4.57: path is 1a 1b 2g 2e 2c 4e 4f 4d 3c 3d 3h 4b 3m CBM Capability
Score of 4.57: path is 1a 1b 2g 2e 2c 4e 4f 4d 3g 3c 3h 4b 3m CBM Capability
Score of 4.57: path is 1a 1b 2g 2e 2c 4e 4f 4c 3g 3c 3h 4b 3m CBM Capability
Score of 4.54: path is 1a 1b 2g 2c 4e 4f 4d 3c 3n 3h 4b 3m CBM Capability
Score of 4.54: path is 1a 1b 2g 2c 4e 4f 4d 3c 3d 3h 4b 3m CBM Capability
Score of 4.54: path is 1a 1b 2g 2c 4e 4f 4d 3g 3c 3h 4b 3m CBM Capability
Score of 4.54: path is 1a 1b 2g 2c 4e 4f 4c 3g 3c 3h 4b 3m CBM Capability
Score of 4.54: path is 1a 1b 2g 2e 2c 4e 4f 4d 3c 3n 4b 3m CBM Capability
Score of 4.5: path is 1a 1b 2g 2c 4e 4f 4d 3c 3n 4b 3m CBM Capability
Score of 4.47: path is 1a 1b 2g 2e 2c 4e 4f 4d 3g 3c 3n 3h 4b 3m CBM Capability
Score of 4.47: path is 1a 1b 2g 2e 2c 4e 4f 4d 3g 3c 3d 3h 4b 3m CBM Capability
Score of 4.47: path is 1a 1b 2g 2e 2c 4e 4f 4c 3g 3c 3n 3h 4b 3m CBM Capability
Score of 4.47: path is 1a 1b 2g 2e 2c 4e 4f 4c 3g 3c 3d 3h 4b 3m CBM Capability
Score of 4.43: path is 1a 1b 2g 2c 4e 4f 4d 3g 3c 3n 3h 4b 3m CBM Capability
Score of 4.43: path is 1a 1b 2g 2c 4e 4f 4d 3g 3c 3d 3h 4b 3m CBM Capability
Score of 4.43: path is 1a 1b 2g 2c 4e 4f 4c 3g 3c 3n 3h 4b 3m CBM Capability
Score of 4.43: path is 1a 1b 2g 2c 4e 4f 4c 3g 3c 3d 3h 4b 3m CBM Capability
Score of 4.43: path is 1a 1b 2g 2e 2c 4e 4f 4d 3g 3c 3n 4b 3m CBM Capability
Score of 4.43: path is 1a 1b 2g 2e 2c 4e 4f 4c 3g 3c 3n 4b 3m CBM Capability
Score of 4.38: path is 1a 1b 2g 2c 4e 4f 4d 3g 3c 3n 4b 3m CBM Capability
Score of 4.38: path is 1a 1b 2g 2c 4e 4f 4c 3g 3c 3n 4b 3m CBM Capability

The paths are:
1. 1a 3a 2g 3b 3m CBM Capability
2. 1a 3a 2g 3b 3j 3k 5c 5d 4g 2h 2f 4a 4c 3g 3c 3d 3h 4b 3m CBM Capability
3. 1a 3a 2g 3b 3j 3k 5c 5d 4g 2h 2f 4a 4c 3g 3c 3h 4b 3m CBM Capability
4. 1a 3a 2g 3b 3j 3k 5c 5d 4g 2h 2f 4a 4c 3g 3c 3n 3h 4b 3m CBM Capability
5. 1a 3a 2g 3b 3j 3k 5c 5d 4g 2h 2f 4a 4c 3g 3c 3n 4b 3m CBM Capability
```

<*snip*>

```
14987. 1a 1b 2g 2f 2a 2b 2d 2e 2c 4e 4f 4d 3c 3d 3h 4b 3m CBM Capability
14988. 1a 1b 2g 2f 2a 2b 2d 2e 2c 4e 4f 4d 3c 3h 4b 3m CBM Capability
14989. 1a 1b 2g 2f 2a 2b 2d 2e 2c 4e 4f 4d 3c 3n 3h 4b 3m CBM Capability
14990. 1a 1b 2g 2f 2a 2b 2d 2e 2c 4e 4f 4d 3c 3n 4b 3m CBM Capability
14991. 1a 1b 2g 2f 5g CBM Capability
```

J.3.2 Output Impacts Map

```
Report on the Output Impacts Map
--------------------------------

Starting and Ending (Terminating) Nodes:
```

```
----------------------------------------

Start Nodes (nodes without predecessors):
There are 1 start nodes, comprising:
CBM Capability

End Nodes (nodes without successors):
There are 16 end nodes, comprising:
11a
9i
8h
4b
10d
3h
5j
7j
6e
3g
6c
6a
8c
7i
4a
7a

Isolated Nodes (nodes without successors AND without predecessors):
There are no nodes without either successors or predecessors.

Node Ingress and Egress:
------------------------

Nodes, ordered by ingress:
Ingress of 7: 9f <- 5k 7c 7d 9c 9d 9e 9h
Ingress of 6: 11a <- 8g 8j 9f 10g 10h 11b
Ingress of 5: 8f <- 2d 5e 7c 8b 8d
Ingress of 4: 7c <- 2b 2c 5e 5k
Ingress of 4: 5k <- 2c 5e 5g 5i
Ingress of 4: 9a <- 2c 9b 9c 9d
Ingress of 4: 7d <- 5k 7c 7e 10e
Ingress of 3: 5e <- 1a 1b 1c
Ingress of 3: 9e <- 2a 9g 9h
Ingress of 3: 7g <- 2b 7e 9h
Ingress of 3: 11b <- 2c 5e 5k
Ingress of 3: 9c <- 2c 5k 9d
Ingress of 3: 3b <- 3a 7h 8e
Ingress of 3: 3c <- 3d 3e 5a
Ingress of 3: 3h <- 3c 3d 3f
Ingress of 3: 3d <- 3c 5f 5i
Ingress of 3: 5j <- 5d 5h 5k
Ingress of 3: 8b <- 7c 8a 8e
Ingress of 3: 8h <- 8f 8g 8i
Ingress of 2: 3a <- CBM Capability 8e
Ingress of 2: 2c <- 1a 2f
Ingress of 2: 8a <- 1c 2c
Ingress of 2: 2b <- 2a 2c
Ingress of 2: 2d <- 2b 2c
Ingress of 2: 7f <- 2c 5e
Ingress of 2: 9d <- 2c 7f
Ingress of 2: 4b <- 7g 8i
Ingress of 2: 5c <- 5a 5d
Ingress of 2: 10b <- 5b 5e
Ingress of 2: 5g <- 5c 5d
Ingress of 2: 5d <- 5e 5h
Ingress of 2: 9h <- 5g 7e
Ingress of 2: 6e <- 6d 6f
Ingress of 2: 10e <- 7d 10f
Ingress of 2: 7k <- 7h 8e
Ingress of 2: 10a <- 8b 10b
Ingress of 2: 9b <- 9c 9d
Ingress of 2: 9i <- 9f 9h
Ingress of 2: 10d <- 10b 10c
```

```
Ingress of 1: 1a <- CBM Capability
Ingress of 1: 1b <- CBM Capability
Ingress of 1: 1c <- CBM Capability
Ingress of 1: 7h <- CBM Capability
Ingress of 1: 2a <- 1b
Ingress of 1: 2e <- 1c
Ingress of 1: 4a <- 2c
Ingress of 1: 2f <- 2e
Ingress of 1: 3g <- 3b
Ingress of 1: 3f <- 3d
Ingress of 1: 3e <- 5a
Ingress of 1: 5a <- 5b
Ingress of 1: 5b <- 5e
Ingress of 1: 6b <- 5e
Ingress of 1: 8c <- 5e
Ingress of 1: 5h <- 5e
Ingress of 1: 5i <- 5e
Ingress of 1: 5f <- 5e
Ingress of 1: 8d <- 5k
Ingress of 1: 6a <- 6b
Ingress of 1: 6c <- 6b
Ingress of 1: 6d <- 6b
Ingress of 1: 6f <- 6d
Ingress of 1: 7a <- 7b
Ingress of 1: 7b <- 8e
Ingress of 1: 7j <- 7c
Ingress of 1: 7e <- 7c
Ingress of 1: 8e <- 7h
Ingress of 1: 8i <- 7h
Ingress of 1: 7i <- 7k
Ingress of 1: 8g <- 8f
Ingress of 1: 8j <- 8g
Ingress of 1: 10f <- 9a
Ingress of 1: 9g <- 9h
Ingress of 1: 10c <- 10a
Ingress of 1: 10h <- 10f
Ingress of 1: 10g <- 10h
Ingress of 0: CBM Capability <-

Nodes, ordered by egress:
Egress of 13: 5e -> 7f 11b 7c 6b 8c 8f 5h 5d 5k 5i 5f 5b 10b
Egress of 11: 2c -> 7f 4a 5k 11b 9c 9a 7c 8a 2b 2d 9d
Egress of 7: 5k -> 11b 9c 9f 7d 7c 8d 5j
Egress of 6: 7c -> 9f 8f 8b 7j 7d 7e
Egress of 5: CBM Capability -> 1a 1b 1c 7h 3a
Egress of 5: 9h -> 9g 9e 9i 9f 7g
Egress of 5: 8e -> 7k 7b 3b 3a 8b
Egress of 4: 7h -> 3b 7k 8e 8i
Egress of 4: 9d -> 9f 9b 9a 9c
Egress of 3: 1c -> 5e 2e 8a
Egress of 3: 2b -> 7g 7c 2d
Egress of 3: 9c -> 9a 9f 9b
Egress of 3: 3d -> 3f 3h 3c
Egress of 3: 5a -> 3e 3c 5c
Egress of 3: 5d -> 5c 5g 5j
Egress of 3: 6b -> 6a 6c 6d
Egress of 3: 7e -> 7d 7g 9h
Egress of 3: 8g -> 8h 11a 8j
Egress of 2: 1a -> 5e 2c
Egress of 2: 1b -> 5e 2a
Egress of 2: 2a -> 9e 2b
Egress of 2: 8f -> 8h 8g
Egress of 2: 3c -> 3h 3d
Egress of 2: 5b -> 5a 10b
Egress of 2: 10b -> 10d 10a
Egress of 2: 5g -> 5k 9h
Egress of 2: 5h -> 5d 5j
Egress of 2: 5i -> 3d 5k
Egress of 2: 9f -> 11a 9i
Egress of 2: 7d -> 9f 10e
Egress of 2: 6d -> 6e 6f
```

```
Egress of 2: 8b -> 10a 8f
Egress of 2: 8i -> 8h 4b
Egress of 2: 10f -> 10e 10h
Egress of 2: 10h -> 11a 10g
Egress of 1: 3a -> 3b
Egress of 1: 2e -> 2f
Egress of 1: 8a -> 8b
Egress of 1: 9e -> 9f
Egress of 1: 7g -> 4b
Egress of 1: 2d -> 8f
Egress of 1: 7f -> 9d
Egress of 1: 11b -> 11a
Egress of 1: 9a -> 10f
Egress of 1: 2f -> 2c
Egress of 1: 3b -> 3g
Egress of 1: 3f -> 3h
Egress of 1: 3e -> 3c
Egress of 1: 5c -> 5g
Egress of 1: 5f -> 3d
Egress of 1: 8d -> 8f
Egress of 1: 6f -> 6e
Egress of 1: 7b -> 7a
Egress of 1: 10e -> 7d
Egress of 1: 7k -> 7i
Egress of 1: 10a -> 10c
Egress of 1: 8j -> 11a
Egress of 1: 9b -> 9a
Egress of 1: 9g -> 9e
Egress of 1: 10c -> 10d
Egress of 1: 10g -> 11a
Egress of 0: 4a ->
Egress of 0: 3g ->
Egress of 0: 3h ->
Egress of 0: 4b ->
Egress of 0: 5j ->
Egress of 0: 8c ->
Egress of 0: 6a ->
Egress of 0: 6c ->
Egress of 0: 6e ->
Egress of 0: 7a ->
Egress of 0: 7j ->
Egress of 0: 7i ->
Egress of 0: 8h ->
Egress of 0: 11a ->
Egress of 0: 9i ->
Egress of 0: 10d ->

Nodes, ordered by ingress+egress:
Ingress+Egress of 16: 1a 1b 1c -> 5e -> 7f 11b 7c 6b 8c 8f 5h 5d 5k 5i 5f 5b 10b
Ingress+Egress of 13: 1a 2f -> 2c -> 7f 4a 5k 11b 9c 9a 7c 8a 2b 2d 9d
Ingress+Egress of 11: 2c 5e 5g 5i -> 5k -> 11b 9c 9f 7d 7c 8d 5j
Ingress+Egress of 10: 2b 2c 5e 5k -> 7c -> 9f 8f 8b 7j 7d 7e
Ingress+Egress of 9: 5k 7c 7d 9c 9d 9e 9h -> 9f -> 11a 9i
Ingress+Egress of 7: 2d 5e 7c 8b 8d -> 8f -> 8h 8g
Ingress+Egress of 7: 5g 7e -> 9h -> 9g 9e 9i 9f 7g
Ingress+Egress of 6: 2c 5k 9d -> 9c -> 9a 9f 9b
Ingress+Egress of 6: 2c 7f -> 9d -> 9f 9b 9a 9c
Ingress+Egress of 6: 3c 5f 5i -> 3d -> 3f 3h 3c
Ingress+Egress of 6: 5k 7c 7e 10e -> 7d -> 9f 10e
Ingress+Egress of 6: 7h -> 8e -> 7k 7b 3b 3a 8b
Ingress+Egress of 6: 8g 8j 9f 10g 10h 11b -> 11a ->
Ingress+Egress of 5: -> CBM Capability -> 1a 1b 1c 7h 3a
Ingress+Egress of 5: CBM Capability -> 7h -> 3b 7k 8e 8i
Ingress+Egress of 5: 2a 2c -> 2b -> 7g 7c 2d
Ingress+Egress of 5: 2c 9b 9c 9d -> 9a -> 10f
Ingress+Egress of 5: 3d 3e 5a -> 3c -> 3h 3d
Ingress+Egress of 5: 5e 5h -> 5d -> 5c 5g 5j
Ingress+Egress of 5: 7c 8a 8e -> 8b -> 10a 8f
Ingress+Egress of 4: CBM Capability -> 1c -> 5e 2e 8a
Ingress+Egress of 4: 2a 9g 9h -> 9e -> 9f
Ingress+Egress of 4: 2b 7e 9h -> 7g -> 4b
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Ingress+Egress of 4: 2c 5e 5k -> 11b -> 11a
Ingress+Egress of 4: 3a 7h 8e -> 3b -> 3g
Ingress+Egress of 4: 5b -> 5a -> 3e 3c 5c
Ingress+Egress of 4: 5b 5e -> 10b -> 10d 10a
Ingress+Egress of 4: 5c 5d -> 5g -> 5k 9h
Ingress+Egress of 4: 5e -> 6b -> 6a 6c 6d
Ingress+Egress of 4: 7c -> 7e -> 7d 7g 9h
Ingress+Egress of 4: 8f -> 8g -> 8h 11a 8j
Ingress+Egress of 3: CBM Capability -> 1a -> 5e 2c
Ingress+Egress of 3: CBM Capability -> 1b -> 5e 2a
Ingress+Egress of 3: CBM Capability 8e -> 3a -> 3b
Ingress+Egress of 3: 1b -> 2a -> 9e 2b
Ingress+Egress of 3: 1c 2c -> 8a -> 8b
Ingress+Egress of 3: 2b 2c -> 2d -> 8f
Ingress+Egress of 3: 2c 5e -> 7f -> 9d
Ingress+Egress of 3: 3c 3d 3f -> 3h ->
Ingress+Egress of 3: 5a 5d -> 5c -> 5g
Ingress+Egress of 3: 5e -> 5b -> 5a 10b
Ingress+Egress of 3: 5d 5h 5k -> 5j ->
Ingress+Egress of 3: 5e -> 5h -> 5d 5j
Ingress+Egress of 3: 5e -> 5i -> 3d 5k
Ingress+Egress of 3: 6b -> 6d -> 6e 6f
Ingress+Egress of 3: 7d 10f -> 10e -> 7d
Ingress+Egress of 3: 7h 8e -> 7k -> 7i
Ingress+Egress of 3: 7h -> 8i -> 8h 4b
Ingress+Egress of 3: 8b 10b -> 10a -> 10c
Ingress+Egress of 3: 8f 8g 8i -> 8h ->
Ingress+Egress of 3: 9a -> 10f -> 10e 10h
Ingress+Egress of 3: 9c 9d -> 9b -> 9a
Ingress+Egress of 3: 10f -> 10h -> 11a 10g
Ingress+Egress of 2: 1c -> 2e -> 2f
Ingress+Egress of 2: 2e -> 2f -> 2c
Ingress+Egress of 2: 3d -> 3f -> 3h
Ingress+Egress of 2: 5a -> 3e -> 3c
Ingress+Egress of 2: 7g 8i -> 4b ->
Ingress+Egress of 2: 5e -> 5f -> 3d
Ingress+Egress of 2: 5k -> 8d -> 8f
Ingress+Egress of 2: 6d 6f -> 6e ->
Ingress+Egress of 2: 6d -> 6f -> 6e
Ingress+Egress of 2: 8e -> 7b -> 7a
Ingress+Egress of 2: 8g -> 8j -> 11a
Ingress+Egress of 2: 9f 9h -> 9i ->
Ingress+Egress of 2: 9h -> 9g -> 9e
Ingress+Egress of 2: 10a -> 10c -> 10d
Ingress+Egress of 2: 10b 10c -> 10d ->
Ingress+Egress of 2: 10h -> 10g -> 11a
Ingress+Egress of 1: 2c -> 4a ->
Ingress+Egress of 1: 3b -> 3g ->
Ingress+Egress of 1: 5e -> 8c ->
Ingress+Egress of 1: 6b -> 6a ->
Ingress+Egress of 1: 6b -> 6c ->
Ingress+Egress of 1: 7b -> 7a ->
Ingress+Egress of 1: 7c -> 7j ->
Ingress+Egress of 1: 7k -> 7i ->

Mutual Dependencies:
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Number of SCCs is 75
Number of non-trivial SCCs is 2

Non-trivial SCC:
3c 3d

Non-trivial SCC:
7d 10e

Cycles and Paths:
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Number of elementary cycles: 2
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Maximum cycle length: 2
Minimum cycle length: 2

Histogram of Cycle Lengths (cycle length, instances of cycles of that length):
(2,2)

Prevalence of nodes in cycles:
Node 10e appears in 1 cycles out of 2 (50.0% of cycles)
Node 7d appears in 1 cycles out of 2 (50.0% of cycles)
Node 3d appears in 1 cycles out of 2 (50.0% of cycles)
Node 3c appears in 1 cycles out of 2 (50.0% of cycles)

The cycles are:
1. 10e 7d
2. 3d 3c

Number of paths: 1668
Maximum path length: 16
Minimum path length: 4

Histogram of Path Lengths (path length, instances of paths of that length):
(4,9)
(5,33)
(6,67)
(7,133)
(8,187)
(9,232)
(10,261)
(11,258)
(12,213)
(13,144)
(14,75)
(15,44)
(16,12)

Prevalence of nodes in paths:
Node CBM Capability appears in 1668 paths out of 1668( 100.0% of paths)
Node 5e appears in 1287 paths out of 1668( 77.16% of paths)
Node 5k appears in 1035 paths out of 1668( 62.05% of paths)
Node 5g appears in 795 paths out of 1668( 47.66% of paths)
Node 9f appears in 794 paths out of 1668( 47.6% of paths)
Node 11a appears in 779 paths out of 1668( 46.7% of paths)
Node 7c appears in 775 paths out of 1668( 46.46% of paths)
Node 5d appears in 642 paths out of 1668( 38.49% of paths)
Node 1c appears in 599 paths out of 1668( 35.91% of paths)
Node 1a appears in 594 paths out of 1668( 35.61% of paths)
Node 5c appears in 477 paths out of 1668( 28.6% of paths)
Node 1b appears in 461 paths out of 1668( 27.64% of paths)
Node 9i appears in 443 paths out of 1668( 26.56% of paths)
Node 8f appears in 388 paths out of 1668( 23.26% of paths)
Node 9h appears in 368 paths out of 1668( 22.06% of paths)
Node 7e appears in 341 paths out of 1668( 20.44% of paths)
Node 7d appears in 330 paths out of 1668( 19.78% of paths)
Node 2c appears in 330 paths out of 1668( 19.78% of paths)
Node 5h appears in 324 paths out of 1668( 19.42% of paths)
Node 10f appears in 320 paths out of 1668( 19.18% of paths)
Node 9a appears in 320 paths out of 1668( 19.18% of paths)
Node 9c appears in 320 paths out of 1668( 19.18% of paths)
Node 8g appears in 291 paths out of 1668( 17.45% of paths)
Node 8h appears in 195 paths out of 1668( 11.69% of paths)
Node 9e appears in 186 paths out of 1668( 11.15% of paths)
Node 5b appears in 183 paths out of 1668( 10.97% of paths)
Node 5a appears in 177 paths out of 1668( 10.61% of paths)
Node 8b appears in 175 paths out of 1668( 10.49% of paths)
Node 2f appears in 165 paths out of 1668( 9.89% of paths)
Node 2e appears in 165 paths out of 1668( 9.89% of paths)
Node 10h appears in 160 paths out of 1668( 9.59% of paths)
Node 10e appears in 160 paths out of 1668( 9.59% of paths)
Node 9b appears in 156 paths out of 1668( 9.35% of paths)
Node 5i appears in 144 paths out of 1668( 8.63% of paths)
Node 9d appears in 140 paths out of 1668( 8.39% of paths)
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Node 7f appears in 100 paths out of 1668( 6.0% of paths)
Node 8j appears in 97 paths out of 1668( 5.82% of paths)
Node 9g appears in 92 paths out of 1668( 5.52% of paths)
Node 8d appears in 92 paths out of 1668( 5.52% of paths)
Node 2b appears in 90 paths out of 1668( 5.4% of paths)
Node 4b appears in 81 paths out of 1668( 4.86% of paths)
Node 10g appears in 80 paths out of 1668( 4.8% of paths)
Node 7g appears in 80 paths out of 1668( 4.8% of paths)
Node 10d appears in 47 paths out of 1668( 2.82% of paths)
Node 10c appears in 41 paths out of 1668( 2.46% of paths)
Node 10a appears in 41 paths out of 1668( 2.46% of paths)
Node 3h appears in 36 paths out of 1668( 2.16% of paths)
Node 5j appears in 32 paths out of 1668( 1.92% of paths)
Node 2a appears in 32 paths out of 1668( 1.92% of paths)
Node 7j appears in 31 paths out of 1668( 1.86% of paths)
Node 3d appears in 30 paths out of 1668( 1.8% of paths)
Node 11b appears in 28 paths out of 1668( 1.68% of paths)
Node 3c appears in 24 paths out of 1668( 1.44% of paths)
Node 2d appears in 20 paths out of 1668( 1.2% of paths)
Node 8a appears in 15 paths out of 1668( 0.9% of paths)
Node 7h appears in 13 paths out of 1668( 0.78% of paths)
Node 6b appears in 12 paths out of 1668( 0.72% of paths)
Node 10b appears in 12 paths out of 1668( 0.72% of paths)
Node 3f appears in 12 paths out of 1668( 0.72% of paths)
Node 8e appears in 9 paths out of 1668( 0.54% of paths)
Node 5f appears in 9 paths out of 1668( 0.54% of paths)
Node 3e appears in 9 paths out of 1668( 0.54% of paths)
Node 6e appears in 6 paths out of 1668( 0.36% of paths)
Node 6d appears in 6 paths out of 1668( 0.36% of paths)
Node 3g appears in 4 paths out of 1668( 0.24% of paths)
Node 3b appears in 4 paths out of 1668( 0.24% of paths)
Node 6f appears in 3 paths out of 1668( 0.18% of paths)
Node 6c appears in 3 paths out of 1668( 0.18% of paths)
Node 6a appears in 3 paths out of 1668( 0.18% of paths)
Node 8c appears in 3 paths out of 1668( 0.18% of paths)
Node 7i appears in 2 paths out of 1668( 0.12% of paths)
Node 8i appears in 2 paths out of 1668( 0.12% of paths)
Node 7k appears in 2 paths out of 1668( 0.12% of paths)
Node 4a appears in 2 paths out of 1668( 0.12% of paths)
Node 3a appears in 2 paths out of 1668( 0.12% of paths)
Node 7b appears in 1 paths out of 1668( 0.06% of paths)
Node 7a appears in 1 paths out of 1668( 0.06% of paths)

Number of nodes not covered by at least one path from 'CBM Capability': 0 (0.0% of nodes)
(All nodes are covered by at least one path from 'CBM Capability')

Paths that start at each starting node:
1668 paths start from node CBM Capability (100.0% of paths)

Number of paths that terminate at each terminating node:
779 paths terminate in node 11a (46.7% of paths)
443 paths terminate in node 9i (26.56% of paths)
195 paths terminate in node 8h (11.69% of paths)
81 paths terminate in node 4b (4.86% of paths)
47 paths terminate in node 10d (2.82% of paths)
36 paths terminate in node 3h (2.16% of paths)
32 paths terminate in node 5j (1.92% of paths)
31 paths terminate in node 7j (1.86% of paths)
6 paths terminate in node 6e (0.36% of paths)
4 paths terminate in node 3g (0.24% of paths)
3 paths terminate in node 6c (0.18% of paths)
3 paths terminate in node 6a (0.18% of paths)
3 paths terminate in node 8c (0.18% of paths)
2 paths terminate in node 7i (0.12% of paths)
2 paths terminate in node 4a (0.12% of paths)
1 paths terminate in node 7a (0.06% of paths)

Top 25 most critical paths based on a combined 'prevalence of nodes in paths' score are:
Score of 1027.0: path is CBM Capability 1c 5e 5k 9f 11a
Score of 1026.17: path is CBM Capability 1a 5e 5k 9f 11a
Score of 1004.0: path is CBM Capability 1b 5e 5k 9f 11a
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Score of 991.0: path is CBM Capability 1c 5e 5k 7c 9f 11a
Score of 990.29: path is CBM Capability 1a 5e 5k 7c 9f 11a
Score of 983.67: path is CBM Capability 1c 5e 7c 9f 11a
Score of 982.83: path is CBM Capability 1a 5e 7c 9f 11a
Score of 971.29: path is CBM Capability 1b 5e 5k 7c 9f 11a
Score of 971.0: path is CBM Capability 1c 5e 5k 9f 9i
Score of 970.17: path is CBM Capability 1a 5e 5k 9f 9i
Score of 960.67: path is CBM Capability 1b 5e 7c 9f 11a
Score of 949.88: path is CBM Capability 1c 5e 5d 5g 5k 9f 11a
Score of 949.25: path is CBM Capability 1a 5e 5d 5g 5k 9f 11a
Score of 948.0: path is CBM Capability 1b 5e 5k 9f 9i
Score of 943.0: path is CBM Capability 1c 5e 5k 7c 9f 9i
Score of 942.29: path is CBM Capability 1a 5e 5k 7c 9f 9i
Score of 932.63: path is CBM Capability 1b 5e 5d 5g 5k 9f 11a
Score of 930.44: path is CBM Capability 1c 5e 5d 5g 5k 7c 9f 11a
Score of 929.89: path is CBM Capability 1a 5e 5d 5g 5k 7c 9f 11a
Score of 927.67: path is CBM Capability 1c 5e 7c 9f 9i
Score of 927.43: path is CBM Capability 1c 5e 5k 7d 9f 11a
Score of 926.83: path is CBM Capability 1a 5e 7c 9f 9i
Score of 926.71: path is CBM Capability 1a 5e 5k 7d 9f 11a
Score of 926.0: path is CBM Capability 1c 5e 5k 9c 9f 11a
Score of 925.29: path is CBM Capability 1a 5e 5k 9c 9f 11a

Bottom 25 most critical (Top 25 least critical) paths based on a combined 'prevalence of
nodes in paths' score are:
Score of 402.0: path is CBM Capability 1b 2a 2b 7g 4b
Score of 402.0: path is CBM Capability 1a 5e 5b 5a 3e 3c 3d 3f 3h
Score of 401.69: path is CBM Capability 1c 2e 2f 2c 7f 9d 9c 9b 9a 10f 10h 11a
Score of 400.67: path is CBM Capability 1c 2e 2f 2c 7f 9d 9c 9b 9a 10f 10e 7d 9f 9i
Score of 400.6: path is CBM Capability 1c 2e 2f 2c 7c 8b 10a 10c 10d
Score of 400.15: path is CBM Capability 1c 2e 2f 2c 9d 9c 9b 9a 10f 10h 10g 11a
Score of 399.1: path is CBM Capability 1c 2e 2f 2c 8a 8b 8f 8g 8h
Score of 397.25: path is CBM Capability 1c 2e 2f 2c 2b 7g 4b
Score of 395.85: path is CBM Capability 1c 2e 2f 2c 7f 9d 9c 9a 10f 10h 10g 11a
Score of 393.13: path is CBM Capability 1b 2a 2b 2d 8f 8g 8h
Score of 391.29: path is CBM Capability 7h 8e 8b 8f 8g 8h
Score of 391.1: path is CBM Capability 1c 2e 2f 2c 2b 2d 8f 8g 8h
Score of 388.7: path is CBM Capability 1b 5e 5b 5a 3e 3c 3d 3f 3h
Score of 383.23: path is CBM Capability 1c 2e 2f 2c 7f 9d 9b 9a 10f 10h 10g 11a
Score of 378.71: path is CBM Capability 1c 2e 2f 2c 7f 9d 9c 9b 9a 10f 10h 10g 11a
Score of 372.36: path is CBM Capability 1c 2e 2f 2c 2b 7c 8b 10a 10c 10d
Score of 370.0: path is CBM Capability 1b 2a 2b 7c 8b 10a 10c 10d
Score of 369.43: path is CBM Capability 1c 8a 8b 10a 10c 10d
Score of 363.88: path is CBM Capability 1a 2c 8a 8b 10a 10c 10d
Score of 339.6: path is CBM Capability 7h 8e 3b 3g
Score of 338.8: path is CBM Capability 7h 8e 7k 7i
Score of 338.4: path is CBM Capability 7h 8e 7b 7a
Score of 324.6: path is CBM Capability 1c 2e 2f 2c 8a 8b 10a 10c 10d
Score of 284.86: path is CBM Capability 7h 8e 8b 10a 10c 10d
Score of 283.33: path is CBM Capability 7h 8e 3a 3b 3g

Top 25 most critical paths based on a normalised combined 'node ingress and egress' score
are:
Score of 8.71: path is CBM Capability 1c 5e 5k 7c 9f 11a
Score of 8.57: path is CBM Capability 1b 5e 5k 7c 9f 11a
Score of 8.57: path is CBM Capability 1a 5e 5k 7c 9f 11a
Score of 8.5: path is CBM Capability 1c 5e 5k 9f 11a
Score of 8.38: path is CBM Capability 1c 5e 5k 7c 7d 9f 11a
Score of 8.33: path is CBM Capability 1c 5e 7c 9f 11a
Score of 8.33: path is CBM Capability 1b 5e 5k 9f 11a
Score of 8.33: path is CBM Capability 1a 5e 5k 9f 11a
Score of 8.25: path is CBM Capability 1b 5e 5k 7c 7d 9f 11a
Score of 8.25: path is CBM Capability 1a 5e 5k 7c 7d 9f 11a
Score of 8.17: path is CBM Capability 1b 5e 7c 9f 11a
Score of 8.17: path is CBM Capability 1a 5e 7c 9f 11a
Score of 8.14: path is CBM Capability 1c 5e 5k 7c 9f 9i
Score of 8.14: path is CBM Capability 1c 5e 5k 7d 9f 11a
Score of 8.14: path is CBM Capability 1c 5e 5k 9c 9f 11a
Score of 8.14: path is CBM Capability 1a 2c 5k 7c 9f 11a
Score of 8.0: path is CBM Capability 1c 5e 5i 5k 7c 9f 11a
Score of 8.0: path is CBM Capability 1c 5e 5k 7c 7e 9h 9f 11a
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Score of 8.0: path is CBM Capability 1c 5e 5k 7c 8f 8h
Score of 8.0: path is CBM Capability 1c 5e 7c 7d 9f 11a
Score of 8.0: path is CBM Capability 1b 5e 5k 7c 9f 9i
Score of 8.0: path is CBM Capability 1b 5e 5k 7d 9f 11a
Score of 8.0: path is CBM Capability 1b 5e 5k 9c 9f 11a
Score of 8.0: path is CBM Capability 1a 5e 5k 7c 9f 9i
Score of 8.0: path is CBM Capability 1a 5e 5k 7d 9f 11a

Bottom 25 most critical (Top 25 least critical) paths based on a normalised combined 'node
ingress and egress' score are:
Score of 4.5: path is CBM Capability 1c 2e 2f 2c 7f 9d 9a 10f 10h 10g 11a
Score of 4.5: path is CBM Capability 1b 2a 2b 2d 8f 8g 11a
Score of 4.5: path is CBM Capability 1b 2a 2b 7c 7e 7g 4b
Score of 4.5: path is CBM Capability 1b 2a 2b 7c 7j
Score of 4.5: path is CBM Capability 1a 2c 8a 8b 10a 10c 10d
Score of 4.43: path is CBM Capability 1c 8a 8b 8f 8g 8h
Score of 4.38: path is CBM Capability 1c 2e 2f 2c 7f 9d 9b 9a 10f 10h 10g 11a
Score of 4.33: path is CBM Capability 1b 2a 9e 9f 9i
Score of 4.22: path is CBM Capability 1b 2a 2b 2d 8f 8g 8j 11a
Score of 4.22: path is CBM Capability 1b 2a 2b 7c 8b 10a 10c 10d
Score of 4.2: path is CBM Capability 7h 8e 3b 3g
Score of 4.14: path is CBM Capability 1b 2a 2b 2d 8f 8h
Score of 4.13: path is CBM Capability 1b 2a 2b 2d 8f 8g 8h
Score of 4.1: path is CBM Capability 1c 2e 2f 2c 8a 8b 10a 10c 10d
Score of 4.0: path is CBM Capability 7h 8i 8h
Score of 4.0: path is CBM Capability 7h 8e 8b 10a 10c 10d
Score of 4.0: path is CBM Capability 7h 8e 3a 3b 3g
Score of 4.0: path is CBM Capability 7h 8e 7k 7i
Score of 3.8: path is CBM Capability 7h 8e 7b 7a
Score of 3.75: path is CBM Capability 7h 8i 4b
Score of 3.75: path is CBM Capability 7h 3b 3g
Score of 3.67: path is CBM Capability 1b 2a 2b 7g 4b
Score of 3.5: path is CBM Capability 7h 7k 7i
Score of 3.43: path is CBM Capability 1c 8a 8b 10a 10c 10d
Score of 3.25: path is CBM Capability 3a 3b 3g

The paths are:
1. CBM Capability 1a 5e 7f 9d 9f 11a
2. CBM Capability 1a 5e 7f 9d 9f 9i
3. CBM Capability 1a 5e 7f 9d 9b 9a 10f 10e 7d 9f 11a
4. CBM Capability 1a 5e 7f 9d 9b 9a 10f 10e 7d 9f 9i
5. CBM Capability 1a 5e 7f 9d 9b 9a 10f 10h 11a
```

<*snip*>

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1664. CBM Capability 7h 8e 8b 8f 8g 11a
1665. CBM Capability 7h 8e 8b 8f 8g 8j 11a
1666. CBM Capability 7h 8i 8h
1667. CBM Capability 7h 8i 4b
1668. CBM Capability 3a 3b 3g
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19. ABSTRACT
This study considered the implications of adopting Condition Based Maintenance (CBM) within the military Land domain. A 'CBM technology impacts map' was developed, capturing the inputs required to generate a CBM-based capability, the expected effects resulting from that capability, and their causal relationships. The map was developed through reviewing the literature, internal DSTO workshops and two rounds of Delphi-based surveys of subject matter experts (SMEs). This map and associated material were then analysed using a triangulation approach to identify the key inputs, effects and issues relating to developing and implementing a CBM-based maintenance capability. Further, the analysis elicited the costs and benefits associated with adopting CBM in the military Land domain, and highlighted key areas of risk and opportunity.