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The Role of Reliability Data Bases in Deploying CBM+, RCM and PHM with TLCSM

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Abstract—The total life cycle systems management [TLCSM] imperative for military systems holds the program manager accountable for “total system performance (hardware, software, and human), operational effectiveness, and suitability, survivability, safety, and affordability”. Condition Based Maintenance Plus [CBM+], Reliability Centered Maintenance [RCM] and prognostic health management [PHM] for critical sub-systems, such as propulsion, are considered essential program elements in meeting this responsibility for total life cycle sustainability.  

A key enabler for CBM+, RCM and PHM is adequate and accessible reliability data bases [RDB] as a primary source of the information needed to design and develop cost effective system provisions for initial deployment of new or upgraded propulsion systems. In addition, cost effective sustainment of military propulsion systems implies continued maintenance and enhancement of RDB to address the inevitable emerging reliability issues that were neither anticipated nor detected during propulsion system design and development.

The expectations of TLCSM and the resultant deployment of CBM+, RCM and PHM will place increasing demands on RDB in terms of data collected, archived and processed to provide actionable information for maintainers, engineers and leaders responsible for maintenance process and configuration management, and mission planners and operational leadership.

The scope of RDB coverage will expand to include records of individual propulsion system usage and other variables affecting propulsion system reliability. Integration with associated cost and logistics data bases will facilitate CBM+ & RCM application. Advanced analysis tools will support proactive oversight of deviations from expected reliability using machine intelligence to alleviate information overload on RDB users. RDB will evolve based on, and supporting, advanced models of propulsion system reliability that are automatically updated in response to field data and provide timely and dependable forecasts of propulsion system reliability, maintenance effort and logistical requirements.

1. INTRODUCTION

The DoD Defense Acquisition System Directive [1] states policy as: “4.2. The primary objective of Defense acquisition is to acquire quality products that satisfy user needs with measurable improvements to mission capability and operational support, in a timely manner, and at a fair and reasonable price.

The US Department of Defense Acquisition Guidebook [2] states in Section 4.1.3. - Total Life Cycle Systems Management (TLCSM) in Systems Engineering: “It is fundamental to systems engineering to take a total life cycle, total systems approach to system planning, development, and implementation. Total life cycle systems management (TLCSM) is the planning for and management of the entire acquisition life cycle of a DoD system. Related to the total systems approach, DoD Directive 5000.1, E1.29, makes the program manager accountable for TLCSM”. (See Table 1.)

The Defense Acquisition Guidebook continues: “Because of TLCSM, the program manager should consider nearly all systems development decisions in context of the effect that decision will have on the long term operational effectiveness and logistics affordability of the system.”

This paper addresses the role of reliability data bases (RDB) in the deployment of TLCSM through the implementation of Condition Based Maintenance Plus (CBM+), Reliability Centered Maintenance (RCM) and prognostic health management (PHM).

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1 “U.S. Government work not protected by U.S. copyright.”
2 IEEEAC paper #1587, Version 5, Updated January 28, 2008
Reliability data bases are commonly maintained in industry and the military where complex, critical equipment is subject to sustained operation and repeated maintenance. RDB typically record all significant maintenance activity with emphasis on equipment failures. See Cooke & Bedford [13] for a more detailed description.

RDB for military systems may encompass many hundred nominally identical systems (i.e., pieces of equipment) with a service lives measured in decades. See Millar, et al [14] for an example. In addition to calendar based records of maintenance actions (including both scheduled preventive maintenance and unscheduled tasks in response to fault indications and failures) archived data may encompass measures of cumulative usage (e.g., operational cycles and duration) and configuration logs for individual systems.

Ideally the RDB will also retain, or enable retrieval of, salient findings from servicing, preventive maintenance, repairs and shop visits, including parts replacements. Thus the RDB provides the data necessary to measure and understand the systems' reliability over time and as a function of usage and configuration. This information may be used to track the reliability of system components and assess impacts on system availability. RDB can also provide information on the effectiveness of maintenance actions and inform continuous improvement of maintenance practices.

### 2. TOTAL LIFE CYCLE SYSTEMS MANAGEMENT

The Defense Acquisition Guidebook [2] Section 5.1.1, Total Life Cycle Systems Management, defines TLCSM as the "implementation, management, and oversight, by the designated Program Manager, of all activities associated with the acquisition, development, production, fielding, sustainment, and disposal of a DoD weapon or materiel system across its life cycle" with reference to DoD Directive 5000.1 [1].

TLCSM is stated to include, among other imperatives and as a major initiative, the need to consider product support and life cycle logistics in DoD acquisition strategies with enhanced sustainment as a key performance criteria. Achieving this goal is expected to yield increased reliability and a reduced logistics footprint with performance-based logistics (PBL) strategies as a key enabler.

A 2002 article in Program Manager Magazine by Louis A. Kratz, Randy T. Fowler and Jerry D. Cothran [3] traces the emphasis on TLCSM to the 2001 Quadrennial Defense Review’s (QDR) focus on transformation of US defense to a "capability-based" strategy to repel 21st Century threats. Affordably projecting and sustaining military power anywhere necessary is stated to be one of the top DoD transformation goals and that this requires "dramatic improvements in our sustainment capability to achieve rapidly deployable and employable forces with significant reductions in logistics footprint."

This publication anticipates revisions to DODI 5000.1 [1] and DODD 5000.2 [4] to mandate the performance based logistics as the preferred strategy for sustainment, implemented through public-private partnerships employing health monitoring and prognostics to manage defense assets. (The F/A-18 E/F program is cited as a pioneer in anticipating this mandate, as the first naval aviation platform deployed under a PBL strategy.)

This reference also notes that the subsequent formation of the DoD Joint Logistics Board and its Future Logistics Enterprise led to the determination that Total Life Cycle Systems Management was one of the six initiatives necessary to achieve the sustainment capabilities identified by the 2001 QDR. These initiatives also include Condition Based Maintenance Plus (CBM+), further described below, and Enterprise Integration to ensure the "real-time, actionable data required to deploy and sustain combat power rapidly with minimal footprint" [3].

The synergy of these initiatives in exemplified by the importance given to CBM+ and Enterprise Integration as enablers for TLCSM in providing the necessary information systems, asset state awareness and analysis tools to effectively optimize fleet sustainment activities. This integration is essential to timely reliability data collection, analysis and dissemination as actionable information and guidance to DoD planners, war fighters, maintainers, logisticians, program managers and systems engineers. In this context, Louis A. Kratz, Randy T. Fowler and Jerry D. Cothran [3] envisage integrated functional, public and private enterprise, partnerships to provide a support infrastructure informed by real-time situational awareness based on outcomes monitored automatically by embedded instrumentation and prognostics.

In 2005, Kenneth J. Kreig, the Under Secretary of Defense for Acquisition, Technology and Logistics issued a
memorandum to the secretaries of the military departments [5] that detailed the calculation of Total Life Cycle Systems Management (TLCMSM) Metrics. These define the measures of Operational Availability, Mission Reliability, Cost per Unit of Usage, Logistics Footprint, and Logistics Response Time.

Review of the definition of these metrics reveals that the first two, Operational Availability and Mission Reliability, are derived from data typically found in reliability data bases (RDB). The defined TLCMSM and variable Cost per Unit of Usage metrics are based on aggregated cost data not usually incorporated in reliability databases, but as discussed below, a subset of the cost data is also relevant and necessary for thorough reliability centered maintenance (RCM) program analysis.

The two logistics related metrics, Logistics Footprint, and Logistics Response Time, are derived from data not usually considered part of a reliability data base, and might be considered irrelevant to our interest here. However, efforts to manage these metrics can be expected to result in increased interest in reliability and maintenance data that would be most readily available from RDB, and possibly changes in the data collected, and the analysis of this and other salient data. Furthermore, the capabilities of the logistics processes employed, and any enhancements, may affect the selection of optimal maintenance processes through RCM and thus the needs for, and usage of, RDB.

As the DoD moves to an integrated, cross-functional TLCMSM process it seems likely that reliability, cost and logistics data will migrate to a common data base to facilitate fully informed and optimal decision making by all parties involved – an issue particularly sensitive in public/private partnerships, notably those governed by PBL.

In this context the dependability, accuracy and timeliness of RDB contents may be critical to the effectiveness and viability of PBL arrangements.

In particular, rather detailed and specific measures of the usage of individual assets and their subsystems and components are likely to be required – data that is central to effective prognostics, and thus RCM and CBM+. RDB are the most likely hosts for such usage data, information that enables precise component lifing, meaningful reliability assessments and mission based availability projections.

The objective of this paper is to examine the roles of reliability data bases in this emerging TLCMSM acquisition and operational environment and the requirements and capabilities necessary to support these roles. The above outline supports the thesis that comprehensive, accurate and timely RDB will increasingly perform a critical supportive and enabling role in the deployment of TLCMSM. The rest of this paper examines this thesis in the context of Condition Based Maintenance Plus [CBM+] and Reliability Centered Maintenance [RCM], including the application of Prognostic Health Management [PHM].

### 3. CONDITION BASED MAINTENANCE PLUS

A draft DoD Instruction [7], Condition Based Maintenance Plus (CBM+) for Materiel Management, identifies CBM+ as “the primary reliability driver in the Total Life Cycle Systems Management (TLCMSM) supportability strategy of the Department of Defense” in concert with Continuous Process Improvement and Performance Driven Outcomes achieved via Performance Based Logistics.

The Defense Acquisition Guidebook [2], Section 5.2.1.2: Condition Based Maintenance Plus (CBM+) provides this definition of CBM+: “a set of maintenance processes and capabilities derived, in large part, from real-time assessment of weapon system condition, obtained from embedded sensors and/or external tests and measurements. The goal of CBM+ is to perform as much maintenance as possible at pre-determined trigger events. A trigger event can be physical evidence of an impending failure provided either by inspection or diagnostic technology, or could be operating hours completed, elapsed calendar days or other periodically occurring situation (i.e., classical scheduled maintenance).”

This reference notes that “embedded diagnostics and prognostics to signal the need for maintenance”, preventive maintenance to preempt unscheduled maintenance, and “use of maintenance data analysis that correlates external variables with the requirement to accomplish a maintenance action” are CBM+ “tenets”. It is notable that adequate RDB incorporating relevant usage data are necessary to all of these capabilities.

Figure 1 provides an integrated view of CBM+ from a DoD acquisition web site which emphasizes the integration of Condition Based Maintenance and Reliability Centered Maintenance, noting the relevance of integrated data, databases and decision support tools. However, this and other references offer no specific details on the role of RDB and RDB analysis tools in implementing CBM+.
An Air Force fact sheet for 21st Century Expeditionary Logistics, titled Conditioned-Based (sic) Maintenance Plus (CBM+) [6], expands on the above to identify the need to implement specific enabling technologies and concepts:

1. Prognostics
2. Diagnostics
3. Automatic Identification Technology
4. Integrated Information Systems
5. Joint Total Asset Visibility
6. Data Analysis
7. Reliability Centered Maintenance
8. Portable Maintenance Aids
9. Interactive Electronic Technical Manuals
10. Interactive Training

These have been reordered here to show these elements span the spectrum from tools providing new data that will have to be integrated into RDB (1 & 2), or facilitating data collection (3 & 4), direct uses of RDB data (5, 6 & 7), and items that are likely to be affected by the availability of RDB information (8, 9 &10). Automatic Identification Technology [AIT] further implies visibility of weapon system configuration, a key data set for analyzing and projecting weapon system reliability and availability.

Considering the above, what are the specific contributions RDB can make to CBM+? On one hand, the described functionality might be implemented via an autonomous system embedded in the weapon system, possibly with the acquisition of some external tests and measurements, or alternatively incorporating off-board maintenance aids. However, such architectures - with fully dispersed RDB resident in each weapon system - seem unlikely to be the most cost effective.

Furthermore, the need for "Joint Total Asset Visibility" is evident to approach optimal maintenance and asset management. Understanding the capability, scheduled maintenance requirements and expected availability of each asset is essential to effective and efficient integrated operations and logistics. Thus one function for RDB, possibly partially distributed but with essential centralized elements, is to enable the acquisition and analysis of aggregated data from individual weapon systems.

So far this view makes one audacious and unrealistic assumption – that the deployed CBM+ process is fully adequate and satisfactory for the life of the weapon system. However, such foresight is hardly to be expected. Well after OPEVAL we expect to learn much from service experience to refine, mature and enhance equipment maintenance processes and system configuration. In
practice, CBM+ depends on dynamic CPI and CIP to approach tolerable system safety, availability and affordability.

Thus, another role for RDB is the collection & preservation of the data needed to continuously validate and correct expected system and component failure modes and reliability. The other side of this coin is the need to monitor the effectiveness of the CBM+ maintenance processes and CBM and PHM sensors, models and analysis tools, including the reliability of CBM+ infrastructure and execution.

Another technology emerging from the implementation of CBM+ and prognostics is particularly relevant to the topic of RDB: more sophisticated measures of sub-system and component usage to supplement the conventional focus on flight cycles and operating hours. These arise naturally from reliability centered maintenance (RCM) with its bottom-up approach to preventive maintenance, as sub-system and component failure rates are usually modeled by multi-variate life usage indicators (LUI).

Such advanced usage based component lifing may be more expedient and cost effective than diagnostics and prognostics based on embedded sensors and it is enabled by the growing availability of high fidelity models of system behavior and component lives. However, the concomitant increase in the volume and complexity of the data that must be collected, analyzed and possibly archived will have great impact on the size and complexity of RDB. And, again, RDB will need to support validation and continuous improvement the underlying models of component failure modes and reliability.

It is clear that expanded RDB data collection and analytical capability is an essential enabler for the deployment of CBM+ within the DoD and a crucial element guiding the enhancement of CBM+ via Continuous Process Improvement (CPI). This insight applies not only to future platforms such as F-35, the Joint Strike Fighter, but implies the need to improve the coverage and utilization of RDB for legacy platforms. The latter will not only improve the maintainability and availability of current aviation assets, the lessons learned and tools developed will be crucial to the rapid maturity of CBM+ applied to future systems through operational evaluation (OPEVAL) and entry into service (EIS).

Thus the third aspect of RDB usage is the generation and improvement of more generic models of component and system reliability for TLCSM based requirements, definition and development of future systems. In summary, RDB should be specified and designed to support three aspects of TLCSM system acquisition and deployment: effective and satisfactory CBM+ deployment, the capability to responsively and proactively mature and update the CBM+ process and the weapon system configuration as necessary to achieve TLCSM objectives, and the accumulation of a knowledge base to enhance future TLCSM based acquisitions.

4. RELIABILITY CENTERED MAINTENANCE

Again referring to a variety of DoD documentation, the following describes the expectations for this element of CBM+. “At its core, CBM+ is maintenance performed on evidence of need provided by Reliability Centered Maintenance (RCM) analysis and other enabling processes and technologies” [8].

“RCM is a logical, structured process used to determine the optimal failure management strategies for any system, based on system reliability characteristics and the intended operating context. RCM defines what must be done to a system to achieve the desired levels of safety, reliability, environmental soundness, and operational readiness, at best cost. RCM is to be applied continuously throughout the life cycle of any system.

As one of the key enablers of CBM+ and the life cycle sustainment of DoD weapons systems, RCM is conducted to ensure that effective maintenance processes are implemented. RCM provides a logical decision process for determining optimum maintenance approaches and establishes the evidence of need for both reactive and proactive maintenance tasks.” [9]

Figure 2, found in a Naval Air Systems Command Management Manual defining guidelines for RCM [10], and many other sources, illustrates the process of RCM definition, implementation and update. This reference makes evident the essential role of RDB in RCM implementation, providing the information needed to plan and schedule on-condition, hard time, failure finding and age exploration tasks, and generate the metrics for RCM program monitoring and evaluation.

Figure 2 also includes feedback of "in-service data and operator/maintainer input" for two purposes - RCM task evaluation and FMECA analysis – both activities where RDB are essential to collect and retain the necessary information.

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3 Which can be interpreted to include all usage based PM tasks, whether based on flight cycles, operating hours or more complex component life usage metrics.
A recent instruction issued by the Commander, Naval Air Systems Command, emphasizes that RCM is a "continuing, integrated activity...for making affordable management decisions" as a TLCSM process, and that as such RCM influences design and development requirements, defines the preventive maintenance [PM] program for test & evaluation and sustainment, updates PM for initial deliveries and subsequent major modifications, and guides maintenance and design improvements throughout production, deployment, operations and sustainment. Crucially, RCM is "based on the reliability of the various components, the efficacy of maintenance actions, the severity of the consequences related to safety and mission if failure occurs, and the cost effectiveness of the task."

Again, RDB are the medium for acquisition, retention and dissemination of the information needed for all of these RCM activities and functions. Thus, the RDB supporting RCM should encompass comprehensive records of equipment and component usage, faults indications and failures (including safety & operational consequences), scheduled and unscheduled maintenance actions and their costs and outcomes, and salient operator and maintainer observations.

5. PROGNOSTIC HEALTH MANAGEMENT (PHM)

Prognostic health management depends on effective measures to detect degradation and impending failure well in advance of any loss of mission capability. Coupled to dependable tools to model remaining useful life, an essential PHM element, this allows delay of what would otherwise be unscheduled maintenance activity to a scheduled preventive maintenance event, or another convenient time with the least impact on equipment availability and maintenance workload.

Prognostic health management (PHM) is a key complement to CBM+ and RCM.

Condition based maintenance is designed to eliminate unnecessary maintenance, but it also introduces an undesirable element of variability into maintenance planning and execution compared to well rationalized hard time maintenance policies. The unscheduled maintenance needed to correct an impending failure detected during inspection or automated fault detection leads to redundant
maintenance downtime and increased cost. As the principles of Six Sigma teach us, variability is the enemy of quality - in this case predictable availability and mission effectiveness. An effective PHM capability mitigates this uncertainty and recovers the full CBM benefits.

RCM and PHM have evident synergies. Both require in-depth knowledge of failure modes and effects, with detail understanding of failure probability as a function of usage and state – at the individual component level. PHM adds a valuable option to the menu of available RCM tasks by mitigating the impact of failures on "safety, environment, operations and economics" (Figure 2).

Reliability data bases are a critical enabler of PHM. They are necessary to validate PHM fault-to-failure models and inform ongoing improvement to PHM provisions, which can then be leveraged via RCM to achieve CBM+ objectives with reduced cost and maintenance effort. This role requires enhanced RDB capabilities and scale to collect and retain the component level reliability information at a granularity in terms of usage and configuration often lacking in current data bases. PHM also requires tracking and capturing the root cause of on-condition equipment maintenance down through successive levels of maintenance to the component replacement level.

Greater automation of RDB analysis is the key to cost-effective RDM support for PHM. The operational acceptability of PHM depends on low error rates, particularly false negatives, which otherwise soon erode PHM's advantages. Reactive and workload intensive engineering investigation is unable to sustain the rapid and early identification and mitigation of emergent and unexpected failure modes (a fact of life in equipment with operating lives measured in decades) needed to maintain PHM dependability.

5. SUMMARY & CONCLUSIONS

NAVAIR Instruction 4790.21 [12], issued in 1989, addresses the need to collect and apply maintenance data "generated in flight" for "rapid feedback of maintenance and diagnostic data to organizational (O), intermediate (I), and Depot (D) level maintenance personnel in the performance of maintenance tasks" and "higher level command reporting requirements" and this imperative clearly extends to data generated during the maintenance process, at all levels.

Implementation of TLCSM via CBM+ and RCM, enabled by advanced diagnostics and PHM, requires extension of the scope of RDB definition to encompass relevant system and component usage (including environmental exposure), records of operational impacts, and maintenance cost data. The primary purpose is informed implementation of CBM+ and RCM to achieve TLCSM requirements.

The concept of RDB as the essential feedback channel to enable continuous improvement of system maintenance processes and tools, including CBM+ & RCM, for DoD systems is inadequately captured in the references cited and the many others consulted.

Comprehensive RDB must capture endogenous and exogenous drivers of system and maintenance process performance metrics. This data, properly analyzed, does more than enable CBM+, it is the foundation for CBM+ maturation and continuous improvement, improvements to other maintenance processes, component improvement programs [CIP], and is necessary to inform TLCSM throughout the acquisition process.

Comprehensive and dependable RDB with integrated usage and cost data are a critical element for cost effective performance based logistics (PBL), not only to enable PBL terms with acceptable risk levels but also to guide the ongoing and effective continuous process improvement (CPI) and component improvement programs (CIP) that are fundamental to achieving the expected gains in safety, availability and affordability.

Finally, RDB accumulated through rigorous CBM+ and RCM implementation will provide the basis to define and implement better informed acquisition of new weapon systems to achieve yet higher levels of TLCSM more cost effectively and earlier in the life cycle.

In sum, the synergy between CBM and RCM that yields CBM+ and sustains deployment of TLCSM is founded on reliability data bases and its full expression is dependent on RDB with enhanced scope and automated analytical capabilities. RDB are essential to the effective integration of all elements of CBM+ and must be given full consideration in the deployment of TLCSM. The architecture of CBM+ infrastructure must account for the role of RDB, including their essential role in providing the feedback to guide continuous process improvement and component improvement programs.
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BIOGRAPHY

Richard Millar is employed at NAVAIR as an Aerospace Engineer responsible for Science and Technology programs in Propulsion and Power controls and diagnostics. He has over 35 years experience in the design and development of gas turbine engines and their application to aircraft propulsion & power systems. He had worked in this field at General Electric, United Technologies, Roll-Royce, Boeing, Lockheed Martin and BAE Systems prior to joining NAVAIR in 2003.

Dr. Millar holds a Bachelors and Masters in Engineering (Carleton) and an MSc in Management (MIT). He is a graduate of the D.Sc. program in Systems Engineering at The George Washington University.