



NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

**CONDITION-BASED MAINTENANCE IMPLEMENTATION AND
POTENTIAL IN USMC GROUND TRANSPORT**

by

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ABSTRACT

The U.S. Marine Corps is transitioning to a Condition Based Maintenance Plus (CBM+) strategy, which detects subcomponent anomalies in advance through data analytics so maintenance can be conducted before failure occurs. We studied the implementation of CBM in industry, and identified common themes, including guidelines for identifying platforms most suited to CBM---in particular those that are critical and costly to replace. We studied people and processes for implementation of CBM+ and identified critical barriers, including orders and policies that delineate Marine Corps maintenance strategy and many legacy policies directly conflict with CBM+ strategies. Inspections heavily influence maintenance actions at the operational unit level and hinder implementation of CBM+ initiatives. Competing priorities reduce focus and capacity necessary to change maintenance strategies.

Our primary recommendations for improving CBM+ implementation are focused on aligning the effort with other enterprise priorities and aligning policies to permit and support innovation in implementing CBM+. Existing tools within the Marine Corps policy refinement process, such as the Total Life Cycle Management Cross Functional Team model, can be used to establish a CBM+ guiding coalition. We recommend creating an environment that fosters short-term wins through interim exceptions to policy and consolidating these gains in a single volumized maintenance order. The Field Supply and Maintenance Analysis Office can be utilized as a key contributor in communicating and enabling the CBM+ vision for Marine Corps maintenance through evaluating, training, and consolidating best practices of CBM+ processes. This further supports the current Commandant's priority initiatives, both Force Design 2030 and Talent Management 2030. Reducing unnecessary maintenance actions and cross-functional training will support both retention and development of high-performing Marines.

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I. INTRODUCTION AND BACKGROUND

In 2020, Marine Corps Order 4151.22 and Commandant White Letter 2-20 were published to implement Condition-Based Maintenance Plus (CBM+) as a ground maintenance strategy to improve operational availability and reduce life cycle costs. The Fleet Marine Force is still operating under preventative and corrective maintenance strategies instead of CBM+ strategies. The transition to a CBM strategy which is predicated on both detecting a mechanical failure before it occurs and only conducting PM based on need instead of time, is set to disrupt many of the Marine Corps' existing maintenance business practices.

During the course of our work, the Third Marine Logistics Group (3d MLG) completed a one-year pilot program for "D" Table of Authorized Materiel Control Number equipment in concert with a policy waiver. In the absence of immediately available technology that supports CBM+ efforts, the 3d MLG CBM+ strategy focused on people and process improvements. An example of 3d MLG's improvements was the removal of non-value-added administrative steps in the maintenance cycle. They showed substantial year-over-year improvements in maintenance cycle time, days in shop, other metrics.

The work was conducted in two phases, and details of the effort are reported in two capstone reports, which are attached in Appendices A and B.

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II. CBM IN INDUSTRY

Stuetelberg and Thomas (2021) studied the literature on CBM and predictive maintenance, both of which have been widely adopted in industry, and conducted a multi-case study analysis of three industries that have relevant operational similarity to Marine Corps ground transportation---mining, railroads, and heavy equipment. They interviewed maintenance experts at Freeport-McMoRan, Union Pacific, Caterpillar. Their primary findings are below.

A CBM strategy is heavily predicated on collecting and analyzing data. Companies that are successful with this strategy all possess an internal data analytics department staffed with specialized professionals in this field.

A CBM strategy serves to establish a decision-making framework to conduct maintenance or not. To even be able to reach a maintenance decision point in the first place, successful companies implemented some form of a maintenance control center where they were able to detect an equipment anomaly (in real-time via networked sensors or through amassed data analysis), draw a conclusion if maintenance was required or not, and most importantly, inform the equipment operator/owner of the need for maintenance before a catastrophic failure occurred.

Both the data analysis and maintenance control center ideas identified above are enabled by effective and interoperable software and hardware suites. Each company interviewed emphasized the need for user-friendly and easily navigated systems that essentially provided them with a “dashboard” where equipment health could be referenced at a glance.

A CBM strategy is not a one size fits all approach. Across all industries, each company prioritized using this strategy for costly pieces of equipment, low- density assets that are crucial to revenue-producing activities, or equipment where unplanned mechanical failure presented significant worker safety risks.

A successful CBM strategy operates as a system. Significantly distilled, the components of this system entail on-board networked sensors or the timely ability to collect maintenance data from equipment, the capability to effectively catalog or monitor said data, experienced professionals who could make informed maintenance decisions based on both equipment data and their intuition, and lastly, the means to communicate maintenance actions in a time appropriate and effective manner.

Their complete report is available in Appendix A.

III. ORGANIZATIONAL CHANGE FOR CBM+

Harding and Pennington (2022) reviewed ground maintenance policies in depth in light of the requirements to implement CBM+ and interviewed military and civilian ground maintenance subject matter experts across the USMC ground maintenance community.

Four major themes emerged as barriers to CBM+ implementation in the Marine Corps. First, there is a lack of clear and consistent understanding of CBM+ across the Fleet Marine Force. Second, there is conflict among various orders and policies that delineate Marine Corps maintenance strategy and many legacy policies directly conflict with CBM+ strategies. Third, inspections heavily influence maintenance actions at the operational unit level and hinder implementation of CBM+ initiatives. Finally, competing priorities reduce focus and capacity necessary to change maintenance strategies.

Four themes emerged as opportunities to support CBM+ implementation. First, leaders within the organization need to drive the CBM+ maintenance strategy implementation process. Second, interim exceptions to policy (ETP) for policies that restrict CBM+ maintenance strategies can accelerate integration. Third, experiences at 3d MLG demonstrate opportunities to remove non-value-added tasks within maintenance processes to achieve measurable and observable gains by integrating CBM+ processes prior to adopting sensors and other technology solutions. Finally, ownership in the change process and the application of cross-training within operational units will make CBM+ implementation more effective.

Their primary recommendations for improving CBM+ implementation as a ground maintenance strategy in the Marine Corps are:

Align CBM+ with Force Design 2030 and Talent Management 2030

A sense of urgency should be built for CBM+ implementation by communicating to the FMF how CBM+ supports the current CMC priority initiatives. The alignment of CBM+ benefits to the objectives of FD2030 and TM2030 should be communicated throughout the FMF to build a greater sense of urgency to change maintenance strategies.

Establish a CBM+ Guiding Coalition

A CBM+ guiding coalition would guide, coordinate, and communicate CBM+ implementation throughout the Marine Corps. The guiding coalition should be directed and led by owners of Marine Corps maintenance policy that have sufficient level of authority to initiate and approve enterprise policy change. Existing tools within the Marine Corps policy refinement process, such as the Total Life Cycle Management Cross Functional Team (CFT) model, can be used to establish a CBM+ guiding coalition.

Refine and Communicate CBM+ Vision

A strategic communication plan needs to be developed to promulgate the vision of a CBM+ maintenance strategy as well as build the knowledge and education in the force on CBM+ practices, processes, and benefits. We recommend the CBM+ CFT provide an updated CBM+ vision that clarifies its association with FD2030/TM2030 and empowers units to seek out improved maintenance practices and provide bottom-up refinement to the CBM+ CFT.

Resolve Conflicts Between Maintenance Policies

We recommend creating an environment that fosters short-term wins through interim ETPs and consolidates gains in a single volumized maintenance order. Operational units need to be empowered to seek out process improvements and opportunities to apply CBM+ practices. The restrictive nature of current orders and constraints placed by required non-value-added maintenance actions present obstacles to Marines seeking to update processes to incorporate CBM+ principles.

Develop CBM+ Education for Commanders

We recommend incorporating CBM+ and maintenance concepts central to Marine Corps maintenance strategy into training and logistics seminars for leaders. Promulgating a CBM+ information paper is an effective tool to provide commanders and FMF CBM+ awareness and education in an expedient manner. CBM+ should be incorporated in the Commander's Materiel Readiness Handbook to improve leaders' familiarity and provide a quick reference to principal components of the Marine Corps maintenance strategy.

Utilize FSMAO to Support CBM+ Integration

Inspections are an enabling force in the maintenance community that reinforce maintenance strategy and processes. The Field Supply and Maintenance Analysis Office (FSMAO) can be utilized as a key contributor in communicating and enabling the CBM+ vision for Marine Corps maintenance through evaluating, training, and consolidating best practices of CBM+ processes.

The above recommendations target areas of opportunity for the Marine Corps to generate urgency, empower broad-based action, and solidify CBM+ as a ground maintenance strategy. Our recommendations use available organizational tools within the Marine Corps and provide options for leaders and policymakers to proactively drive CBM+ implementation. There are immediate gains that the Marine Corps can achieve through people and process improvements rather than waiting on the acquisition process and CBM+ technology to mature. Enterprise-wide integration of CBM+ as a ground maintenance strategy plays an important role in enabling logistics as the pacing function for the Marine Corps and supports FD2030/TM2030 objectives.

Their complete report is available in Appendix A.

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APPENDIX A

INCORPORATING PREDICTIVE MAINTENANCE BEST PRACTICES INTO MARINE CORPS TRAINING AND OPERATIONS

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LIST OF ACRONYMS AND ABBREVIATIONS

AI	Artificial Intelligence
C2	Command and Control
CBA	Cost-Benefit Analysis
CBM	Condition Based Maintenance
CBM+	Condition Based Maintenance Plus
CLC2S	Common Logistics Command and Control System
CM	Corrective Maintenance
CMA	Condition Monitoring Advisor
CMC	Condition Monitoring Center
CMMS	Computerized Maintenance Management System
CONUS	Continental United States
CSS	Combat Service Support
DOD	Department of Defense
EABO	Expeditionary Advanced Basing Operations
ERP	Enterprise Resource Planning
EUL	Expected Useful Life
EW	Electronic Warfare
FCMC	Fleet Condition Monitoring Center
FOS	Feasibility of Support
GCSS-MC	Global Combat Support Systems Marine Corps
GS	General Schedule
GTO	Ground Transportation Order
GTR	Ground Transportation Request
GUI	Graphical User Interface
HCDC	High-Cost Driver Component
HIMARS	High Mobility Artillery Rocket System
HUMS	Health and Usage Monitoring System
JLTV	Joint Light Tactical Vehicle
ILP	Integrated Locomotive Planner
IT	Information Technology

LAV	Light Armored Vehicle
MAGTF	Marine Air-Ground Task Force
MARDIV	Marine Division
MAW	Marine Aircraft Wing
MCO	Marine Corps Order
MCS	Maintenance Control System
MDR	Master Data Repository
MEF	Marine Expeditionary Force
MLG	Marine Logistics Group
MOS	Military Occupational Specialty
MPF	Maritime Prepositioning Force
MSC	Major Subordinate Commands
MTBF	Mean Time Between Failures
MTTF	Mean Time to Failure
NOTM	Networking on the Move
OCONUS	Outside Continental United States
OEM	Original Equipment Manufacturer
PdM	Predictive Maintenance
PM	Preventative Maintenance
PMCS	Preventative Maintenance Checks and Services
P-F Curve	Prevention-Failure Curve
PSR	Precision Scheduled Railroading
ROI	Return on Investment
RUL	Remaining Useful Life
TBM	Time Based Maintenance
TM	Technical Manual
TMR	Transportation Movement Requests
TPCT	Transportation Planning Capacity Tool

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I. INTRODUCTION

On January 17, 2020, the Marine Corps Deputy Commandant of Installations and Logistics signed Marine Corps Order (MCO) 4151.22, Condition Based Maintenance Plus (CBM+), into effect—thus establishing a new maintenance policy for the Marine Corps. This action was significant because the initial steps towards implementing CBM+ marked a noteworthy change in the direction and strategy of ground equipment, aviation ground support, and facilities support maintenance practices across the service. Specifically, MCO 4151.22 is intended to transition the Marine Corps from legacy scheduled maintenance practices where equipment is serviced on a regular schedule based on elapsed time and counter reading based off the odometer or vehicle use hour meter to the CBM+ approach where maintainers will “perform maintenance only upon evidence of need” (Department of Defense [DOD], 2020, p. 3) to include pertinent data, research, or other forms of evidence that demonstrate repair is required. Ultimately, the purpose of the Marine Corps’ transition from scheduled maintenance practices, also known as Time Based Maintenance (TBM), to that of CBM+ is to take a more proactive approach to maintenance in order to realize “increased military equipment operational availability, align enterprise integration goals and objectives, and increase readiness of Marine Air-Ground Task Force (MAGTF) resources available to support Fleet Marine Force Commanders” (DOD, 2020, p. 2). This change will be increasingly important as the Marine Corps transitions to the Expeditionary Advanced Basing Operations (EABO) concept as the “expeditionary logistics enterprise must support and sustain smaller, more lethal units from far greater distances across a dynamic and fully contested battlespace” (DOD, 2020, p. 1).

A. BACKGROUND

Prior to publishing MCO 4151.22, the Marine Corps primarily utilized a TBM strategy consisting of both reactive maintenance and proactive maintenance. Reactive maintenance, more commonly known as corrective maintenance (CM), is “performed for items that are selected to run to failure or those that fail in an unplanned or unscheduled manner” (DOD, 2008, p. 14). Notably, the majority of CM performed occurs on items and equipment where failure was unexpected or not likely to occur. Proactive maintenance, more commonly known as preventative maintenance (PM), is “scheduled maintenance that

can be based on calendar time, equipment-operating time or a cycle such as the number of starts, air vehicle landings, rounds fired, or miles driven)” (DOD, 2008, p. 15). Typically, PM is scheduled based upon one of the metrics listed above being reached but can also be performed in an unscheduled manner when degradation of a component is detected or apparent. For example, an operator observes that the engine is operating at higher-than-normal temperatures and conducts unscheduled maintenance to identify and fix the issue. The various maintenance approaches and characteristics are depicted below in Figure 1.

Maintenance Approaches				
Category	Reactive	Proactive		
	Run-to-fail	Preventive	Predictive	
Sub-Category	Fix when it breaks	Scheduled maintenance	Condition-based maint.-diagnostic	Condition-based maint.- prognostic
When Scheduled	No scheduled maintenance	Maintenance based on a fixed time schedule for inspect, repair and overhaul	Maintenance based on current condition	Maintenance based on forecast of remaining equipment life
Why Scheduled	N/A	Intolerable failure effect and it is possible to prevent the failure effect through a scheduled overhaul or replacement	Maintenance scheduled based on evidence of need	Maintenance need is projected as probable within mission time
How Scheduled	N/A	Based on the useful life of the component forecasted during design and updated through experience	Continuous collection of condition monitoring data	Forecasting of remaining equipment life based on actual stress loading
Kind of Prediction	None	None	On- and off-system, near-real-time trend analysis	On- and off-system, real-time trend analysis

Figure 1. Spectrum of Maintenance Approaches. Source: DOD (2020).

For ground units in the Marine Corps, preventative maintenance is scheduled in a desktop application called Global Combat Systems Support Marine Corps (GCSS-MC) per the equipment's technical manual (TM). The TM lists specific preventative maintenance checks and services (PMCS) or inspections that must occur based on specific time intervals. These time intervals can include daily, weekly, monthly, quarterly, semi-annually, annually, or bi-annually. As preventative maintenance is conducted, usage information retrieved manually from the equipment odometer or vehicle use hour meter is

manually input into GCSS-MC by the maintainers. Corrective maintenance is based upon the need for maintenance, such as when issues are identified during actual operation, limited technical inspections, or routine PMCS. Once an issue is identified, the respective unit's maintenance section inducts the piece of equipment. This process entails inspection and troubleshooting, identification of the deficiency, requisition of required maintenance parts, application of those parts, and finally, a quality inspection to include a road test ensuring that the issue was addressed and the equipment is operational. This entire process is captured within GCSS-MC with primarily manual data inputs and the uploading of scanned information such as the limited technical inspection worksheet.

Although the formal adoption of CBM+ by the Marine Corps in 2020 is a relatively new development, and implementation is in its infancy, predictive maintenance (PdM) and condition-based maintenance (CBM) have been in existence since the 1940s. They have been growing in prominence throughout industry since approximately the late 1990s and early 2000s (Shin & Jun, 2015). Over the last two decades—in profit-driven settings such as the manufacturing, mining, and railroad industries—leadership and maintenance managers realized the power and efficiency of harnessing equipment usage data in ever-more powerful and effective computer hardware/software suites to guide maintenance actions. Although industry-specific implementation and maintenance metrics utilized vary considerably by sector or type of equipment, the implementation of CBM has provided civilian corporate leadership with a “decision-making strategy where the decision to perform maintenance is reached by observing the condition of the system and/or its components” (Shin & Jun, 2015, p. 120).

As the current force structure stands, the preponderance of Marine Corps ground equipment located in the active component resides within the Fleet Marine Force, more commonly referred to as the operational component. The Fleet Marine Force is broken down into three separate Marine Expeditionary Forces (MEF) located both within the Continental United States (CONUS) and Outside Continental United States (OCONUS). I MEF's headquarters is located in Camp Pendleton, CA, II MEF's in Camp Lejeune, NC, and III MEF's in Okinawa, Japan. Each MEF is further broken down into four Major Subordinate Commands (MSC) that each have a distinctive role and mission within the

MEF. Marine Division (MARDIV) is the ground combat element and is comprised mainly of infantry units and combat support units such as artillery and combat engineers. Marine Logistics Group (MLG) is the logistics element and is comprised of task-organized logistics formations that provide distribution, maintenance, supply, medical, and multiple other forms of combat service support. The Marine Aircraft Wing (MAW) is the aviation element, primarily composed of flying squadrons with limited ground formations that provide aviation support such as refueling, runway maintenance, etc. The Marine Information Group (MIG) serves as the headquarters element of the MEF and possesses unique capabilities such as intelligence and communications battalions. Although each MSC owns a large ground fleet, the majority of ground equipment and ground vehicles reside within the Marine Division and the Marine Logistics Group as they both maintain extensive fleets to support their respective mission sets. Not only do the fleets within the MARDIV and MLG account for the most extensive ground fleets, but they routinely experience the highest operational tempos during both training and operations. These forces may be the likely initial candidates for a CBM+ due to the high operational tempo they experience.

Additionally, ground vehicles and systems also reside within the reserve component, the supporting establishments such as Training and Education Command, and prepositioning programs to include Blount Island Command and its subordinate elements. However, the ground assets that reside at these commands do not experience the same operational tempo observed within the active component and may be more suited for CBM+ implementation when the program reaches greater maturity.

At its core, a CBM or PdM strategy utilizes data to identify or predict when equipment will need to be serviced before failing. However, the exact process of how required data for a CBM strategy is captured, analyzed, and used to inform maintenance decisions varies by industry and context. One key metric known as remaining useful life (RUL), uses component- or system-specific data to estimate “the amount of time the equipment can continue performing its functions under design specifications” (Al-Dahidi et al., 2016, p. 2). Although a CBM strategy is largely predicated on measuring a piece of equipment’s RUL, there is no standardized method for capturing, analyzing, and

incorporating this information into the decision-making process, as RUL methodologies, estimations, and calculations differ significantly by industry or type of equipment. The DOD's (2008) CBM+ guidebook introduces eight building blocks of CBM+ that complement and support one another and are largely reliant on the use of sensors, data, and other electronically enabled processes and actions which differs significantly from the current TBM construct. They are defined in Table 1.

Table 1. Building Blocks of CBM+. Source: DOD (2008).

Building Blocks of CBM+	Definition
Data management	Acquiring data (sensors or other techniques), manipulating data into meaningful form, storing data, transmitting data, accessing data for analysis, and providing data to decision-makers.
Communications	Sharing of maintenance information and other data among all elements of the CBM+ environment should be possible, regardless of the data storage location.
Health assessment	Using the inputs from condition monitoring of a system behavior and providing an assessment of its operational condition.
Condition monitoring	Converting an output from the sensor to a digital parameter representing a quantifiable physical condition and related information.
Sensors	Monitoring, recording, or transmitting equipment or component operating parameters or conditions using physical devices.
Human interfaces	Providing operators with actionable information regarding maintenance or operations that suggest or support management or technical decisions.
Decision support	Making maintenance and related support decisions based upon the available condition data.
Analytics	Determining the current health state of equipment and projecting this assessment into the future, taking into account estimates of future usage profiles.

B. PURPOSE AND SCOPE

As the Marine Corps has only recently adopted a CBM+ strategy and many civilian organizations have been effectively employing some aspect of CBM or PdM for well over 20 years, there is a clear opportunity to identify and carry over best practices from industry as the Marine Corps moves forward with implementation. In a business context, increased operational availability and readiness translate to greater profitability and competitiveness within a given field or sector. In a defense context, increased operational availability and readiness provide commanders with additional warfighting capability and a potential edge or advantage over any prospective enemy. As such, this capstone project examines existing scholarship on CBM and PdM implementation, to explore the processes and systemic factors industry uses to inform their maintenance strategy. More specifically, this analysis identifies where and how industry leverages a CBM or PdM strategy to realize both time and labor efficiencies as well as cost savings throughout their maintenance activities. Using the case study methodology, best practices in the mining, railroad, and heavy equipment industries that are relevant to the Marine Corps are identified and brought forward. This research can better inform the ongoing transition from the service's traditional TBM strategy to a CBM+ approach so that, ideally, the Marine Corps is better prepared to meet and excel in the challenges of the future operating environment.

1. Problem Statement

The Marine Corps is actively transitioning to a CBM+ strategy that will challenge existing policies, operating procedures, current equipment configurations, and information technology (IT) systems. How can the service leverage existing best practices, maintenance strategies, and technologies from industry to ensure the success and viability of the 2020 CBM+ directive?

2. Primary Research Question

Which maintenance practices and strategies does industry currently use that the Marine Corps can translate to the implementation of the CBM+ strategy in a defense context?

3. Secondary Research Questions

1. What components in ground systems do companies in our sample industries routinely monitor with CBM/PdM technologies?
2. How does industry identify legacy systems that will be cost-effective and compatible with the Marine Corps' CBM+ initiative?
3. What are the appropriate maintenance metrics the Marine Corps should use for its CBM+ strategy?

C. ORGANIZATION

Chapter II provides additional background pertaining to CBM and PdM with emphasis on examining literature on military CBM applications, relevant maintenance metrics, and IT infrastructure. It also includes a review of CBM implementation organizational and cultural challenges. Chapter III details the methodology for this project, accounting for participants, procedure, professional domains, question sets, case study construction, and analysis. Chapter IV includes three distinct case studies on the mining, railroad, and heavy equipment industries, which are compiled based on interviews and industry-specific professional journals. Chapter V covers the analysis of the above-stated case studies with a focus on identifying best practices in industry that are pertinent to the Marine Corps. Finally, Chapter VI ties together best practices identified in Chapter V and summarizes current limitations, factors required for successful implementation, and suggestions for future research.

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II. LITERATURE REVIEW

Over the last two decades, thousands of scholarly works and articles have been published on CBM and PdM—spanning multiple industries and contexts. Despite the wide range of sources identified, there is seemingly limited availability of relevant sources that address the military application of a CBM/PdM strategy for ground equipment. The majority of existing military CBM/PdM publications consist of articles exclusively addressing military aviation, official policies and orders that lack analysis, or platform-specific articles that are extremely narrow in focus. Therefore, to gain a greater understanding of CBM/PdM implementation centered on ground military equipment, we review relevant military sources and literature on CBM/PdM enabling concepts such as metrics and IT infrastructure, and examine scholarly sources detailing organizational challenges and considerations for successful CBM implementation. By targeting sources in these categories, we hope to better understand the Marine Corp’s current status with CBM+ implementation and how to maximize the efficiency and effectiveness of this transition. This chapter builds greater awareness of concepts and ideas that are later revisited in the individual case studies that ultimately informed our analysis and recommendations.

A. OVERVIEW OF CONDITION-BASED MAINTENANCE/PREDICTIVE MAINTENANCE IN MILITARY APPLICATIONS

Rajesh and Francis contrast the applicability of CBM/PdM techniques used by the Australian Air Force to that of ground vehicles and offer recommendations through a cost-benefit analysis (CBA) lens. Two notable concepts identified in this article were the definition of and delineation between “continuous” and “periodic” data collection periods and “on-board” and “off-board” data collection methods (Rajesh & Francis, 2012). Continuous data review is directly enabled by on-board data collection methods. Periodic data review and off-board data collection methods are generally employed together, as periodic data review requires a less responsive process for accessing and downloading equipment usage data. Rajesh and Francis identify the obvious trade-offs in the two interconnected concepts of data collection and review. In the case of continuous review

using onboard sensors, equipment managers endure higher sensor/technology costs and the potential for inaccurate readings on account of mass amounts of unfiltered raw data to achieve a more responsive system that theoretically provides a real-time analysis of a piece of equipment's status (Rajesh & Francis, 2012). In the case of periodic review using off-board sensors, equipment managers accept a higher degree of risk in "missing failure events occurring between successive inspections" (Rajesh & Francis, 2012, p. 5) in order to lower system costs and the time expenditures required to analyze a consistent flow of data. There will be a decision point on how the Marine Corps wants to collect data from its various platforms and systems, accepting aspects of the trade-offs identified above.

According to Murugan and Le, the ability to detect anomalies within assemblies, components, or subcomponents that indicate degradation is occurring is foundational to a successful CBM+ strategy. In the instance of equipment that is capable of continuous data review, an operator or maintenance manager needs to have the ability to detect and interpret when degradation is occurring so that a prediction window of when a component will fail can be identified and appropriate maintenance action can be taken. In practice, this is achieved through the use of a Health and Usage Monitoring System (HUMS), which communicates with on-board sensors to capture and display pertinent maintenance information. The use and integration of a HUMS is relevant to the application of CBM because the system provides "a thorough understanding of the ways in which system conditions are degenerated together with the ability to detect, identify, prognosticate anomalies, and communicate all conditions that require maintenance immediately" (Murugan & Le, 2012, p. 2). Additionally, Murugan and Le's (2012) study specified that in order for an equipment monitoring system to be useful, it needs to be linked to the correct type and number of sensors that account for a "number of key factors such as sensor redundancy, sensor optimization, cost-benefit analysis or return-on-investment analysis for each added sensor in the vehicle and the associated hardware/software expenditure" (p. 17). Legacy military equipment that possesses rudimentary monitoring systems that do not provide sufficient data or visibility to fully enable a CBM+ approach would require retrofit that could have a greater cost than benefit.

In addition to identifying the applicability of monitoring systems capable of continuous data review, Murugan and Le (2012) specifically examined the applicability of CBM on components and subassemblies deemed to be high-cost driver components (HCDC). Using Murugan and Le's criteria, they identified engines, transmissions, alternators, and batteries as HCDCs for U.S. Army ground vehicles, as maintenance required to repair these components is both time-consuming and costly. Further, they emphasized that placing sensors on HCDCs must yield a meaningful long-run return on investment (ROI). The benefit of sensors and required hardware/software expenditures must be greater in terms of operational availability than the additional maintenance costs and increased downtime incurred without sensor-enabled vehicles. Incorporating Murugan and Le's ideas into our research, it is apparent that the Marine Corps will face another set of decision points accounting for how relevant prognostics data is displayed, what equipment components constitute HCDCs, and whether the pursuit of the two aforementioned concepts is cost-effective and worth the associated investment to either retrofit existing equipment, or build these requirements into future system acquisitions.

Anders Soderback and Camilla Östman's (2010) incorporated several of the concepts and ideas identified above while introducing others by examining the applicability of a CBM approach on one specific Swedish military vehicle variant. They examine the viability of retrofitting an existing military vehicle with sensors through the study of how and where CBM is used in industry, what subcomponents or assemblies are most compatible with a CBM approach, and how to collect, manage, and analyze pertinent maintenance data. Notably, Soderback and Ostman's research on data management complements the two articles detailed above through the distinction between monitoring data and trending data. By citing previous scholarship, Soderback and Ostman identified that "monitoring is an important activity for detecting problems that have already happened. Trending is about identifying potential problems before they happen" (p. 22). Furthermore, Soderback and Ostman identified that to effectively identify trends in data to inform maintenance activities; a given organization requires the ability to perform eleven data management and analysis sub-functions. From an IT systems standpoint, Soderback and Ostman advocate for user-friendly software, automated data acquisition, and

automated data management, which support the ability to identify trends in data. From a data accuracy perspective, they denote that flexibility, reliability, accuracy, redundant monitoring is important to building a holistic site picture of a piece of equipment's health. And lastly, from a decision-making standpoint, they infer that monitors that correlate data into actionable readouts, detailed alerts, and data consolidation ultimately provides the situational awareness to conduct maintenance or not. This idea is especially relevant to the implementation of a CBM strategy by the Marine Corps because many of the data analysis and management practices required for CBM to be successful will require both hardware/software upgrades and changes to institutional maintenance procedures.

In summary, the review of existing military research of CBM illuminates four key ideas and concepts that will be carried forward throughout our research—namely, under which circumstances industry uses continuous or periodic maintenance data collection intervals, which HCDCs are monitored, how pertinent maintenance data are captured on a HUMS if onboard sensors are used, and how the vast amount of data gleaned from multiple systems is correctly trended to build predictive models that ultimately inform maintenance decisions.

B. CONDITION-BASED MAINTENANCE AND PREDICTIVE MAINTENANCE ENABLING CONCEPTS

The existing CBM military literature is largely focused on data collection methods on individual pieces of equipment such as onboard or offboard sensor placement, the use of HUMS systems, and so forth. To gain some insight on how to apply these concepts, we examine how industry measures and utilizes data to inform and implement a comprehensive CBM or PdM strategy—specifically, how the data gathered from a given component can be analyzed and modeled to reasonably determine the EUL or RUL of said component or piece of equipment. To achieve this end, we reviewed 10 articles that detail how different maintenance metrics are relevant and how IT infrastructures impact CBM implementation.

1. P–F Curve

The P–F curve is a way to visually depict the operating condition of a specific asset or component throughout its life cycle and is depicted below in Figure 2. The component or equipment begins its life cycle in the normal state where degradation has not occurred yet, and performance has not been inhibited in any way. As time and usage progress, wear begins to occur—leading to the dangerous state and the beginning of degradation. Point (P) is defined as when the component or equipment is beginning to transition from a normal operational state to demonstrating anomalies that could lead to failure, and after crossing this point the condition of said component or equipment begins to degrade much more rapidly. Point (F) is the functional failure in which the component or equipment reaches critical failure requiring corrective maintenance actions to be performed (Bousdekis et al., 2020). The P–F curve assumes that the cause of the failure, beginning when the component or equipment enters the dangerous state, will take time to develop and then culminate with the functional failure. The P–F interval is the time interval from when P occurs until F. The concept of the P–F curve is highly relevant to a CBM/PdM because the whole point of this maintenance technique is to create an inspection window shorter than the P–F interval to ensure that the chance of running the equipment to failure is mitigated, or actively monitor for when a piece of equipment reaches point P. When applied correctly, “the predicted failure impact can be eliminated or mitigated while maintenance operations are optimized” (Bousdekis et al., 2020, p. 59). However, the identification of what values P and F are for the specific component or equipment requires preexisting data and knowledge. In many instances, those values are unknown, and time and additional maintenance resources are required to collect data and refine estimations so that maintenance actions are optimized and failures can be accurately predicted and thus prevented. The P–F curve is relevant to Marine Corps CBM+ implementation because it essentially enables the maintenance decision-making process that CBM is predicated on through the detection of an anomaly prior to potential failure, decision, or action to conduct maintenance and ultimate avoidance or mitigation of functional failure.

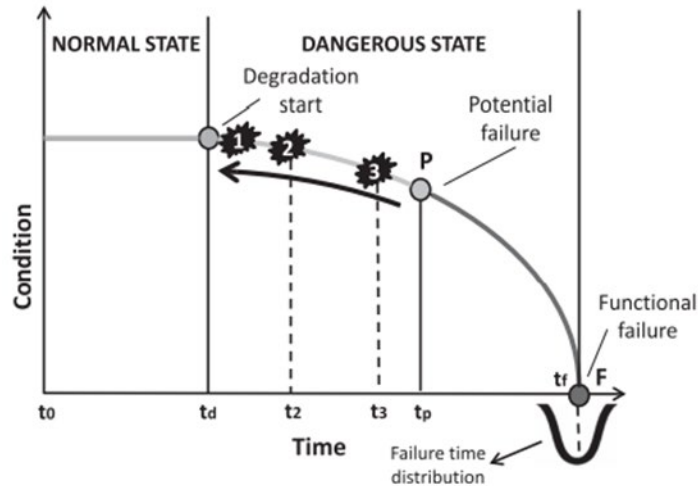


Figure 2. Prevention Failure (P-F) Curve. Source: Bousdekis et al. (2020)

2. Expected Useful Life and Remaining Useful Life Estimation

EUL and RUL are two of the most important metrics to the implementation and execution of a CBM and PdM strategy. EUL is defined as the expected time, miles, or other noteworthy metric that a piece of equipment is forecasted to last for given that routine maintenance is conducted as prescribed. Some type of EUL is typically estimated by equipment manufacturers to provide customers, maintainers, or equipment operators a general baseline for the life expectancy of that piece of equipment. Additionally, there are two synonymous metrics that coincide with EUL: mean time between failure (MTBF) and mean time to failure (MTTF). The key distinction between MTBF and MTTF is the type of system or parts that are being examined. Specifically, MTBF is “only relevant for machines or equipment that can be fixed and put back into operation after a failure occurs,” while MTTF is “used as a measure of reliability once a non-repairable asset fails and is considered to have reached the end of its useful life” (*Mean Time Between Failures [MTBF]*, n.d.). Within the context of Marine Corps ground equipment, MTTF would be mostly applicable to components the service views as consumables, including nonrepairable suspension assemblies (springs or shocks), air filters, and so forth, since once these components fail, they must be replaced. As such, the use and measurement of MTBF is more relevant to the Marine Corps application of CBM+ because this metric is inherently used on HCDCs such as engines, transmissions, and transfer cases that are not

consumables. Theoretically, if the Marine Corps could accurately estimate a given component's MTBF and monitor the health of said component through the application of a CBM+ strategy, the service could increase equipment longevity and decrease maintenance expenditures.

RUL is defined as “the amount of time the equipment can continue performing its functions under its design specifications” (Al-Dahidi et al., 2016, p. 2) and is one of the primary metrics for a successful CBM/PdM strategy. When calculated accurately, RUL estimation allows for organizations to avoid unscheduled system shutdowns to conduct corrective maintenance, thereby “[increasing] the system availability and safety, while reducing maintenance costs” (Al-Dahidi et al., 2016, p. 2). However, if RUL estimation is inaccurate and an organization is either grossly under- or overestimating the remaining longevity of a certain component or piece of equipment, any potential process gains will be lost as a result of replacing components that are still viable (RUL underestimation) or running components to failure (RUL overestimation).

There are two methods to calculate RUL: either a model-based or data-driven approach. “Model-based approaches use physics models to describe the degradation behavior of the equipment” (Al-Dahidi et al., 2016, p. 2). The model-based approach comes with significant limitations as it requires maintainers to make bold assumptions, which can contribute to issues with RUL uncertainty or accuracy. A data-driven approach does not use any specific model but relies entirely upon equipment health data pertaining to the piece of equipment in question (Al-Dahidi et al., 2016). Using raw data on a piece of equipment's health, a model can be built that enables maintainers to forecast degradation and failures for that piece of equipment or component but requires a significant amount of run to failure data to accurately capture when degradation and failures are occurring. Both approaches could be potentially problematic for the Marine Corps because of the extreme disparities in operating environments, inconsistent equipment use across the different major subordinate commands (MSC), and the general difficulty of gathering accurate data across the service on equipment that degrades slowly and is safety-critical (Al-Dahidi et al., 2016).

3. Information Technology Infrastructure

IT infrastructure is a critical component for the success of a CBM or PdM strategy and is defined as

the combination of reliable services that are shared throughout the firm and coordinated centrally, usually by the firm's IT department as well as the tangible assets such as hardware platforms, operating systems, network and telecommunications technologies (e.g., e-mail, instant messaging, and groupware), software applications, databases, intranet, and the Internet. (Durmusoglu, 2009, p. 365)

Within the realm of logistics and maintenance, IT infrastructure is commonly referred to as logistics information management systems. Logistics information management is defined as enabling the “delivery of the right information to the right people at the right time with the right information security protection” (North Atlantic Treaty Organization, 2012, p. 23). The Marine Corps logistics establishment primarily relies on GCSS-MC as the primary logistics information management system for tracking maintenance activities, scheduling/documenting CM and PM, and submitting parts and material requisitions for the purpose of ensuring “supply chain effectiveness and providing timely combat support information” (Aronin et al., 2018, p. 1).

As depicted in Table 2, many of the CBM+ building blocks initially outlined by the DOD are heavily reliant upon IT infrastructure. The Marine Corps transitioned to GCSS-MC in 2011 and in doing so was able to replace four legacy supply and maintenance IT systems that had been in place since the 1970s in an attempt to “deliver integrated functionality across maintenance, transportation, finance, engineering, health, and manpower systems, and provide a common base for all logistics chain management” (Aronin et al., 2018, p. iii). Notably, although GCSS-MC is the base enterprise resource planning (ERP) system for the Marine Corps, its functional gaps are augmented by the Transportation Capacity Planning Tool (TCPT), which tracks equipment usage, and the Common Logistics Command & Control System (CLC2S), which manages logistical and maintenance data. Many of the characteristics of the Marine Corps' existing IT infrastructure and maintenance systems is applicable because they not directly align with

the CBM+ building block tenets outlined by the DOD or current scholarship on the topic. A few relevant systems in use by the Marine Corps are depicted and described in Table 2.

Table 2. Marine Corps IT Systems by Capability and Functionality. Source: Headquarters Marine Corps MCBULL 4081 (2012).

System	Capability	Functionality
Global Combat Support System Marine Corps/Logistics Chain Management (GCSS-MC/LCM)	-Provides user the capability to see what equipment needs to be repaired, where the parts are located, and who is available to perform the work -Allows user to plan for and schedule maintenance resources and to have the ability to review item configuration, readiness information, and past historical and ownership data -Provides the capability to determine when and where supplies, such as inventory, purchase orders, and work orders, should be deployed within the supply chain -Provides the capability to manage a service parts inventory in a multi-location environment -Provides capability to project future requisitions of consumables, repairable, and general supply items at the MAGTF level based on expiration dates, lot numbers, and usage -Provides capability to source an item from an external vendor and create a purchase requisition for items not available internally at the retail level	-Conduct maintenance, logistics-chain, and supply-chain management -Generate maintenance and supply readiness reports -Track repair orders, parts, and availability of maintenance personnel -Maintain asset visibility across the Marine Corps -Manage a service parts inventory -Create purchase orders to requisition parts from external agencies
Transportation Capacity Planning Tool (TCPT)	-Provides the commander a decision support tool for transportation and engineering equipment, planning, management, and mission execution -Allows transportation planners throughout the MAGTF to view transportation capacity through movement requests, personnel, and equipment resources -Provides a dashboard view of transportation and engineer resource capacity for planning, tracking, and development of convoys and other transportation related missions -Provides units a standard method to electronically manage organic transportation and engineer resources -Provides units a standard method to electronically submit and track transportation requests beyond organic capability -Extends MAGTF distribution capability through seamless transportation movement requests (TMR) and rapid request integration	-Manage organic and nonorganic transportation equipment -Dispatch transportation and engineering equipment electronically -Manage organic engineer equipment -Manage licensing of personnel -Associate equipment to convoy tracker -Manage transportation movement requests (TMRs) -Manage ground transportation requests (GTR) and ground transportation orders (GTO) -Manage and track operator safety/mishap records -Track and report mileage, hours, and fuel data -Operate on NIPRNET, SIPRNET, and CENTRIX networks -Enterprise and deployable configurations
Common Logistics Command & Control System (CLC2S)	-Provides a means for commanders and staff to request, track, and prioritize support requests in near real time -Provides improved management and control of tactical level resources and service support requirements while providing the MAGTF commander and staff with an automated means to quickly view warfighting readiness and critical asset availability -Provides units the ability to electronically submit and track requests for logistics services from inception to completion -Provides logistics situational awareness and decision-making support with integrated personnel, supplies, and equipment data -Provides combat operations center with the MAGTF LogC2 capability to support the MAGTF Common Operational Picture -Extends GCSS-MC into the combat operations center by aggregating maintenance and supply data, providing feeders into commander's dashboards, reports, and data views	-Manage combat service support (CSS) requests across all six pillars of combat service support and supply classes -Display customized logistics status dashboards -Monitor and display maritime prepositioning force (MPF) offload process -Create serial and landing plans -Report unit level status for ammunition, bulk fuel/liquids, and personnel -Automate and track feasibility of support (FOS) requests -Operate in low bandwidth environments in disconnected operations -Certified to operate on NIPRNET, SIPRNET, and CENTRIXS networks -Enterprise and deployable configurations
Master Data Repository (MDR)	-Centralized database that provides a consolidated location for equipment management information from a vast majority of the automated current and legacy logistics information systems (GCSSMC, MARES, SCS, TFSMS, Item Application, SABRS, CBRN EMS, PBDD, Stores Accounting [MUMMS SS04], Provisioning, TDMS, DIFMS, etc.)	-Copies and loads relevant data from these legacy systems into a single data repository and provides access to legacy applications that have a requirement for equipment readiness, decision support, and workflow automation data -Stores the data required for equipment readiness, decision support, and workflow automation applications through individual interfaces between the applications and the MDR

Throughout our literature review, it became apparent that successful CBM and PdM strategies require functional IT systems capable of providing users with a high level of data quality and visibility of assets being maintained and operated. This means that organizations need to be able to pull relevant maintenance information from a specific piece of equipment within the fleet in a timely and accurate manner. Specifically, the capability to examine the status and health of a particular asset or class of assets within a fleet is imperative to enabling maintenance supervisors to make informed decisions about complex problems within the realm of maintenance (Tretten & Karim, 2014). Further, if there is a significant latency in receiving maintenance information, or the data pulled are not accurate or succinctly analyzed, decision-makers will not have the visibility and, therefore the opportunity to prevent failures prior to them occurring. Ultimately, issues with data synthesis and understanding provided by dysfunctional or inadequate IT systems result in a lower ROI for a CBM/PdM-centric maintenance strategy. In the context of the Marine Corps, this idea emphasizes that the service will need to have the correct type of IT systems that provide enough information to make informed maintenance decisions to achieve an adequate ROI above that of the current TBM strategy.

In addition to having the appropriate systems in place, the interaction between the user and IT platform is of vital importance when dealing with maintenance systems and strategies. The user must be able to navigate throughout the system, entering information and data with the ability to easily identify the most relevant metrics and apply them to real-world maintenance decisions. When systems are difficult to comprehend or use, maintenance organizations create inefficiencies due to user error, general lack of understanding, or a litany of other problems associated with poor human/IT system interface. Specifically, one of the common pitfalls identified throughout several articles detailed that when IT systems are too complex, it is likely that organizations will default to “a limited amount of information being reported to the CMMS” (Tretten & Karim, 2014, p. 296). Essentially, when an IT system is difficult to manipulate or understand, it causes “maintenance personnel to lose focus on the task at hand (the conduct of actual maintenance) and deal with usability issues” (Tretten & Karim, 2014, p. 301). From a Marine Corps perspective, the salient points of this aspect of IT infrastructure include the

need for any current or future systems used in support of CBM+ to be easily understood and operated at all levels of the service (Tretten & Karim, 2014).

Interoperability is another key tenet for logistics information management systems. In “Enhancing the Usability of Maintenance Data Management Systems” (Tretten & Karim, 2014), incompatibility with existing systems was one of the overarching usability issues identified for a computerized maintenance management system (CMMS). A CMMS “provides services to assist the whole maintenance process, e.g., maintenance management, maintenance support planning, maintenance planning, maintenance execution, maintenance assessment, and maintenance improvement” (Tretten & Karim, 2014, p. 290). From this definition, a CMMS accomplishes many of the same tasks as a logistics information management system and, therefore they can be considered synonymous with one another for the purpose of the discussion on interoperability. To ensure that systems are interoperable with one another, specialists that will be utilizing that system need to be brought in to assist with the design. Within the context of the Marine Corps, “we have not organized the efforts under the central theme of logistics information management, nor have we assigned responsibility to a single owner” (Fincher, 2019, para. 9). This has created incompatibility issues across systems as logistics professionals are not the ones dictating what information and data is communicated via these systems (Fincher, 2019).

C. CHALLENGES TO CONDITION-BASED MAINTENANCE AND PREDICTIVE MAINTENANCE IMPLEMENTATION

As detailed in the previous two sections, the successful implementation of a CBM strategy is predicated on the ability to (1) correctly capture pertinent maintenance data, (2) use this data to build metrics and models (EUL, RUL, etc.) of when and where equipment will fail, and (3) conduct required maintenance actions before a component or system fails. Although the integration of these processes is seemingly intuitive, a large amount of scholarship identifies the numerous technological, organizational, and cultural challenges to meeting this end. As such, this section provides an overview of some of the existing scholarship that identifies hurdles to CBM implementation with regards to processes, business practices, and maintenance actions.

1. Synchronizing Technology and Business Practices

According to Bousdekis et al., 2020, one of the key challenges of CBM implementation is the integration of technological capability (data collection and analysis) and human-driven business practices. This article identified that “up to now, most business and scientific interest has focused on the technical implications. Managerial and organizational implications are typically secondary, if even considered. These dimensions may be the most significant barriers for the adoption of predictive maintenance solutions” (Bousdekis et al., 2020, p. 60). Many organizations largely focus on the technology required for a successful CBM strategy, but they lack an understanding of how and where the human workforce fits into the process. This is particularly important in a Marine Corps context, as a large portion of the workforce is transient due to enlistment contracts, frequent turnover of leadership and key technical positions, and the general personnel challenges many military organizations face. A large part of the military workforce is only in place for a short period of time by design, so if hypothetical Marine Corps CBM+ implementation is overly focused on a technologically driven solution versus how people integrate into this process, the service could face more human integration challenges than in industry, which generally has a more fixed and specialized workforce.

2. Maintenance Policies

One key way to address human/technology interface and other challenges of CBM implementation is through sound and clearly articulated maintenance policy. (Shin & Jun, 2015). Shin and Jun examined three different types of CBM approaches and compared and contrasted their applicability by product, industry, and overall cost-effectiveness. Based on existing research, Shin and Jung (2015) asserted that the three principal CBM approaches include a data-driven approach, a model-based approach, and finally a hybrid approach.

They distinguished that a data-driven approach “transforms high-dimensional data into lower dimensional information by using historical data to automatically learn a model of system behavior”, while a model-based approach exploits the “ability to incorporate physical understanding of the target product through an analytical model to represent the behavior of the system” (p. 122). Finally, a hybrid approach incorporates aspects of the two aforementioned approaches to predict when an abnormality (indication of equipment

failure) will occur. Regardless of the CBM approach used, CBM ultimately serves as a decision-making tool to inform how and when to conduct maintenance. This idea directly correlates with maintenance policy because, in order to be successful, an organization needs to have codified procedures on “the parameters to be monitored, determining inspection frequency, and establishing warning limits which will ultimately inform the decision to conduct maintenance” (Shin & Jun, 2015, p. 123).

Although the requirement for a clearly defined maintenance policy is seemingly intuitive, Shin and Jun argue that there is a high degree of variability in which type of CBM approach is most beneficial for a given piece of equipment or industry. In some cases, CBM is not effective, and when it is, the viability of any given approach is dependent on numerous factors, including product life cycle, economic benefits, assets with no or limited data availability, and equipment that is composed of multiple different subsystems (Shin & Jun, 2015). The universal approach widely used with older maintenance strategies such as TBM will likely not succeed with the application of CBM. Instead, implementation will need to entail the correct match of CBM approach with asset type based on the numerous factors identified above.

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III. MULTIPLE CASE STUDIES METHODOLOGY

A. DOMAINS

This study examines the application of a CBM or PdM strategy through a series of three case studies focused on the mining industry, the railroad industry, and heavy equipment. Case studies on mining, railroad, and heavy equipment were chosen as they either operate ground-based equipment, primarily utilize equipment with diesel- or gasoline-powered combustion engines, employ their equipment in a similar manner to that of Marine Corps ground equipment, and use a CBM or PdM based maintenance strategy. Broadly, the criteria identified above all share similarities with the ground assets that the Marine Corps utilizes and thus are relevant for comparison when examining CBM or PdM strategies and implementation. Additionally, the aforementioned industries have utilized a CBM or PdM strategy for a significantly longer period of time than the DOD and have achieved a greater level of maturity and practical experience. Although both commercial and military aviation utilize a CBM/PdM strategy, the characteristics of aviation assets, there are significant differences between aviation and ground assets. Aviation principal end items (complete aircraft) and subcomponents are drastically more expensive with severe consequences in the event of catastrophic failure—which usually results in the total loss of the aircraft and all passengers aboard. Therefore, the aviation industry is required to commit significantly more resources and time to aircraft maintenance and is less relevant to ground equipment than the industries studied.

B. PARTICIPANTS

Four total participants from the industries described previously agreed to be interviewed. These participants all possessed maintenance backgrounds and were managers or leaders directly responsible for maintenance strategy, maintenance execution, maintenance planning, or CBM enabling activities such as data analytics or IT infrastructure. Since each participant had a unique perspective and professional background, their varying backgrounds and perspectives enabled us to collect a broad range of maintenance strategies and methods of implementation across different industries, contexts, and operating environments. Furthermore, the cross-section of experience from

the various participants allowed us to gain a comprehensive perspective as each individual or company had a different take or viewpoint on the effective application and management of CBM strategies. This is notable, because throughout the course of the interview process, we were able to discern or ask elaborating questions on aspects of CBM/PdM that may have been omitted or not discussed in full by previous participants.

C. PROCEDURE

Interview participants were primarily identified based on their occupation and role within their given company or industry and were initially contacted via LinkedIn, existing student/advisor networks, and through referrals from other individuals outside of the scope of the study. Once contacted, we introduced our own professional backgrounds, detailed the scope and purpose of the study, and ensured that all participants were willing to be interviewed and were comfortable with all content discussed being captured and analyzed within our study. Following brief introductions, participants were asked to introduce their experience and history surrounding their involvement within their respective company's CBM or PdM strategy and elaborate on their organization's best practices and what those processes looked like for their respective industry. All interviews were directly guided by the question set detailed below to ensure that we captured all the participants' experiences through the same lens and baseline to ensure the highest degree of uniformity possible given the case study method. All questions were oriented towards either processes or organizational maintenance practices at large, not on the people or human behavior involved within those processes. The primary forms of data collection included both audio recordings and written notes that were gathered during the duration of the interview process. All audio recordings were then transcribed to be referenced in the future to enable effective case development. Procedurally, the duration of interviews typically lasted anywhere between 45 to 90 minutes and interviewees were subsequently contacted to elaborate on any information that was of additional interest or unclear during the initial interview session.

D. QUESTION SET

1. How does your company or organization benefit from the use of CBM/PdM strategy?

2. What types of assets does your organization employ a CBM/PdM strategy to maintain?
3. When did the CBM/PdM strategy originate within your organization?
4. What did the transition to CBM/PdM look like?
5. Since the implementation of CBM/PdM strategy, has your company or organization documented any improvements in operational availability or industry-specific metrics that increase functionality or profitability?
6. What challenges did your organization face during implementation? And how did the organization overcome them?
7. Does your organization implement a CBM/PdM strategy and the conduct of maintenance in a field or austere environment?
8. What type of metrics or maintenance data does your company or organization primarily capture to facilitate a CBM/PdM strategy?
9. What equipment subcomponents or assemblies (transmission, engine, etc.) does your company or organization monitor?
10. How does your company or organization determine expected useful life (EUL) and remaining useful life (RUL) of equipment subcomponents or assemblies?
11. How are EUL/RUL metrics captured and tracked: analog system, sensors that automatically communicate with an Enterprise Resource Planning (ERP) database, hybrid, etc.?
12. Do the systems/sensors utilized by your company or organization automatically input data from the sensor into the centralized ERP/data based discussed earlier?
13. Has your company or organization documented any lessons learned on the implementation and management of utilizing a PdM that could be relevant to a military application?

14. How does the information provided by CBM/PdM strategy inform operational decision-making and asset allocation?
15. What other benefits has your company or organization experienced from implementation of PdM?

E. CONSTRUCTION OF CASE STUDIES

As defined by Robert Yin (2009), a case study is “an empirical inquiry that investigates a contemporary phenomenon in depth and within its real-life context, especially when the boundaries between phenomenon and context are not clearly evident” (p. 18). In order to examine our topic to the required degree of depth, participant interviews were supplemented through the examination of industry or profession-specific journals and publications. The supplemental literature examined was oriented on the current application of CBM/PdM within a given industry. These sources were meaningful to the compilation of our case studies because they detailed how and where select industries were creating efficiencies through the use and practical application of CBM/PdM strategies. Further, the information identified in industry-specific literature was relevant because it provided tangible examples of CBM/PdM best practices, which we were able to compare with information provided by interview participants. Once a baseline was established through both interviews and industry-specific publications, and once we had a sound understanding of a given industry’s utilization and implementation of CBM/PdM, we were able to compile and bring forward procedures, challenges to implementation, and identify those relevant within a military context.

F. ANALYSIS

Based on the case studies, we conducted a thematic analysis—looking at common themes across the industries to evaluate the case studies’ applicability within the context of the Marine Corps’ implementation of CBM+ for ground systems. This evaluation is intended to examine the common themes required for successful implementation as well as some tentative considerations for CBM+ execution in a garrison or deployed environment. As this project is qualitative, the desired output of our research is essentially a listing of ideas, concepts, and factors surrounding CBM that should be accounted for as the service moves forward with such a large undertaking. This analysis appears in Chapter

V following the case studies. A process flow chart of our methodology is depicted in Figure 3 below.

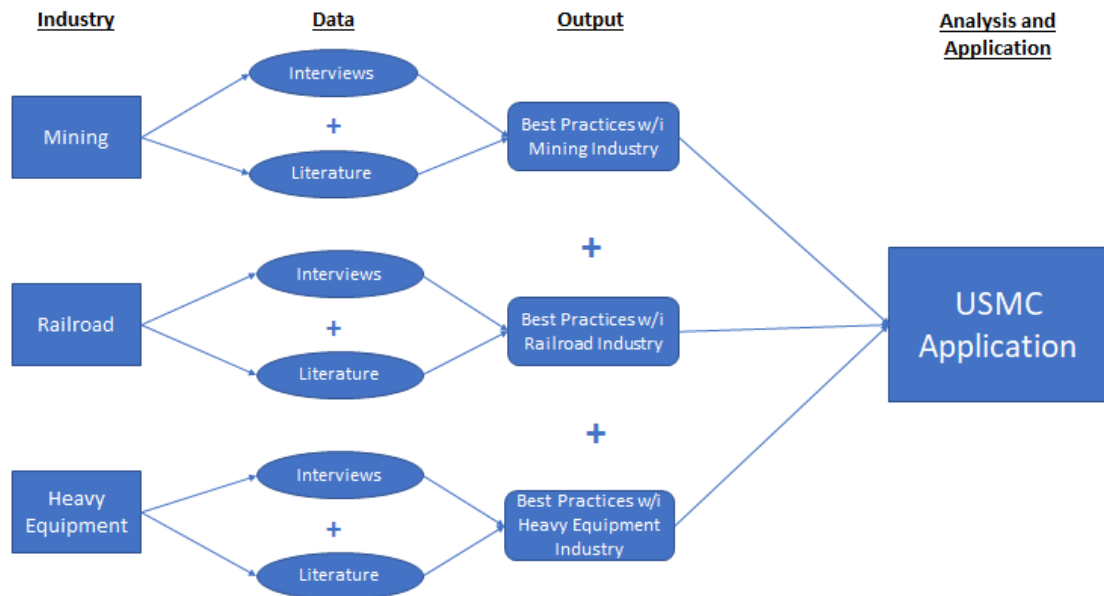


Figure 3. Process Flow Chart Detailing Case Study Construction as They Apply to the Marine Corps' Application of CBM+

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IV. CASE STUDIES

As discussed in Chapter III, our methodology consists of creating case studies from the mining, railroad, and heavy equipment industries that utilize CBM/PdM. Three case studies were developed to highlight these companies' and industries' best practices in CBM/PdM. The case studies briefly introduce each company, the role and title of the interviewee, and then the best practices discussed during the interview process. The case studies are organized by grouping best practices and lessons learned into the five themes detailed below in Figure 4.

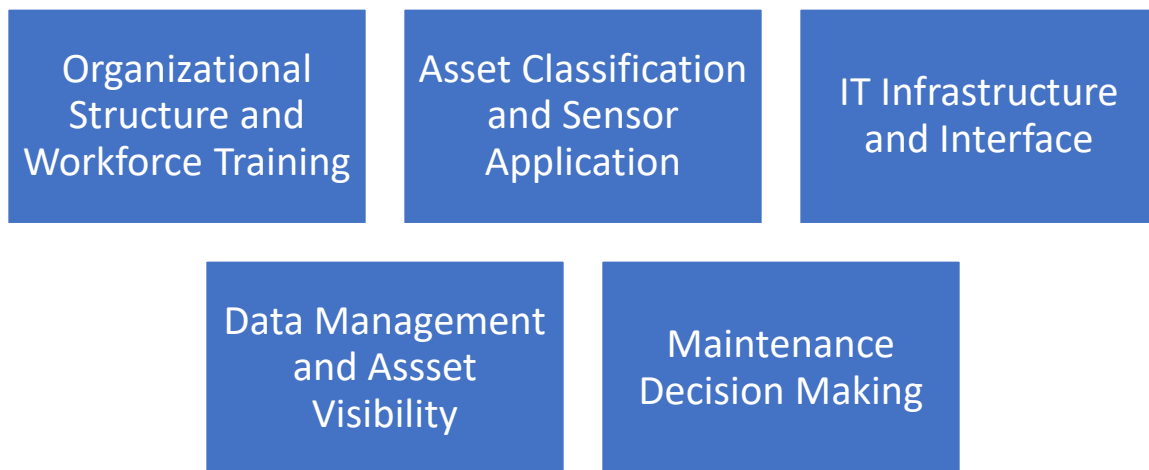


Figure 4. Themes of Analysis

A. MINING INDUSTRY CASE STUDY

1. Background

Freeport-McMoRan is an industry-leading mining company based out of Phoenix, Arizona that conducts operations worldwide. The company focuses on the mining and extraction of minerals such as copper, gold, silver, and molybdenum (Freeport-McMoRan,

n.d.). They lead the world in producing molybdenum and are considered to be one the world's largest producers of copper. The assets Freeport-McMoRan uses for daily operations include large mining trucks, various types of heavy equipment, and machinery used for the processing and mineral extraction from raw ore (Participant 1, personal communication, July 28, 2021). Our interviewee from Freeport-McMoRan was a Data Scientist who is currently employed within their data analytics department and has experience monitoring, executing, and supervising their data collection activities used to enable the companies PdM strategy across multiple types of assets.

2. Organizational Structure and Workforce Training

As an extremely large and well-resourced corporation, Freeport-McMoRan has the means to insource the majority of the functions and departments required to implement a successful CBB/PdM strategy. Freeport-McMoRan has a robust and dedicated internal data analytics department that operates in support of their mining operations and maintenance of their equipment fleet. While the data analytics department is relatively new and has only been in existence since 2016, Freeport-McMoRan now operates with approximately 70 data scientists on staff at all times. The department is focused on four initiatives across the entirety of the corporation: metals optimization, predictive maintenance, machine learning operations, and education. The structure of the department is also fairly fluid as teams are created to work on a certain initiative and then when complete they are dissolved, freeing them up to be assigned to a different project (Participant 1, personal communication, July 28, 2021). The centralization of the data analytics department enables Freeport-McMoRan to not only make decisions at specific mines, but also to make better decisions across the entirety of the enterprise. Our interviewee stated that the initial investment into creating a data analytics department was viewed as relatively small expenditure within Freeport-McMoRan's operational budget but has yielded a notable return on investment when compared to increased expenditures on maintenance costs or replacement assets they would have otherwise encountered. Furthermore, our interviewee believes the value of the data analytics team is its ability to solve problems resulting in increased efficiency throughout the entirety of the organization (Participant 1, personal communication, July 28, 2021).

One notable example includes Freeport-McMoRan's transition of their Baghdad, Arizona Copper Mine to an entirely networked approach where over several years, the company synthesized both aspects of a PdM strategy with that of artificial intelligence (AI) models designed to optimize ore yield finally realizing a 10% throughput increase during the fourth quarter of 2018 (Conger et al., 2020). The increase in throughput was able to be achieved due to both the collection of usage of throughput and maintenance data by their networked sensors. This real-time data enabled data scientists to primarily increase ore yields which was enabled in part by the ability to also monitor equipment health thus preventing catastrophic failures. Although this example details the benefits of integrating maintenance and mining data automation, from a purely maintenance perspective, the standing data scientist department has enabled Freeport-McMoRan to increase visibility of equipment health within the organization without incurring additional expenses or information latency that is commonly associated with an external outsourced data monitoring service or contract.

3. Asset Classification and Sensor Application

Freeport-McMoRan classifies their sensor-enabled assets in two general categories: 1) equipment that has an extremely high cost of replacement and 2), equipment that poses a workplace safety risk and/or equipment that would directly impact revenue streams in the event of failure or a breakdown (Participant 1, personal communication, July 28, 2021). Some of Freeport-McMoRan's equipment such as ore haulers (extremely large dump trucks) or ore crushers have large capacities and limited redundancy within a given mining site so an unexpected catastrophic failure causes significant reductions to operational throughput, resulting in a reduced production and revenue. This instance is notable because revenue lost due to a broken asset can be significantly larger than the cost to repair the broken asset. This idea is important because it determines how and where Freeport-McMoRan uses sensors. It is not economically feasible to utilize a PdM strategy on every asset that they own. Instead, Freeport-McMoRan weights their efforts and expenditures to selectively equip and monitor specific assets that are critical to operations and associated revenue streams, could present a safety risk with catastrophic failure, or are assets that have an exorbitantly high cost of replacement.

In terms of sensor application, companies like Freeport-McMoRan that employ a PdM strategy can either acquire equipment with sensors factory preinstalled or retrofit legacy equipment with after market sensor suites. Notably, the vast majority of equipment assets owned and operated by Freeport-McMoRan came with manufacturer-installed sensors when they were initially acquired (Participant 1, personal communication, July 28, 2021). By purchasing equipment that is already largely compatible with a PdM strategy, companies like Freeport-McMoRan can avoid the complexity and cost that typically ensues when deciding to retrofit legacy equipment. Additionally, Freeport-McMoRan uses both primary sensors to directly monitor high cost or high-risk equipment mentioned earlier, and in some instances, also uses secondary or tertiary sensors to monitor the functionality of primary sensors to ensure they are functioning as intended (Participant 1, personal communication, July 28, 2021). Suppose a secondary or tertiary sensor detects that a malfunction or fault on the primary sensor is occurring. In that case, action can be taken immediately to fix the primary sensor ensuring that equipment remains operational and that the company is not collecting tainted or inaccurate data.

4. IT Infrastructure and Interface

Prior to adopting their PdM strategy, Freeport-McMoRan already had their IT infrastructure established and operational, as stated by the interviewee (Participant 1, personal communication, July 28, 2021). During the initial stages of the adoption of a PdM strategy, Freeport-McMoRan installed networked equipment and sensors that required maintainers to manually download data to their data management software (Conger et al., 2020). However, in the last few years as costs to incorporate wireless networks drastically reduced, Freeport-McMoRan transitioned to installing automated data collection systems at each of their mining locations to include austere environments (Conger et al., 2020). Notably, this transition enabled Freeport-McMoRan's data scientists and maintainers to achieve visibility of all networked assets, including sensor banks at entire mines, to the status of individual ore hauler or conveyor bearing assembly at any of the corporation's remote locations. The interoperability between the various types of equipment utilized by Freeport-McMoRan and the ability to use software to monitor and log equipment health in real-time has been one of the key drivers to the company's successful PdM strategy. More

specifically, Freeport-McMoRan's IT infrastructure is centered on a Microsoft Azure program supplemented by various other software programs that are all compatible with Azure (Participant 1, personal communication, July 28, 2021). By using Microsoft Azure, Freeport-McMoRan was able to

create an Industrial Internet of Things platform to improve their mining operations. This solution enables Freeport-McMoRan to extract meaningful insights from their data to improve decision-making and address such issues as safety improvement, asset management and optimization of mine operations. (Arkan, 2016, para. 5)

Notably, Freeport-McMoRan only purchases software systems that are already compatible with Microsoft Azure to eliminate compatibility issues or create the requirement to adjust existing IT infrastructure (Participant 1, personal communication, July 28, 2021). As a private corporation that has the ability to choose the specific systems they purchase based on need and fiscal suitability, Freeport-McMoRan is not constrained by the acquisitions regulations associated with the public sector.

In addition to Freeport-McMoRan's ability to collect and analyze large amounts of data within the analytics department, the company has proven to be effective in operationalizing the data to inform maintenance actions at the lowest and most basic levels of the organization. Azure enables a visualization tool called PI Vision to convert maintenance data into charts, graphs, or other graphics that are easily referenced and digested by human operators or maintainers (Participant 1, personal communication, July 28, 2021). Equipment operators or maintainers can open this platform from a tablet or other networked device at any mine location and quickly orient themselves on trends or anomalies within a given piece of networked equipment without having to sift through raw data. By using software that is easy to use and digest, Freeport-McMoRan enables maintainers and operators to identify maintenance trends in the field, thus remaining focused on revenue-producing activities.

5. Data Management and Asset Visibility

The IT infrastructure that Freeport-McMoRan has constructed has enabled their data management processes to be extremely streamlined, requiring very little input from employees outside of creating or updating algorithms for machine learning. The gold

standard for data management and asset visibility is being able to view real-time data (Participant 1, personal communication, July 28, 2021). The ability to achieve real-time data visibility is contingent on Freeport-McMoRan's vehicle sensors continuously transmitting data into their data management systems (Conger et al., 2020). This means that those involved within the PdM strategy, regardless of location, can view a specific asset and monitor specific metrics while that piece of equipment is conducting operations. Their ability to continuously transmit data from sensors into data management software and then apply algorithms to the data collected creates significant manpower efficiencies. The models are built from the data gathered and are predictive, by generating forecasts on the health of equipment in the future. This allows for maintainers and operators to develop greater situational awareness in developing their maintenance plan for future operations. For example, personnel from Freeport-McMoRan's data analytics department can view the temperature of an ore hauler transmission that is located at a mine on the other side of the world in real-time from their company headquarters. This asset visibility provides Freeport-McMoRan the ability to identify specific trends relating to asset health and maintenance even though equipment may be operating in vastly different environments.

6. Maintenance Decision Making

The metrics that drive the maintenance decision-making process at Freeport-McMoRan include failures by type of asset and part, man-hours saved, and cost reductions directly contribute to a greater bottom line for the company. While tracking failures by asset and part is relatively simple considering their infrastructure and data management system, it still remains difficult to quantify the amount of man-hours saved and the cost savings from those man-hours. Freeport-McMoRan is not the only company in the mining industry examining these metrics as Rio Tinto is "aiming to save \$1.2 billion in maintenance costs by the end of FY2022 and reduce downtime by 20%" (Operating Strategies, 2018, p. 49). When new equipment is purchased from the manufacturer Freeport-McMoRan initially uses the manufacturer's specifications as the EUL (Participant 1, personal communication, July 28, 2021). For example, when a new ore hauler is purchased, the baseline for EUL for the engine is the number of hours or miles that the engine is expected to last based on what the manufacturer states. However, as data

is collected and time progresses, the Freeport-McMoRan data science department is able to refine the EUL of equipment based on its usage and the environment it operates in (Participant 1, personal communication, July 28, 2021). However, the refinement of the EUL takes a significant amount of time due to the amount of data required to confirm a deviation from the manufacturer's published specifications.

B. RAILROAD INDUSTRY

1. Background

Union Pacific is an industry-leading class I rail transportation company based out of Omaha, Nebraska and is one of the largest transportation companies in the nation, second to BNSF Railroad (Union Pacific, n.d.). Union Pacific primarily operates in 23 states in the western and gulf areas of the United States specializing in the transportation of bulk materials to include fuel and liquids with hubs in major population centers. The company currently owns approximately 7,600 locomotives powered by diesel-electric engines and owns or leases a large number of rail cars (Union Pacific, n.d.). Notably, since 2009, Union Pacific has spent approximately \$3.9 billion to purchase new locomotives (Union Pacific, n.d.), or conduct more fuel-efficient engine overhauls resulting in the replacement or upgrade of roughly 80% of the existing fleet (Participant 2, personal communication, October 18, 2021). Prior to 2013, Union Pacific primarily utilized a TBM approach and then transitioned to a CBM approach using mileage as a metric vice time (Participant 2, personal communication, July 30, 2021). Union Pacific, and the entirety of the railroad industry has been forced to invest heavily in their own infrastructure since the 1980s when the railroads were federally deregulated by the Staggers Rail Act of 1980. Our interviewee is a Director, System Locomotive Facility which is the equivalent of a depot-level maintenance facility. He has direct industry experience in the realm of locomotive operations and planning, with a background as a locomotive maintenance manager.

2. Organizational Structure and Workforce Training

Union Pacific has seen an overall increase in workforce effectiveness since implementing an automated maintenance control system (MCS), a computerized system that replaced an analog system of manually tracking work orders and repair receipts on paper. Union Pacific has seen a marked increase in how quickly certain repairs are being

made. Our interviewee stated that the change has been beneficial to Union Pacific as the MCS has been a driving factor in increasing employee production from approximately two hours of value-added activities during an eight-hour work day per employee to approximately six hours of value-added production during the same period (Participant 2, personal communication, July 30, 2021). Furthermore, our interviewee attributed the increases in production to the ability to essentially track and benchmark how many hours a given repair would take, which enabled Union Pacific to both hold their maintenance workforce accountable to reasonable repair times and greatly assisted with organizational maintenance planning as the company standardized time expectations associated with a given repair or inspection (Participant 2, personal communication, July 30, 2021). This is notable in the context of CBM and maintenance decision making in the sense, that once data is received from an individual locomotive indicating that mechanical degradation is occurring, maintenance leadership could decide whether to act on making repairs or not based on the projected labor time to make the repair, cost of the replacement part, and operational demand of the given asset.

The benefits of introducing the MCS have far outweighed the costs, but implementation came with some organizational resistance (Participant 2, personal communication, July 30, 2021). As the railroad industry has been in existence for approximately 150 years, Union Pacific needed to work through some traditional and cultural barriers to get the entire maintenance workforce on board with using an automated system as many of the employees initially didn't appreciate the level of visibility the system provided on their day-to-day productivity, or simply did not understand how to effectively use or leverage tablets, computers, and associated software systems and tools. Furthermore, our interviewee attributed some of the resistance within the organization and initial issues with the use of the automated MCS with the fact that a significant portion of Union Pacific's maintenance labor force are individuals in their 40s through 60s who have been with the company for many years, and did not have a working knowledge of computer or tablet use (Participant 2, personal communication, July 30, 2021).

3. Asset Classification and Sensor Application

Interestingly, and in contrast to some other industries examined, Union Pacific uses a run to failure approach on many of their larger and more expensive locomotive components such as diesel engine turbos and power assemblies because it is more cost-effective to rebuild or replace these parts upon failure instead of conducting maintenance to prevent failure (Participant 2, personal communication, July 30, 2021). This approach is enabled in part by Union Pacific's robust maintenance infrastructure where large locomotive repair shops are located in direct proximity to high usage "major classification yards" such as North Platte, NE, Chicago, IL, Fort Worth, TX, and Roseville, CA. Basically, maintenance capability and locomotive repair parts are co-located near large rail hubs, allowing Union Pacific to replace parts that are run to failure with little additional effort (Participant 2, personal communication, October 18, 2021). However, the decision to run a given part to failure is based on a series of inspections and where maintainers essentially gauge if failure is imminent or not. If failure is determined to be imminent based on inspection, the part will be replaced. Suppose the component is expected to have a reasonable remaining life as determined by the inspection which is informed with usage data. In that case, it is left in place for reassessment at the next inspection period or until it is operationally run to failure.

Regarding direct sensor application, Union Pacific is active in using sensors to track mileage and hours on the whole of the locomotive fleet and examine individual components (Participant 2, personal communication, July 30, 2021). In this model, Union Pacific uses networked sensor suites on the actual locomotives, including sensors on each of the locomotives 16 power assemblies, and networked scanners along major routes to provide redundancy for tracking total miles and usage data. Union Pacific's approach to monitoring power assemblies is notable because these parts wear out at different intervals, so failure in one assembly does not directly correlate with the same level of wear on the 15 other assemblies within the same locomotive.

4. IT Infrastructure and Interface

As discussed previously, Union Pacific has had to invest significantly within their rail infrastructure to include IT infrastructure upgrades which have directly enabled the

company's transition from a TBM strategy to that of a hybrid CBM strategy. Notably, Union Pacific's transition from a TBM to CBM approach was seemingly more driven by the loosening of federal standards that had previously directed railroads to conduct certain locomotive services at given time intervals regardless of need (Participant 2, personal communication, July 30, 2021). Although significant government regulation remains in place, the loosening of standards allowed Union Pacific to take a more process/wear-driven approach to maintenance, which is the company's current strategy. In practice, this blended approach could be classified as a CBM hybrid strategy because Union Pacific uses both legacy systems that remain generally oriented on a TBM approach as well as newer systems that enable a CBM approach. Union Pacific's legacy system is their MCS which enables the company to plan and schedule maintenance tasks, track assets, and troubleshoot components all within one consolidated system (Participant 2, personal communication, July 30, 2021). Since Union Pacific primarily sources their locomotives from General Electric, upon MCS roll-out, they were given the option to either purchase the system outright from General Electric and manage their own maintenance processes, or have General Electric manage their maintenance systems on a contract basis (Participant 2, personal communication, July 30, 2021). Union Pacific opted to administer MCS internally because they already had a dedicated IT department and wanted to maximize potential cost savings (Participant 2, personal communication, July 30, 2021).

Since the purchase of MCS, Union Pacific has adopted a newer software program called Integrated Locomotive Planner (ILP) that interfaces with the existing MCS platform (Participant 2, personal communication, July 30, 2021). This means that while ILP is running, MCS is running in the background inputting data into the ILP software. The interoperability between the two systems has enabled the new ILP system to pull data from their locomotive fleet without significant changes to existing IT infrastructure. More specifically, ILP enables Union Pacific maintenance leadership to view much of the same information that is found within their MCS while providing additional visibility to include assigning manpower to individual repairs and tracking work history on a given locomotive (Participant 2, personal communication, July 30, 2021). As discussed in section (a) of this case study, the ability to plan and supervise maintainer activities has increased maintenance

productivity by approximately 200% while also enabling the Union Pacific a higher degree of fidelity in forecasting maintenance activities. Notable to the broader topic of human/system interface, ILP features a more user-friendly graphical user interface (GUI) that enables users to conduct trend analysis and view graphs and charts capturing data on specific pieces of equipment or components.

5. Data Management and Asset Visibility

Building on what is detailed above, MCS is the primary data management system for Union Pacific. Specific data captured within MCS includes locomotive usage, work order history by individual Union Pacific employee, and operational history of an asset. When data is input into ILP it is automatically uploaded into the MCS where it will be held for approximately two years, enabling users to instantly view any historical data within that two-year window (Participant 2, personal communication, July 30, 2021). When data becomes older than two years it is archived at the Union Pacific Headquarters in Omaha, Nebraska, but is still accessible by users upon request (Participant 2, personal communication, July 30, 2021).

Union Pacific maintenance leadership is able to view any locomotive within their fleet and their major components in real-time from the user's workstation. Our interviewee stated that with ease, he could search for any specific locomotive by serial number and the ILP dashboard and would be able to view where it was located, the locomotive's operational status, and the state of major components with networked sensors including active fault codes, historical maintenance schedules, and forecasted maintenance tasks based upon historical usage of that asset (Participant 2, personal communication, July 30, 2021). This capability is notable and supports a CBM approach, because by pulling data from networked locomotives and sensors located along Union Pacific routes in real-time, the company is able to monitor the health and efficacy of their fleet to ensure everything is functioning properly.

Asset visibility also allows Union Pacific to determine if a fault code triggered on a locomotive presented a legitimate threat to the health of the asset, or may have been sent in error. This capability was developed internally by Union Pacific with the intent of screening for erroneous fault codes so that maintenance resources are not wasted

remedying a mechanical issue that did not exist. To achieve this end, the Union Pacific data department created algorithms within their operating systems to determine if a fault code, or combination of fault codes, met the criteria for immediate corrective action or a potential catastrophic failure (Participant 2, personal communication, July 30, 2021). In application, if a locomotive logs a specific amount or combination of fault codes that have historically resulted in a catastrophic failure, this information creates an alert at Union Pacific's 24-hour maintenance control center for action (Participant 2, personal communication, July 30, 2021).

For example, when a locomotive travels through a tunnel the engines generally operate at a higher temperature due to the lack of air flow within the tunnel (Participant 2, personal communication, July 30, 2021). In this instance, it is not uncommon for locomotives to log fault codes indicating that the engines are operating at a higher-than-normal temperatures. Union Pacific's algorithms are able to account for the location of the locomotive (in a tunnel) and the time frame associated with the code (how long it takes for the train to transit the tunnel) to determine that the fault code is likely erroneous (Participant 2, personal communication, July 30, 2021). This specific capability, and the associated algorithms used to facilitate the process were developed internally to Union Pacific with organically collected data and software. The practice of internally managing maintenance data processes (such as the example provided as well as other instances) is notable because Union Pacific has saved millions of dollars compared to competitors who outsourced similar data interpretation capabilities to outside parties. Further, by internally managing the majority of data-driven maintenance activities, Union Pacific has been able to decrease its reliance on Original Equipment Manufacturer services and inputs creating even greater savings (Participant 2, personal communication, October 18, 2021).

6. Maintenance Decision Making

At Union Pacific, the primary metric that drives maintenance decision-making is mileage on their assets and specific components (Participant 2, personal communication, July 30, 2021). Since the transition from a TBM approach in 2013, Union Pacific has been able to develop a maintenance approach that is CBM enabled and thus can be best classified as a hybrid approach because they intentionally incorporate aspects of TBM and CBM.

Specifically, the company conducts maintenance inspections at various usage intervals to examine the condition of components and look for degradation. The usage intervals that Union Pacific utilizes for all locomotive inspections (regardless of age) include “M1” for 25,000 miles, “M2” for 50,000 miles, “M3” for 100,000 miles, and “M6” for 300,000 miles (Participant 2, personal communication, July 30, 2021). At each interval the inspections become more rigorous accounting for both the previous inspection steps as well as additional details associated with the more complex inspection. Union Pacific also utilizes an oil analysis program to inspect the condition of oil within their locomotives. Originally, this program was located internally to Union Pacific, but due to the costs of maintaining the program they opted to outsource this service to an external lab (Participant 2, personal communication, July 30, 2021). For example, before the transition to a hybrid approach, Union Pacific would change locomotive oil every three months as required by their PM schedule at a cost of approximately \$2,653 in parts, lubricants, and labor per oil change (Participant 2, personal communication, October 18, 2021). Upon transition to the new program, Union Pacific gained the ability to postpone oil changes if a locomotive had not met the mileage threshold for an oil change, or an oil sample analysis deemed that the oil was still within specifications. Our interviewee stated that the oil analysis program has been successful in reducing maintenance costs at Union Pacific since many of their assets were receiving oil changes before they actually required them when using the legacy PM schedule (Participant 2, personal communication, July 30, 2021).

As detailed in a previous section of this case study, since the implementation of a hybrid CBM strategy, Union Pacific still conducts federally mandated maintenance as required by law (such as annual handbrake inspections, etc.), while applying a far greater degree of flexibility to conduct repairs and services no longer federally regulated. An example of Union Pacific’s maintenance and operational strategy includes the company’s use of Precision Scheduled Railroading (PSR) which is defined as “a railroad strategy that uses departure schedules and point to point delivery methods to achieve low operating ratios and consolidate railroad networks” (Elliot, 2020, para. 3). More specifically, the PSR concept results in a very lean operation by minimizing the total amount of assets in use at any given time. This idea has benefitted Union Pacific in a maintenance decision-making

context, because from approximately 2019 to present, Union Pacific has been able to take approximately 1,000 locomotives out of daily use without any notable reduction to capacity (Participant 2, personal communication, July 30, 2021). From a maintenance lens, the reduction of the Union Pacific Locomotive fleet by approximately 14% has enabled the company to realize significant savings to include the furlough of approximately 25% of the maintenance workforce since fewer assets are used and require maintenance (Participant 2, personal communication, July 30, 2021). Notably, our interviewee stated that in the short term, the benefits of implementing PSR and reducing the locomotive fleet have been relatively clear, however it is yet to be seen how this decision will affect the long-term health of the Union Pacific locomotive fleet as a smaller share of the fleet is now carrying an increased workload (Participant 2, personal communication, July 30, 2021).

C. HEAVY EQUIPMENT CASE STUDY

1. Background

Caterpillar is the world's leading manufacturer of construction and mining equipment, diesel and natural gas engines, industrial gas turbines, and diesel-electric locomotives totaling \$41.7 billion in sales in 2020 (*About Caterpillar*, n.d.). Many of Caterpillar's manufactured assets and components such as wheeled vehicle diesel engines are already used by the Marine Corps and Caterpillar also provides data-driven maintenance services throughout the entirety of their equipment product line to remotely monitor the health and functionality of networked equipment. Our interviewees from Caterpillar included the Caterpillar Defense Director of Business Development and the Director of Caterpillar's Fleet Condition Monitoring Center (FCMC) who both have years of industry experience developing and maintaining PdM equipment and systems.

2. Organizational Structure and Workforce Training

Caterpillar differs from Freeport-McMoRan and Union Pacific because their primary source of revenue is through the sale, maintenance, and monitoring of heavy equipment assets rather than the use of these assets for revenue-producing activities like mining, construction, or transportation (*About Caterpillar*, n.d.). Although Caterpillar's business model is different than Freeport-McMoRan's and Union Pacific's, the way they organize and employ their maintenance monitoring branch, which is known as the

Caterpillar Fleet Monitoring Center, is extremely relevant to this research. The Caterpillar Fleet Monitoring Center is largely comprised of individuals known as Condition Monitoring Advisors (CMAs) whose primary role within the company is to work with clients (like large mining or construction companies) to actively track the health and functionality of Caterpillar assets employed by the client. Caterpillar's CMAs fulfill this role through the analysis of five elements of CBM: equipment site conditions, repair history, inspections, electronic data, and scheduled oil sampling fluid analysis (Participant 3, personal communication, August 23, 2021). In practice, Caterpillar's CMAs use electronic data as well as "aggregating, correlating, and interpreting" the other Caterpillar elements of CBM to ultimately make a maintenance recommendation to their clients (Participant 3, personal communication, August 23, 2021). This is notable because the CMAs largely hail from previous positions as mechanics. They are highly familiar with equipment use and maintenance and use a multidisciplinary approach of examining data in the context of their hands-on experience to make a maintenance recommendation (Participant 3, personal communication, August 23, 2021). Furthermore, our interviewee stated that the CMAs take a proactive role similar to that of a "detective or medical doctor" to determine why a piece of equipment is currently having, or will have a future mechanical issue (Participant 3, personal communication, August 23, 2021).

For example, if diagnosing why an engine filter may be plugged, the CMA will use their experience to identify questions such as, "Why is that filter plugged? What's going on in the system? What's the iron (levels in a given lubricant) like? Is there dirt entry (into the filter system)?" The questions developed are then answered using collected data about that particular asset (Participant 3, personal communication, August 23, 2021). Although CMAs, are well versed in the interpretation of data from dashboards and prepared equipment reports, the organization also has a dedicated data department that is solely responsible for the construct of algorithms and tools that are used to decipher and build models using large amounts of data (Participant 3, personal communication, August 23, 2021). Our interviewee acknowledged the value of the mixed approach of a dedicated data department that enables the CMAs, but mainly attributed the success of the Caterpillar Fleet Monitoring Center to the CMAs' ability to leverage their intuition and industry

experience to determine the causation and remedy of current or future equipment maintenance issues following the work flow in Figure 5 detailed below. (Participant 3, personal communication, August 23, 2021).

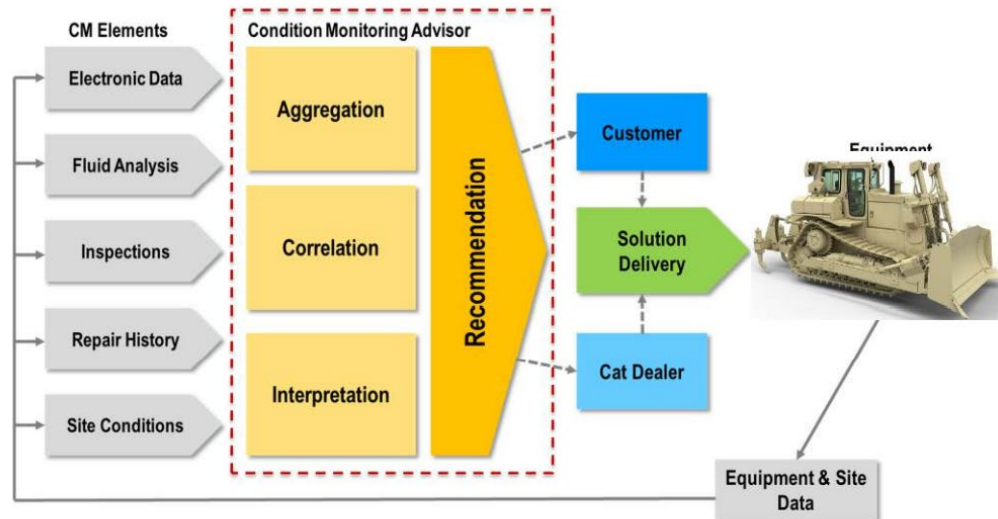


Figure 5. Caterpillar Condition Monitoring Elements and Condition Monitoring Advisor Work Flow. Source: Participant 3, personal communication, August 23, 2021, slide 6.

3. Asset Classification and Sensor Application

As an equipment manufacturer that also provides associated maintenance and maintenance monitoring services to customers, Caterpillar takes a hands-on approach to its customers' maintenance planning and scheduling if they elect to buy a service or monitoring package. When a customer comes to Caterpillar to purchase equipment or services for their existing fleet, Caterpillar will help the customer decide which equipment meets the criteria to be worth actively monitoring. Caterpillar emphasizes the importance of creating and capturing value, and therefore if value (increased readiness / decreased repair costs) is not being created from monitoring a specific type of asset, then they recommend to the customer that it is not worth monitoring (Participant 3, personal communication, August 23, 2021). In practice, for Caterpillar customers, the priority is

monitoring assets that are either extremely expensive to repair or replace or consistent equipment readiness is crucial to day-to-day revenue-producing activities.

Using an example from the mining industry, an ore hauler would meet the criteria for monitoring because if that piece of equipment experiences a catastrophic failure, the mining company could experience a high opportunity cost for every hour or day that the ore hauler is not operational. It would be worthwhile for a customer to pay for Caterpillar's monitoring services. Using the same logic, it would not make sense for a customer to use Caterpillar's monitoring service or retrofit legacy equipment with sensors for equipment that is low value, equipment for which they have excess inventory, or that is not critical to day-to-day revenue-producing activities. To enable their monitoring service, Caterpillar has manufactured more than 900,000 pieces of equipment with factory-installed sensors that are compatible with the existing FCMC construct providing remote "real-time diagnostics/prognostics" (Participant 3, personal communication, August 23, 2021, slide 2). Additionally, Caterpillar also provides condition monitoring services to customers that utilize equipment not manufactured by Caterpillar. In these instances, Caterpillar is able to retrofit customers' existing non-Caterpillar manufactured assets by embedding a product link box that sends data about the equipment's health via cellular or satellite connection to the Fleet Monitoring Center (Participant 3, personal communication, August 23, 2021).

4. IT Infrastructure and Interface

Caterpillar's IT infrastructure enables the company to receive and push data and information to their customers quickly. Caterpillar has developed many of these IT capabilities internally to the company and has invested significantly doing so. One of the systems that Caterpillar developed is the Condition Monitoring Dashboard, which enables the Fleet Monitoring Center, Caterpillar dealers, and customers to monitor equipment condition in real-time (Participant 3, personal communication, August 23, 2021). From this dashboard, the Fleet Monitoring Center can view the electronic data being fed in real-time from the customers equipment and fluid analysis inspections, then aggregate all data points together using algorithms developed by the Caterpillar data department to create a picture detailing the health of the piece of equipment in question. In addition to maintenance reports, Caterpillar can also view if equipment is being operated in a responsible manner

such as if the operator is wearing a seatbelt while equipment is in use or if they are coasting in neutral during operations (Participant 3, personal communication, August 23, 2021).

Caterpillar also developed another application called CatInspect that can be accessed via mobile device, tablet, or computer. The purpose of this application is to track when a customer or dealer performs an equipment inspection and record all pertinent information from the inspection to build the maintenance history of a given piece of equipment that can be referenced in the future (Participant 3, personal communication, August 23, 2021). Additionally, CatInspect provides insight to the CMA on the consistency and quality of inspections. Suppose inspections are not being completed to the desired standard or recommended time interval. In that case, the CMA will continue to encourage the customer to conduct inspections as prescribed to help reduce the chance of maintenance issues in the future.

Another application that Caterpillar employs is a program called VisionLink. This program essentially takes the fault codes that are being generated from the product link box to enable the Fleet Monitoring Center or customer to view the green, yellow, or red fault codes associated with a specific piece of equipment. A green code means that equipment is functioning as intended, yellow codes indicate that maintenance is required, and red fault codes represent a mechanical issue that needs to be inspected and corrected immediately. Within VisionLink, Caterpillar clients can customize how often they receive reports to include on a daily, weekly, or monthly basis, or if they only want a report when a red fault code is identified (Participant 3, personal communication, August 23, 2021).

Across the various IT platforms detailed above, our interviewee stated they had enabled Caterpillar to generate more than 9,300 maintenance recommendations for customers from January 2021 to August 2021 (Participant 3, personal communication, August 23, 2021). Additionally, by using devices such as smart phones or tablets which a large portion of society is familiar with, and by sending reports with a very intuitive severity scale (green, yellow, and red “stoplight construct”), Caterpillar has attempted to make the interface with their systems as easy as possible. Notably, the simplification of their systems, and more so the hierarchy and organization of fault codes is intended to enable clients to quickly sort through and prioritize maintenance actions as some account

holders with large fleets theoretically could receive thousands of codes per week (Participant 3, personal communication, August 23, 2021).

5. Data Management and Asset Visibility

Customers who purchase Caterpillar's condition monitoring service receive both CMA human feedback on recommended maintenance activities as well as access to Caterpillar's Condition Monitoring Dashboard to view their own equipment statuses. This real-time visibility is supported by Caterpillar's existing IT infrastructure and can be utilized worldwide given the client has data connectivity (Participant 3, personal communication, August 23, 2021). Electronic data streams directly from the assets being monitored to the Caterpillar Fleet Monitoring Center where the CMA looks for the specific trends or indicators within the data as also informed by the four other elements of condition monitoring. The key point to note is that the raw data flows automatically from the piece of equipment being monitored to the Fleet Monitoring Center where various algorithms clean and organize the data for CMA analysis (Participant 3, personal communication, August 23, 2021). However, although our interviewee specified and implied a large degree of data-enabled autonomy within Caterpillar's condition monitoring business model, he further stated that it is not without flaws and Caterpillar still has a lot of work to do to refine and enhance their data management and analysis processes (Participant 3, personal communication, August 23, 2021). Additionally, suppose a customer does not purchase Caterpillar's condition monitoring services. In that case, neither Caterpillar nor the customer will have the access to Caterpillar's data management or visibility of their assets that has been described.

6. Maintenance Decision Making

Most notable to this research, and regardless of how an equipment anomaly or maintenance issue is detected by a CMA, our interviewee stated that one of the most critical aspects of effective condition monitoring is what the customer does with the maintenance recommendation once received from the CMA. Some companies that use the Caterpillar monitoring service are extremely proactive and essentially have a maintenance control center established where maintenance recommendations are received from the Caterpillar CMA and acted on quickly (Participant 3, personal communication, August 23, 2021). In

this model, the overall system works as designed; a mechanical issue is detected, the CMA generates the maintenance recommendation, and the customer acts on this recommendation by servicing the equipment internal to their organization or outsourcing the repair to Caterpillar or a third party (Participant 3, personal communication, August 23, 2021). Companies that are not as proactive create latency from when a maintenance recommendation is received until it is acted on, which results in inefficiencies and higher levels of otherwise preventable breakdowns (Participant 3, personal communication, August 23, 2021).

One notable example of where Caterpillar's Condition Monitoring program was correctly employed includes an intentionally unspecified company with more than 150 sites that Caterpillar monitors. In this scenario, company leadership was concerned that some of the respective site managers were overlooking Caterpillar generated maintenance recommendations so the company made a change to their System Application and Product in Processing platform so that it would directly interface with Caterpillar's systems. This change resulted in the forced integration of Caterpillar maintenance recommendations to daily business activities so that the respective site managers would be forced to see, or at least acknowledge that one of their pieces of equipment had an emergent maintenance issue. Ultimately the decision to take maintenance action or not still resided with the individual site manager, however in the new business model, the site managers were at least aware of an issue in real-time compared to their previous maintenance practices where they were unintentionally, or deliberately postponing maintenance actions. Although our interviewee chose not to specify quantitative metrics of how the company improved, he stated that this change in business practices and general maintenance awareness significantly benefited the company (Participant 3, personal communication, August 23, 2021).

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V. ANALYSIS

A. INTRODUCTION

In order to maintain consistency, the analysis below is organized in the same five themes that were applied to the respective case studies. This approach enables us to categorize and examine best practices, concepts, and themes identified in industry that we have determined to be relevant to the Marine Corps' implementation of CBM+. Additionally, since there is some bleed over by both organizational theme and use or non-use by a given company, our analysis is further organized in a "Topic and Discussion" format to ensure salient points are brought forward and discussed in a useful level of detail as they relate to their applicability to Marine Corps ground systems. All recommendations and areas for additional research will be addressed in the following chapter.

B. ORGANIZATIONAL STRUCTURE AND WORKFORCE TRAINING

1. Internal Data Analytics Department or Branches

a. Topic: The three companies examined throughout our research each had their own organic or internal data analytics or data science department. The maturity and functionality of the data departments varied by company, but a noticeable commonality appeared that all three companies chose to insource this capability to the highest degree possible to achieve both cost savings and organizational flexibility. Additionally, our Freeport-McMoRan respondent mentioned that in an instance when a data-driven problem set arose that exceeded the company's internal capacity or experience, Freeport-McMoRan would contract assistance through an external consulting firm or agency. However, any data-driven projects contracted to external entities are conducted on a partnered basis so that Freeport-McMoRan personnel either gain experience on the process so it can be internalized in the future, or retain an understanding of how the problem set is being addressed to ensure alignment with organizational goals.

b. ***Discussion:*** Although there are multiple facets to employing a CBM strategy such as physical equipment inspections, laboratory-based oil analysis, etc., the collection and interpretation of electronic data remains central to a CBM approach. Further, as ground military equipment continues to get more advanced with the factory-installed sensors capable of capturing large amounts of maintenance data, it is critical that the Marine Corps has the ability to receive and analyze this data with an emphasis on retaining the majority of this capability internally to the organization on either a uniformed or General Schedule (GS) employee basis within the fields of data science and IT. These are positions that cannot be filled by anyone as they require a high level of education and familiarity with technology. Transitioning to CBM+ will increase the demand placed upon these professionals and therefore necessitates an increase of both uniformed and GS employees within these fields to ensure that the benefits from CBM+ can be fully realized. Even if the majority of data management or analysis is outsourced to a contractor, a demand remains for this capability to reside internally to the organization to verify, revise, and implement the work from the contractor. An additional consideration would be the intellectual property rights and access to proprietary information, if it were to be outsourced to a contractor as this, can affect asset visibility and clarity of the maintenance data if the Marine Corps does not have access direct access to this data.

2. Fleet Condition Monitoring Center

a. Topic: Caterpillar's concept of a FCMC staffed with experienced and mechanically inclined Condition Monitoring Advisors (CMA) has immediate military application. As detailed in the Caterpillar case study, the FCMC/CMA construct enables Caterpillar personnel to monitor clients' equipment in real-time, writing maintenance recommendations based on emergent equipment issues detected via remote sensors or patterns aggregated through examining equipment site conditions, repair history, oil analysis, and electronic copies of physical inspections. Although our Union Pacific and Freeport-McMoran respondents were unable to go into the same level of detail on the exact processes employed by their maintenance control centers, it was apparent that both companies utilized a similar construct where equipment health was internally monitored in real-time based on data streaming off of their equipment.

b. Discussion: The real-time maintenance monitoring concept detailed above is largely predicated on possessing equipment with factory-installed (or retrofitted) sensors that are capable of remotely and continuously streaming pertinent maintenance data. As it currently stands, this construct and the maturity of implementation at Caterpillar (more than 900,000 networked assets) is not fully compatible with the majority of the Marine Corps ground equipment fleet. However, as the service continues to acquire more advanced equipment, some form of a data-enabled maintenance control center is worth further exploration as it provides in part, the ability to recognize mechanical anomalies before they result in catastrophic failure. Key considerations for employing this idea in a military context include electromagnetic signature management of networked assets, the ideal place for where the added or recapitalized personnel structure to staff the monitoring center should reside, the Battalion, Regiment, or Major Subordinate Command level, and the costs associated with the hardware and software required to facilitate this capability.

3. Condition Monitoring Advisor Experience and Training

a. Topic: Building off the ideas detailed above, Caterpillar’s FCMC is principally staffed by Condition Monitoring Advisors (CMA) that mainly hail from mechanical backgrounds such as former technicians, operators, and other roles where they have hands-on experience with the actual equipment. However, via Caterpillar’s training process and experience gained while in the role of a CMA, these individuals also gain a working knowledge of how to analyze and apply inputs from electronically derived data sets and reports. This approach is noteworthy, because the ideal CMA has both a working knowledge of how Caterpillar’s equipment works and the analytical skill set to aggregate data points and other indicators to generate sound maintenance recommendations.

b. Discussion: Drawing a Marine Corps comparison, Caterpillar’s CMA profile resembles a combination of a Military Occupational Specialty (MOS) 0411 Maintenance Management Specialist and a MOS 3529 Motor Transport Equipment Chief or a MOS 1349 Heavy Equipment Maintenance Chief. Although the two “Chief” MOSs listed above and dozens of others not specified to include Warrant Officers are inherently exposed to both hands-on aspects of maintenance and more managerial roles throughout their career, the Marine Corps implementation of CBM+ could benefit from a reassessment of the roles and skillsets that are currently resident within the various maintenance MOS. Specifically, Caterpillar largely credits the success of their CMAs to the multidisciplinary approach they use, which the Marine Corps could largely benefit from if mimicked correctly.

C. ASSET CLASSIFICATION AND SENSOR APPLICATION

1. Asset Suitability for CBM Approach

a. Topic: Caterpillar, Freeport-McMoRan, and Union Pacific utilize similar strategies to determine what equipment and components within their fleets or customers' fleets should be monitored using a CBM/PdM approach. They intentionally do not monitor every asset across their respective fleets. To inform the decision of where and when a CBM/PdM approach is applicable, our respondents determine whether a given family of assets or components qualifies as high-cost driver components or high risk of failure assets. High-cost driver components are pieces of equipment or major sub-components that are expensive to replace outright. High risk of failure assets are either critical to operational safety, or contribute heavily to revenue-generating activities. As such, any piece of equipment that meets either criterion is prioritized for a CBM/PdM approach because these components or assets directly impact the company's profitability and safety. If placing sensors on a specific asset or component does not increase profitability by reducing costs, increasing revenue streams, or increased safety, then it is generally not worthwhile to utilize a CBM/PdM strategy on that asset or component. Our Caterpillar respondent noted that this analysis is a deliberate effort during a potential client's consultation period to determine what equipment should be monitored to maximize their ROI.

b. Discussion: During the transition to CBM+, not all assets and components within the Marine Corps ground fleet will need sensors installed or maintained under a CBM approach. While the context and equipment usage may differ between industry and the Marine Corps, determining high-cost driver components and high risk of failure components remain the priority. Understanding that industry is driven by profit and the military services are driven by maintaining the highest degree of readiness the budget allows, the Marine Corps will likely need to be even more selective than industry in determining ground equipment CBM+ suitability. In practice, and to enable the Marine Corps to maximize its ROI, this process would likely translate to an in-depth analysis of the multiple existing fleets to determine assets that classify as high-cost driver components focused which could create cost savings, and high risk of failure components that are either critical warfighting capabilities or present significant safety risk. Further, an analysis of existing ground systems should be conducted to ensure asset compatibility with a CBM+ approach as well as ensuring any acquisitions of future ground systems are also compatible. Focusing both on the compatibility of pertinent legacy equipment and future systems with CBM+ will maximize the benefits of such a program for the Marine Corps and reduce costs from having to retrofit equipment after the equipment has been developed.

2. Retrofitting Legacy Equipment

a. Topic: Across the three companies examined, it was more common that they purchased equipment that was already CBM/PdM compatible instead of retrofitting legacy equipment with sensors or other added equipment required to enable CBM. The one deviation from this trend was Caterpillar as they also provide CBM/PdM monitoring services to companies using non-Caterpillar manufactured equipment by installing an aftermarket Caterpillar manufactured product link box. Without this product link box retrofit, Caterpillar would be unable able to provide its condition monitoring services to those specific customers. This trend indicates the cost-effectiveness and complexity of retrofitting existing equipment is not a viable option in the majority of situations and that purchasing systems that are already CBM/PdM compatible is more desirable in the industry context.

b. Discussion: Currently, the majority of vehicles within the Marine Corps ground fleet are legacy systems that lack the sophisticated sensors or remote interface required to enable an advanced CBM+ strategy similar to that of Caterpillar. To make the current fleet or even select families of vehicles CBM+ compatible, a significant amount of retrofitting would need to occur at great expense to the Marine Corps. For future Marine Corps ground system acquisitions, the service should examine if CBM+ is the optimal maintenance strategy for the given asset and ensure that these requirements are built into the capabilities development document so that the manufacture accounts for CBM+ compatibility during research and development. Further, sensor application or retrofit of legacy systems should be a last resort effort reserved for any pieces of equipment or capabilities the service deems as critical. As detailed by the Australian Military CBA of retrofitting ground assets for a CBM strategy, in the majority of instances, retrofitting ground systems leads to higher costs than if the system was purchased with factory-installed sensors compatible with a CBM approach (Rajesh & Francis, 2012).

D. IT INFRASTRUCTURE AND INTERFACE

1. IT Infrastructure Establishment and Improvement

a. Topic: Two key themes become apparent pertaining to IT infrastructure establishment and improvement. First, Freeport-McMoRan made the obvious decision only to acquire systems and platforms already compatible with their existing IT infrastructure. By using compatible programs, Freeport-McMoRan can largely mitigate silos between platforms, additional effort or expenditures to transfer and merge data or manage operations and maintenance activities across an unnecessarily wide spectrum of platforms. Second, Union Pacific and Caterpillar sought to purchase and implement systems and programs with user-friendly “dashboards” that could be accessed via tablet or smartphone app, and were generally intuitive and easy to use. In both instances, this effort was largely focused on ease of use for customers when applicable or accommodating an older or less technologically inclined workforce.

b. Discussion: IT infrastructure must be established and generally functional prior to implementing a successful CBM+/PdM strategy. Even simple and well-established practices in industry such as Wi-Fi-enabled maintenance bays can make the difference in the overall effectiveness and ease of use of a maintenance strategy that is inherently tied to the collection, management, and use of data. Obviously, industry does not need to account for the same constrained acquisition processes, required degree of network security, and system deployability as the military. Examples of these constraints would include being required to bid out contracts for system updates or modifications, prioritization in the reduction of electromagnetic signature to prevent adversary targeting, and being expeditious in nature, meaning having the ability to establish and displace equipment quickly. However, the interoperability and ease of use considerations outlined above should be driving factors in how the Marine Corps envisions the IT infrastructure aspects of CBM+ implementation.

2. Enterprise Resource Planning Software

a. Topic: Both Union Pacific and Caterpillar use Enterprise Resource Planning (ERP) systems for their maintenance activities, enabling their CBM approach. The “CBM enabling” distinction is noteworthy, because in both instances these programs are not strictly purpose-built for CBM, but are still capable of being used to capture data such as the results of equipment inspections, man-hours per repair, and fault codes received from networked equipment as inputs for their CBM approach. The common theme here is that both of these organizations have been able to tailor and apply existing systems to facilitate a CBM approach as long as they are generally interoperable with the systems used by their respective data science departments to build algorithms, and are user friendly so that inputs are captured in a timely, correct, and usable manner.

b. Discussion: The overall effectiveness and value of the Marine Corps' primary maintenance ERP system, Global Combat Service Support–Marine Corps (GCSS-MC), is widely debated across the service with positive or negative views varying based on individual experiences and unit or organizational perspectives. Our research suggests that current aspects of GCSS-MC (equipment repair history) could be used to enable the Marine Corps implementation of CBM+, but the program would likely need to be significantly tailored or upgraded to achieve the same level of viability as its civilian counterparts. An example of an upgrade would include sensors from vehicles being able to automatically upload usage or health data into GCSS-MC databases without the requirement to manually upload that data through the desktop interface. This would enable the service to achieve access and visibility of real-time data, the gold standard that industry strives for. As the system currently stands, maintainers input maintenance and usage data from logbooks into the desktop interface manually at specific PM intervals or when CM. Further, and even with hypothetical improvements to GCSS-MC's functionality, the service would likely need to pursue a sister system or some form of data science department as addressed above to be able to merge this data into formats or models that could be used to predict equipment failure or monitor equipment health in real-time.

E. DATA MANAGEMENT AND ASSET VISIBILITY

1. Continuous vs. Periodic Connectivity of Sensors

a. Topic: Caterpillar, Freeport-McMoRan, and Union Pacific utilize continuously transmitting sensors for the majority of their CBM/PdM capable assets. The value created from using continuous sensors is the ability to view maintenance and operational data in real-time, which leads to a high level of asset visibility across the majority of their fleets. If they had opted for sensors that only transmitted data periodically the same level of asset visibility would not be achieved creating latency between when data was gathered by sensors, and when it was received by the parent system used to capture maintenance data. The use of continuous data collection reduces latency in capturing relevant patterns as networked equipment is continuously transmitting data for maintenance professionals to review and act on. In a military application, one key drawback of continuously transmitting data is the likely increases in the electromagnetic signature of a networked asset which is obviously disadvantageous in concealing the position or activities of a given unit.

b. Discussion: The Marine Corps operates in vastly different environments and contexts than industry which obviously creates additional factors that need to be accounted for in the application of any maintenance strategy. As addressed above in part, industry is not routinely exposed to the same considerations and planning factors inherent to conducting combat operations such as electromagnetic signature management, approved communications windows, and deployed data connectivity. As such, the continuous data transmission models used by Caterpillar or Union Pacific may be acceptable to the service in a garrison or training environment to maximize the cost-effectiveness of CBM+ strategy, but are clearly not suitable in a forward-deployed or high threat environment. As an alternative, it would be rational for the service to pursue equipment, associated software, and processes needed to enable both a continuous and periodic data collection and analysis. Hypothetically with this approach, in a garrison environment where the Marine Corps wanted to maximize CBM+ effectiveness the service could use a model predicated on continuous data transmission similar to Caterpillar's Fleet Conditioning Monitoring Center. In a high threat environment where signature management is applicable, the Marine Corps could use periodic data transmission where all stored data is hard-lined into an associated laptop or tablet for analysis minimizing the need to radiate and potentially expose the equipment or unit's position to potential threats.

2. Interaction with Data

a. Topic: As previously discussed, all three companies examined have automated data management processes in place that require very little human interaction to translate data into a usable format. Routine maintenance data is typically not handled until it is uploaded into the company's primary database which increases accuracy and removes the chance of human error in the data. The first interaction that employees have with the operational and maintenance data is when data scientists apply algorithms or otherwise analyze it. While the data drives decisions within these companies, humans are still responsible for making those decisions and their input is required to synthesize what the data is saying and what the situation dictates. Although data management and aggregation processes are rapidly becoming quicker and more accurate, our Caterpillar respondent stated that Caterpillar is still not at the point of complete data autonomy and requires the input of humans to make decisions (Participant 3, personal communication, August 23, 2021).

b. Discussion: The Marine Corps interaction with data does need to differ significantly from how industry interacts with data. Automated data management could be even more beneficial to the Marine Corps compared to industry due to lack of personnel working specifically within the field of data science. Additionally, the Marine Corps could benefit from increased automation as several current business practices are highly susceptible to human error such as the manual input of equipment milage/hours into GCSS-MC, transcribing or upload of hand written Limited Technical Inspections (results of a physical equipment inspection), etc. The hypothetical automation, or at the least electronic standardization, of the majority of the Marine Corps maintenance and operational data sources via sensors that automatically convey this information or within a tablet-based application, similar to Union Pacific's, could reduce the number of human errors occurring. Thus, providing the Marine Corps with a more accessible and accurate data set for maintenance decisions.

F. MAINTENANCE DECISION MAKING

1. Receiving and Acting on Maintenance Inputs

a. Topic: The ultimate purpose of a CBM or predictive maintenance strategy is to predict that a component or piece of equipment is going to fail, then act on this insight before it fails. Even though this idea is at the center of our research and one of the primary goals of the individuals interviewed, that doesn't always mean it happens. As detailed by one of our Caterpillar respondents, a positive CBM outcome is based on a series of processes and actions done correctly. Extremely simplified—first, the equipment in question needs to be compatible with a CBM approach (sensors, inspection programs, etc.), second, the organization in question needs to have the capability to receive and digest this information, and third, and most important to this portion of the analysis, said organization needs to take action on this information in a timely manner. This third component of a positive CBM outcome is notable because even in instances where a company or organization has all required aspects to enable a CBM strategy, if the decision-making apparatus or processes where the third step resides is faulty, or the organizational culture prioritizes revenue or production at the expense of maintenance activities, it is likely that the whole effort is for naught.

b. Discussion: Although a large part of our research emphasized the importance of data management, systems, and technology as key aspects of a CBM approach, the ultimate success of this strategy hinges on what is done with the information derived across these investments and lines of effort. As the Marine Corps moves forward with CBM+ implementation, equal levels of mental capital (compared to that of actual capital spent on technology, systems, etc.) needs to be expended on how the service will act and decide on all of the information gleaned from systems and technology. As detailed in a previous section, a close examination of Caterpillar's FCMC is a good starting point for both processes and possible aspects of organizational structure to correctly package and relay maintenance decisions to commanders and operational units.

2. Maintenance Metrics—Remaining Useful Life and Expected Useful Life

a. Topic: Although all three respondent companies were familiar with the measurement of EUL and RUL, these metrics were surprisingly not key components of their respective maintenance strategies. Both Freeport-McMoRan and Union Pacific essentially used Original Equipment Manufacturers (OEM) recommendations (how many hours/miles a piece of equipment should last) as their baseline EUL. In this instance both companies seemingly used OEM equipment longevity baselines for more “expectation management” purposes than for maintenance decision making. For example, if a locomotive manufacturer stated that a diesel engine should remain operational for one million hours, Union Pacific used this information more for identifying faulty engines such as one that failed at 400,000 hours, than informing the decision to hypothetically conduct an engine rebuild of a unit approaching ~900,000 hours. Additionally, as private companies that are revenue driven, both Union Pacific and Freeport-McMoRan placed more emphasis on maximizing equipment value than closely monitoring, or adhering to an OEM-derived EUL—these companies would continue to run and repair equipment until it became cost-prohibitive to do so. Lastly, both companies did not fixate on EUL or RUL, because of how difficult these metrics are to capture across different operational environments, tempos, and a litany of other considerations. Specifically, Freeport-McMoRan does capture and log data indicating how long a given piece of equipment or component will last, but this data set seemed to be in a continuous state of refinement due to the countless outside variables that can impact equipment degradation such as operator training, temperature, maintenance technician proficiency, etc.

b. Discussion: There is inherent value to attempting to correctly capture a piece of equipment's EUL upon being newly acquired or fielded, and then attempt to monitor the RUL throughout its life cycle. However, in our discussions with industry, it became readily apparent that both of these metrics, in particular RUL, were not as clean and easy to delineate or estimate as one would think and thus were used inform maintenance activities and decisions, but were not key drivers of these actions. This consideration is especially relevant to the Marine Corps given the diverse environments and hypothetical concepts of employment for the same piece of equipment. For example, the EUL of a Joint Light Tactical Vehicle (JLTV) that is exclusively operated in a desert environment with excessive temperatures and fine particulate matter is likely different than a JLTV that is continuously operated in an extremely cold and snow-covered environment. Although the scenario above intentionally draws stark contrasts and discards countless other factors such as operator/maintenance technician proficiency, adherence to preventative maintenance schedules, etc., it serves to illustrate how the Marine Corps could have added challenges measuring RUL compared to the already challenging civilian application where there is a far higher degree of standardization and regularity.

3. Maintenance Metrics—P-F Curve

a. Topic: Instead of using RUL and EUL as key maintenance metrics, the companies interviewed seemed to place far more emphasis on using the P-F curve to monitor when a piece of equipment transitioned from a “normal state” or operations to that of a “dangerous state” indicating that failure is imminent.

b. Discussion: This distinction identified above is notable, because industry, and particular Freeport-McMoRan, placed more value on equipping individual assets with sensors and monitoring this data than attempting to gauge the RUL of that specific asset. Obviously, these constructs are not mutually exclusive, but our key finding as noted above, is that the measurement of RUL served as a more of a guideline for the longevity of a family of assets but the measurement of the P-F curve was more meaningful for a condition-based maintenance strategy in terms of monitoring the health of an individual piece of equipment. EUL is a useful planning tool or baseline for the fleet at large, but the monitoring for the transition from the normal state and to the dangerous state (regardless of where this occurs within the equipment's EUL) is where industry generated value and actionable maintenance decisions from their condition monitoring strategy.

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VI. CONCLUSION

Our capstone project was centered on researching established companies with large ground equipment fleets that currently employ either a CBM or PdM strategy to determine best practices or considerations that are relevant to the Marine Corps implementation of CBM+. The implementation of CBM+ will hypothetically result in greater cost savings and increased operational availability of ground equipment maintenance across the Marine Corps. The summary of findings and future research opportunities detailed below succinctly captures what we deemed to be most relevant to this endeavor and highlights areas or topics that warrant far greater exploration than what was covered in this project.

A. SUMMARY OF FINDINGS

We were able to compile relevant business practices and additional considerations that we recommend to be addressed in the Marine Corps' implementation of CBM+.

1. IT Infrastructure

IT infrastructure is the key enabler of a successful CBM or PdM program that must be established and generally functional prior to transitioning to a maintenance strategy that is inherently predicated on capturing, analyzing, and applying data to make maintenance decisions. Functional IT infrastructure was foundational for the three companies analyzed. Although several of our respondents fully acknowledged that their systems and applications were not perfect and were continually being refined and improved upon, the base functionality of their systems, and more so the flexibility of how the respective companies were able to apply them (remotely, on easy-to-use tablets/applications, or a “dashboard” that captured equipment health at a glance), appeared to be superior to the Marine Corp's systems in all regards. One significant difference in the companies analyzed and the Marine Corps current systems is the scope and clarity of maintenance data industry is able to collect and access without manually handling data such as electronically annotating hand written odometer readings on Limited Technical Inspections sheets into GCSS-MC. Although this example could be construed as overly specific, the key point is that industry has achieved a much higher degree of functionality within their maintenance systems which in turn directly enables a CBM strategy. Acknowledging that we are not experts on

either the Marine Corps' current ERP or IT infrastructure in general, it appears that the Marine Corps is going to require significant modifications to existing systems or the purchase of additional systems to achieve CBM+ implementation that is comparable to the capability that currently exists in industry.

2. User Interface

Building upon the theme detailed above, user interface must be a primary tenet in the upgrade or procurement of the various hardware and software suites required to enable a CBM+ strategy. The urge to remedy the Marine Corps' existing IT infrastructure gaps with overly complex software must be resisted. Any software or systems purchased should be fairly intuitive to use, efficiently enable maintenance activities, and ensure complexity is not added to operators and maintainers already extensive requirements. By acquiring an easy to use and understand system that automates basic functions like capturing odometer readings, engine hour counts, or other pieces of similar data that are remotely streamed from a sensor-enabled piece of equipment to the new operating system without double handling data or requiring manual user input, the service will benefit from more accurate data. Even with baseline functionality such as being able to accurately correlate a particular component failing around a general operational temperature or mileage, the service would gain efficiencies in both preventing catastrophic failure and accurately troubleshooting problems which would save significant time and resources. At the enterprise level, the ability to baseline trends across a specific piece of equipment and visually display this information through an easy-to-use system would build institutional knowledge and awareness. Hypothetically, at the macro level, platform-specific data would enable the Marine Corps to see if equipment is meeting OEM specifications and identify where notable deficiencies and trends exist across the breadth of the service. At the micro-level such as a battalion that is a principal owner and user of the hypothetical piece of equipment in this scenario, being able to clearly see maintenance trends across the service for the same piece of equipment in an easily accessed display would directly benefit maintenance decision making as maintenance leadership would be able to easily recognize patterns across the service and take action as required. Finally, and also applicable at the micro-level, all of the companies analyzed had success with equipment alerts remotely streaming

off their assets to notify both the operator and maintenance control center that the piece of equipment was experiencing a mechanical issue. By receiving an alert or fault code on their given maintenance system, which often occurs in real-time, the company's software enabled both the operators and maintenance leadership to adjust or cease equipment operation. This system functionality is beneficial because it affords a higher level of supervision and awareness of how high-value assets are being operated, and more importantly, this capability is credited with identifying mechanical issues before they result in catastrophic failure.

3. Retrofitting and Acquisitions

The mass retrofitting of legacy equipment to be CBM+ capable with sensors will likely not yield a desirable return on investment in purely a monetary sense, but has the potential to increase or ensure a higher degree of readiness. Any retrofitting expenditures of legacy equipment or items in the Marine Corps inventory that are not currently compatible with a CBM+ strategy should be reserved for equipment or capabilities the service deems most critical for warfighting activities. Possible existing platforms that meet this low-density, high-value criteria include recovery assets across the wheeled and tracked families of vehicles, any platform capable of long-range fires such as the High Mobility Artillery Rocket System (HIMARS), critical command control (C2) assets such as a JLTV equipped with Networking on The Move (NOTM) system, and any vehicle or platform that provides unique or niche capability like an electronic warfare (EW) equipped Light Armored Vehicle (LAV), etc. In these instances, and hypothetically assuming the Marine Corps would need to spend significant amounts of money to make all of the above-listed platforms CBM+ compatible, the trade-off is a large expenditure to ensure higher levels of readiness and the ability to conduct real-time monitoring on specific critical assets makes sense. Further, the select retrofit of only the most critical capabilities would essentially enable the service to buy down the risk of high-value assets experiencing mechanical failure when it might matter most such as combat operations.

Additionally, the service needs to begin ensuring that future or planned systems account for OEM CBM+ compatibility as this is likely the more cost-effective option. Depending on the additional cost of OEM compatibility, similar rationale as detailed above

is recommended for the prioritization of CBM+ compatible acquisition programs with emphasis on accounting for low-density high-value assets, combat arms systems such as the LAV-25 replacement, and equipment deemed critical to supporting distributed operations and emerging concepts such EABO. However, this is not to say that every future ground acquisition program must be CBM+ compatible because depending on the unit cost of the asset, or intended concept of employment, it may be more cost-effective to use a TBM strategy and replace the asset at a shorter interval than a CBM+ compatible asset with a longer life cycle. Examples of equipment that may not meet the criteria for ensuring CBM+ compatibility is built into the acquisitions process include garrison specific equipment such as aviation ground support assets (fuel trucks, pushback tractors, small cranes for engine replacement) that are only used in CONUS or well-resourced bases in mature theaters of operation, material handling equipment such as the Kalmar, or any item that has a more administrative concept of employment and is generally used in maintenance resource-intense areas where the benefits of a CBM+ strategy may be negligible. In both cases of examining equipment that is appropriate for retrofit or future assets that should be procured as factory compatible with CBM+, a thorough analysis should be conducted to determine if the benefits from acquiring CBM+ compatibility are worth the cost.

4. Personnel Structure and Outsourcing

Data management is not a core competency within the Marine Corps operational forces where the vast majority of equipment that could benefit from CBM+ implementation resides. In the examples of Caterpillar, Union Pacific, and Freeport-McMoRan, each company had a data science department and some form of maintenance control or condition monitoring center (CMC) that were two generally distinct entities that worked with one another. Additionally, throughout our interviews it was implied that industry's data and maintenance monitoring structure did not reside at every equipment location and was centered in more of a headquarters setting or at larger high use facilities. With these ideas in mind, it would be rational for any added Marine Corps data capability or personnel structure to reside at the headquarters level, likely Headquarters Marine Corps Installation and Logistics to essentially clean service level data and build usable algorithms for the

operational forces. Due to the specialized skill set of data personnel, these roles would probably be best suited for GS employees or possibly on a contracted basis. Additionally, the Marine Corps should not attempt to fulfill this role with uniformed personnel due to high turnover, attrition, and etc.

If the service elected to establish a CMC or maintenance control center reminiscent of Caterpillar's FCMC, the service could take this concept in one of two different directions or formulate a hybrid. In the first instance which is administratively oriented on maintenance cost savings, the Marine Corps CMC could reside at the MEF level where uniformed personnel would be able to view equipment health reports in real-time and reach out to the effected units to make them aware of potential equipment issues and ensure that corrective action was being taken via maintenance recommendations similar to that of Caterpillar. In this instance, the MEF condition monitoring staff would essentially act as an extension of the existing Maintenance Management Section. However, instead of focusing on the status of corrective maintenance procedures such as timely supply chain transactions, the appropriate scheduling and conduct of preventative maintenance, and etc., the CBM+ enabled MEF conditioning monitoring staff would use the tools at their disposal to mitigate maintenance issues before they happen opposed to ensuring compliance after the fact which the current construct is largely predicated on. The main emphasis of the CBM+ enabled maintenance control center would be the realization of cost savings through the minimal addition, or repurposing of existing MEF personnel structure (opposed to creating additional billets/structure in the context detailed below) and reduced corrective maintenance expenditures for corrective actions.

In the second instance which is more oriented on tactical situations and maintaining the highest level of equipment readiness possible, the CMC could reside at the Regimental level within the S-4 section. In this construct, Marines could theoretically monitor equipment status in real-time as an extension of the Combat Operations Center or Administration & Logistics Operations Center during training exercises or combat operations in a similar same role as the centralized MEF construct captured above, with the notable distinction of conducting 24-hour tactically oriented operations that directly support the regiment's subordinate elements. This construct is based on the ability to

receive and view equipment data in real-time similar to that of Caterpillar's model so the regimental condition monitoring staff would take the burden of monitoring maintenance activities off of the operational units so they could focus on the training event or operation at hand. Further, in this role, if the regimental condition monitoring staff identified a ground asset that was about to have a catastrophic failure, they would be responsible for notifying the effected unit that failure was likely imminent which would enable the commander to make an informed decision to evacuate that piece of equipment for maintenance actions, or accept the risk of continuing operations with the asset. The main emphasis of this construct is maintaining the highest degree of combat readiness possible and providing real-time maintenance information to the supported units which would be more resource-intensive as a result of the systems and personnel required to duplicate the capability across multiple infantry and artillery regiments, select logistics regiments, individual formations such a Light Armored Reconnaissance battalion, and possibly some Marine Wing Support Squadrons.

It is worth noting that the viability of the hypothetical maintenance monitoring center constructs detailed above are predicated on the maturation of the Marine Corps CBM+ program but still warrant significant thought and planning to ultimately maximize the effectiveness of a CBM strategy. Regardless of the maintenance monitoring construct or concept ultimately adopted by the Marine Corps, it needs to be founded on the timely receipt and interpretation of data and actionable packaging and transmission of this information to the appropriate decision-making authority. The purpose of implementing a CBM+ strategy should be on creating value in either maintenance cost-savings in a garrison environment, or ensuring the highest degree of readiness during training and combat operations, so any processes implemented should not create an administrative burden or latency that outweighs or detract from the overall intent of the strategy.

5. Expected Useful Life and Remaining Useful Life

One of the most notable outputs from our research was the determination that EUL, and especially RUL estimations are not as easily to calculate or critical to a ground equipment-centric CBM strategy as one would think. As previously noted in our research from the three companies examined, they generally use OEM specifications as a piece of

equipment's baseline EUL. As time progresses and data is collected, EUL expectations for a specific equipment variant can be adjusted based on observed equipment health and environmental factors. However, the ability to do so is generally applied to high density / high use assets where a given company is very familiar with the asset and is able to amass a large data set in similar operating conditions—i.e., a large number of the same locomotive variants that have been operating on the same routes for many years. The ability to measure RUL is difficult because this metric is dependent on the EUL value is and therefore changing in the same direction as EUL. As previously stated in our research, there obviously is value to attempting to gage EUL at equipment fielding then measure RUL throughout a piece of equipment's useful life, especially in instances where a piece of equipment is used in same context or operating conditions like generators, manufacturing equipment, etc. However, in the case of Marine Corps vehicles or ground equipment that are frequently exposed to a vast number of non-standardized variables such as operator and maintainer proficiency, different operating environments, and widely fluctuating operational tempos, these metrics are better suited as guideline or considerations for maintenance tasks and decisions, not as the primary driver of a condition-based maintenance strategy.

Once a CBM program has reached maturity, meaning there is sufficient data available to enable the development of predictive models, a useful tool that can be utilized in the analysis of RUL is the P-F curve. As stated previously, EUL and RUL are non-linear and fairly complex metrics to capture. It appeared that the companies examined used these constantly evolving metrics to develop the baseline for the development of P-F curves for their assets. They were not concerned with exactly what EUL and RUL were, but were more concerned about when a sensor detected an anomaly that indicated an asset was now operating in the danger state. Within the context of the Marine Corps, the P-F curve would serve as means to evaluate risk for specific assets during training and real-world operations, as when it is correctly monitored (via sensors and supporting structure detailed throughout our research) it provides an indication if equipment is operating in a normal state or has transitioned to the danger state and requires repair. Namely, the desired outcome of using the P-F curve is to generate a clear understanding of a piece of equipment's health to

facilitate employment and maintenance decisions based on the indicated likelihood (or not) of catastrophic failure.

B. FUTURE RESEARCH OPPORTUNITIES

Our research only included a small sampling of companies and was intended to be very broad. The five emergent themes - organizational structure and workforce training, asset classification and sensor application, IT infrastructure and interface, data management and asset visibility, and maintenance decision making, could warrant extensive additional research. Additionally, it was difficult to quantify the specific benefits and improvements from implementing a CBM or PdM program for the companies examined as the majority of that information was not specifically tracked by our respondents. Although there is ample room to build on our research on how industry CBM/PdM practices could benefit the Marine Corps implementation of CBM+, we believe the topics outlined below would be the most relevant and fruitful for the service.

1. IT infrastructure mapping and business flows. The study of how a company with a successful CBM/PdM program specifically lays out and utilizes their IT infrastructure would be extremely beneficial with emphasis on what systems are used, how they are networked with one another, and what the exact process looks like from initial fault code detection to equipment repair looks like within their given system.
2. Continuous and periodic equipment data collection. An examination of different methodologies for equipment data collection and aggregation would definitely benefit the Marine Corp's CBM+ implementation. Any further research in this area is suggested to focus on electromagnetic signature management in the case of continuous remote data collection and best practices for aggregating periodically collected data that is manually downloaded (HDMI cord from the piece of equipment's on-board hard drive to a laptop or etc.) in communications denied or degraded environments. Further research in this field is meaningful because a CBM strategy is inherently data dependent which is obviously at odds with the austere,

communication degraded, or peer threat areas the Marine Corps will likely operate in.

3. Service level ground equipment prioritization for sensor retrofit. Any further research in this field should conduct a cost-benefit analysis on the retrofit of existing Marine Corps ground assets for CBM+ compatibility. Additionally, we recommend emphasis on only examining equipment or families of assets that the Marine Corps has deemed as critical warfighting capability.

C. FINAL THOUGHTS

At its core, a successful CBM strategy is intended to be a system that detects a maintenance issue prior to failure or significant degradation and provides the equipment owner the information and time to make adjustments to how the equipment is being operated, repair it before failure, or make the deliberate decision to run it to failure. In the context of the Marine Corps distilled to the lowest level, successful CBM+ implementation should provide the service with the tools to inform the conversation between the logistics officer and operations officer so they are able to arm the commander with pertinent information such as projected breakdowns during the period of operation, estimates on corrective maintenance costs following an exercise, and risk to mission or risk force if given pieces of equipment or capabilities are, or are not employed in support of an operation or exercise. Although these are hypothetical examples of how CBM+ outputs could enable a greater understanding of decision points that impact the health or operational employment of a unit's equipment set and are not all-encompassing, the point is, that CBM+ should ultimately serve as a decision-making framework to maximize maintenance cost savings when applicable, ensure the highest degree of combat readiness when it matters most, or both if possible.

With this thought in mind, and although aspects of our research emphasized the correct application of technology, as the Marine Corps moves forward with CBM+, every effort should be made to implement a human-centered, technology-enabled system that can provide staffs and commanders alike clear and actionable

information to make maintenance and operational decisions. Additionally, since CBM+ is a system, the Marine Corps should remain cognizant of what aspects of the system are maintained purely on a uniformed basis, what aspects are centralized at higher headquarters likely in a GS capacity, and what aspects of the process are possibly contracted out. This is important, because as a system, if too many aspects of the Marine Corps final CBM+ system is disaggregated and difficult to access by the most affected stakeholders – commanders at the regimental and battalion level, the service could potentially cede the responsiveness and real-time information that CBM is heavily predicated on thus mitigating potential benefits.

Lastly, it is very unlikely the Marine Corps should, or would be able to perfectly copy industry, however, we believe CBM+ implementation needs to be very methodical accounting for all facets detailed in this research. Throughout this project, we discussed the goal of CBM+ as creating maintenance cost savings and ensuring the highest degree of readiness possible. Although there is some obvious overlap in both of these objectives, emphasis on one or the other is going to create some degree of opportunity cost. For example, with a limitless budget, the Marine Corps could hypothetically retrofit every asset in the inventory to be compatible with CBM+ which would theoretically increase readiness across the service. Inversely, the service could also selectively target certain high use, high breakdown assets for CBM+ compatibility where a smaller expenditure in sensors, etc. could create long-run maintenance cost savings. Although these ideas are fairly intuitive, the takeaway is that the ultimate goal and method of Marine Corps CBM+ implementation is not as clear and as easy to delineate as a for-profit context like industry. Throughout implementation, the service is going to need to examine numerous trade-offs and process adjustments which would be best addressed methodically and deliberately where all required aspects of the CBM system are accounted for and the Marine Corps retains a clear vision of how to best reap the benefits of a CBM+ strategy.

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APPENDIX B

IMPLEMENTING CONDITION-BASED MAINTENANCE PLUS AS A GROUND MAINTENANCE STRATEGY IN THE MARINE CORPS

ABSTRACT

In 2020, Marine Corps Order 4151.22 and Commandant White Letter 2-20 was published to implement Condition-Based Maintenance Plus (CBM+) as a ground maintenance strategy to improve operational availability and reduce life cycle costs. The Fleet Marine Force is still operating under preventative and corrective maintenance strategies instead of CBM+ strategies. Organizational inertia, such as competing priorities, legacy processes, and inspections, has slowed the integration of CBM+ strategies. We reviewed key policy documents and interviewed fifteen subject matter experts relevant to Marine Corps ground transport maintenance policies and practices. Based on this information, we conducted a thematic analysis using an organizational change approach to identify barriers and opportunities that impact CBM+ implementation. We found that immediate gains from CBM+ implementation in the Marine Corps can be achieved through a focus on people and process improvements while technology integration continues. The CBM+ strategy supports Force Design 2030 and Talent Management 2030 objectives and emphasizing this alignment can build momentum for CBM+. In this paper, we make six specific recommendations that apply organizational change concepts to enable effective CBM+ implementation as a ground maintenance strategy in the Marine Corps.

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LIST OF ACRONYMS AND ABBREVIATIONS

BDA	beginning, during, after
CBA	capabilities-based assessment
CBM	condition-based maintenance
CBM+	condition-based maintenance plus
CD&I	Combat Development and Integration
CM	corrective maintenance
CMC	Commandant of the Marine Corps
COMMSTRAT	Communication Strategy and Operations
COTS	commercial off the shelf
DC	Deputy Commandant
DOD	Department of Defense
DODI	Department of Defense Instruction
DODIG	Department of Defense Inspector General
DOTMLPF-P	doctrine, organization, training, materiel, leadership and education, personnel, facilities – policy
DRIS	date received in shop
EFV	expeditionary fighting vehicle
ERP	enterprise resource planning
ETP	exception to policy
FMF	Fleet Marine Forces
FSMAO	Field Supply and Maintenance Analysis Office
GCSS-MC	Global Combat Support System-Marine Corps
HQMC	Headquarters Marine Corps
I&L	Installations & Logistics
ICD	Initial Capabilities Document
IDA	Institute for Defense Analysis
IOT&E	initial operational test and evaluation
JLTV	joint light tactical vehicle
LAV	light armored vehicle
LDO	limited duty officer

LVSR	logistics vehicle system replacement
MAW	Marine Aircraft Wing
MCCDC	Marine Corps Combat Development Command
MCO	Marine Corps Order
MCSC	Marine Corps Systems Command
MCT	maintenance cycle time
MEF	Marine Expeditionary Force
MIG	MEF Information Group
MLG	Marine Logistics Group
MRB	Materiel Readiness Branch
MSC	major subordinate command
MT	motor transport
MTVR	medium tactical vehicle replacement
MVP	minimal viable product
PM	preventative maintenance
SME	subject matter expert
SR	service request
TAMCN	table of authorized materiel control number
TM	technical manual

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EXECUTIVE SUMMARY

The Marine Corps is undergoing organizational change efforts to integrate Condition-Based Maintenance Plus (CBM+) as a maintenance strategy to support ground equipment across the enterprise. Currently, the Marine Corps ground maintenance is based on preventative and corrective maintenance strategies. Enterprise-wide implementation of CBM+ requires the actions and decisions of several stakeholders throughout the Marine Corps from Headquarters Marine Corps down to unit level commanders, staff, maintainers, and operators. The Marine Corps Orders regarding CBM+, MCO 4790.25 and MCO 4151.22, provide definitions for CBM+, but do not present a means for integration into the ground maintenance strategy or a pathway for refinement of existing orders/processes. The Marine Corps is not prepared in its organization-wide policies, processes, and personnel to be technology-empowered and data-driven in its maintenance strategies. The Marine Corps has an excellent opportunity to achieve quick and early gains in the implementation of CBM+ as a maintenance strategy by making changes to the people and process aspects that will not require additional resources and funding. Making necessary adjustments to get the people and processes working efficiently will facilitate effective technology integration.

We furthered our understanding of CBM+ implementation by reviewing ground maintenance policies and interviewing military and civilian ground maintenance subject matter experts. Based on the information collected, we conducted a thematic analysis to identify barriers to and opportunities for change within the Marine Corps ground maintenance community. An organizational change approach and successful change principles informed our recommendations for CBM+ implementation.

Four major themes emerged as barriers to CBM+ implementation in the Marine Corps. First, there is a lack of clear and consistent understanding of CBM+ across the Fleet Marine Force. Second, there is conflict among various orders and policies that delineate Marine Corps maintenance strategy and many legacy policies directly conflict with CBM+ strategies. Third, inspections heavily influence maintenance actions at the operational unit level and hinder implementation of CBM+ initiatives. Finally, competing priorities reduce focus and capacity necessary to change maintenance strategies.

Four themes emerged as opportunities to support CBM+ implementation. First, leaders within the organization need to drive the CBM+ maintenance strategy implementation process. Second, interim exceptions to policy (ETP) for policies that restrict CBM+ maintenance strategies can accelerate integration. Third, experiences at 3d MLG demonstrate opportunities to remove non-value-added tasks within maintenance processes to achieve measurable and observable gains by integrating CBM+ processes prior to adopting sensors and other technology solutions. Finally, ownership in the change process and the application of cross-training within operational units will make CBM+ implementation more effective.

Based on our analysis, the following six recommendations would improve CBM+ implementation as a ground maintenance strategy in the Marine Corps:

- **Align CBM+ with Force Design 2030 and Talent Management 2030**

A sense of urgency should be built for CBM+ implementation by communicating to the FMF how CBM+ supports the current CMC priority initiatives. The alignment of CBM+ benefits to the objectives of FD2030 and TM2030 should be communicated throughout the FMF to build a greater sense of urgency to change maintenance strategies.

- **Establish a CBM+ Guiding Coalition**

A CBM+ guiding coalition would guide, coordinate, and communicate CBM+ implementation throughout the Marine Corps. The guiding coalition should be directed and led by owners of Marine Corps maintenance policy that have sufficient level of authority to initiate and approve enterprise policy change. Existing tools within the Marine Corps policy refinement process, such as the Total Life Cycle Management Cross Functional Team (CFT) model, can be used to establish a CBM+ guiding coalition.

- **Refine and Communicate CBM+ Vision**

A strategic communication plan needs to be developed to promulgate the vision of a CBM+ maintenance strategy as well as build the knowledge and education in the force on CBM+ practices, processes, and benefits. We recommend the CBM+ CFT provide an updated CBM+ vision that clarifies its association with FD2030/TM2030 and empowers units to seek out improved maintenance practices and provide bottom-up refinement to the CBM+ CFT.

- **Resolve Conflicts Between Maintenance Policies**

We recommend creating an environment that fosters short-term wins through interim ETPs and consolidates gains in a single volumized maintenance order. Operational units need to be empowered to seek out process improvements and opportunities to apply CBM+ practices. The restrictive nature of current orders and constraints placed by required non-value-added maintenance actions present obstacles to Marines seeking to update processes to incorporate CBM+ principles.

- **Develop CBM+ Education for Commanders**

We recommend incorporating CBM+ and maintenance concepts central to Marine Corps maintenance strategy into training and logistics seminars for leaders. Promulgating a CBM+ information paper is an effective tool to provide commanders and FMF CBM+ awareness and education in an expedient manner. CBM+ should be incorporated in the Commander's Materiel Readiness Handbook to improve leaders' familiarity and provide a quick reference to principal components of the Marine Corps maintenance strategy.

- **Utilize FSMAO to Support CBM+ Integration**

Inspections are an enabling force in the maintenance community that reinforce maintenance strategy and processes. The Field Supply and

Maintenance Analysis Office (FSMAO) can be utilized as a key contributor in communicating and enabling the CBM+ vision for Marine Corps maintenance through evaluating, training, and consolidating best practices of CBM+ processes.

The above recommendations target areas of opportunity for the Marine Corps to generate urgency, empower broad-based action, and solidify CBM+ as a ground maintenance strategy. Our recommendations use available organizational tools within the Marine Corps and provide options for leaders and policymakers to proactively drive CBM+ implementation. There are immediate gains that the Marine Corps can achieve through people and process improvements rather than waiting on the acquisition process and CBM+ technology to mature. Enterprise-wide integration of CBM+ as a ground maintenance strategy plays an important role in enabling logistics as the pacing function for the Marine Corps and supports FD2030/TM2030 objectives.

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VII. INTRODUCTION

The Marine Corps is seeking to integrate Condition-Based Maintenance Plus (CBM+) as a maintenance strategy to support ground equipment across the enterprise, as directed through the publication of Marine Corps Order 4151.22 in January 2020 and the Marine Requirements Oversight Counsel approval of the CBM+ Initial Capabilities Document (ICD) on April 14, 2022 (Headquarters Marine Corps [HQMC], 2020a). These two authoritative documents outline the requirement to transition to CBM+ but are not prescriptive in addressing the Marine Corps' current maintenance policies, business practices, cultural habits (personnel behaviors), and data analytics capability shortfalls. The introduction of predictive maintenance strategies such as reliability-centered maintenance and CBM+ represent a fundamental change to how maintenance operations are conducted in the Marine Corps and will face obstacles in addition to technical hurdles. Organizational change literature suggests that the adoption of any new system or maintenance practice will experience friction which can be seen in the current CBM+ implementation efforts. This observed friction necessitates a thorough review of organizational dynamics as they relate to CBM+ as a ground maintenance strategy and an evaluation of requirements for full implementation within the ground components of the Fleet Marine Force (FMF). The review will encompass the three pillars of CBM+, which are people, processes, and technology (HQMC, 2020a). If technological programs required to implement CBM+ are within reach and are currently being pursued, people and processes need to be prepared to support the full embrace of the condition-based and predictive maintenance strategy.

A. PROBLEM STATEMENT

The Marine Corps is not prepared in its organization-wide policies, processes, and personnel to be technology-empowered and data-driven in its maintenance strategies. The Department of Defense (DOD) has emphasized the need for the joint force to adopt CBM+ and enable data-driven decision-making (USD[A&S], 2020). Current Marine Corps policies and practices are designed to support preventative and corrective maintenance strategies, but they are not conducive to enabling effective CBM+ implementation. The addition of CBM+ technology will not cure the problem until the people and processes are prepared for this new maintenance approach. The Marine Corps still employs excessively long and wasteful

maintenance practices, which are then inspected and reinforced by HQMC through the Field Supply and Maintenance Analysis Office (FSMAO) inspection teams.

The DOD has been attempting to improve maintenance practices through the adoption of predictive technologies and models for nearly 20 years, but changes have been slow, and many of the lessons learned are currently stove piped within various branches and units. Case analysis from the implementation of condition-based maintenance (CBM) models in the civilian sector and in other service branches suggest that there are a variety of hurdles that organizations face during the adoption of new maintenance models (Stuetelberg & Thomas, 2021). Though CBM+ is not solely a maintenance system, the Marine Corps has faced challenges with the adoption of new technologies, as seen with Global Combat Support System-Marine Corps (GCSS-MC; Fincher, 2016). The Army and Air Force have separately been building predictive analytics capabilities and developing policies to enable CBM (Whitaker, 2019). Subordinate units within the Marine Corps have begun to execute policy and operating procedure updates based on the generalized CBM+ guidance available from HQMC, but the approach is not consistent across commands, and current “exceptions to policy” require additional risk to be assumed by the commander (3d Marine Logistics Group [3D MLG], 2021).

Limited research has been conducted into reviewing what comprehensive changes to policies and operating practices are necessary, specifically within the Marine Corps, to enable the successful implementation of CBM+. A few studies have explored organizational change within the DOD and the Marine Corps, implications of CBM in the private sector and the DOD, and the technological requirements to support CBM. Additionally, the Marine Corps conducted a CBM+ Capabilities Based Assessment (CBA) in 2015 and revalidated the assessment in 2020, which highlighted materiel and non-materiel requirements and gaps (HQMC, 2022). The CBA results call for further analysis into specific actions that leaders can take to empower maintainers for proactive CBM+ implementation.

The purpose of this study is to explore policy and procedural improvements across the Marine Corps required to support effective decision-making utilizing CBM+ in the FMF. We increase knowledge through interviewing subject matter experts (SME) and conducting thematic analysis of our interviews and literature. Based on the published experience of industry and best practices at various levels within the DOD, we observe identifiable barriers and

opportunities for change that impact CBM+ and provide recommendations for full implementation within the ground components of the FMF. Our recommendations will enable leaders to provide appropriate resources and attention to update and change policies for CBM+ implementation. The findings increase understanding of organizational change within the Marine Corps regarding the adoption of new strategies, technologies, and methods.

B. ORGANIZATION

Chapter II provides additional background and literature review of the origins of CBM+ and the initiatives that the DOD and Marine Corps have taken up to this point to implement CBM+ as a ground maintenance strategy. This chapter also provides a review of organizational change approaches that help guide perspectives and recommendations for the Marine Corps' organizational changes in maintenance strategy. Chapter III describes our methodology for interviews and our process for thematic analysis. Chapter IV details the findings and analysis drawn from key documents, scholarly work, and interviews that helped identify themes for barriers and opportunities for change. Chapter V provides a summary and recommendations concerning Marine Corps CBM+ implementation and how it can be achieved most effectively within its current context and operating environment. Lastly, chapter VI provides a summary of key discoveries and includes limitations with this project and suggestions for future research.

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VIII. BACKGROUND AND LITERATURE REVIEW

Condition-based maintenance (CBM) is not a new concept and was first discovered in the private sector in the 1940s in the Rio Grande Railway Company to detect leaks in engines in a predictive manner (Prajapati et al., 2012). DOD Instruction 4151.22 defines CBM as “a maintenance practice based on monitoring the condition of equipment to assess whether it will fail during some future period in order to take appropriate action to avoid the consequences of that failure” (DOD, 2020, p. 13). In essence, the goal of CBM is to perform maintenance only when there is evidence of need to improve the operational availability of equipment and reduce cost. The “plus” in CBM+ emphasizes the integration of technology that expands CBM to include a systems-engineering approach to collect data through embedded sensors to enable analysis and maintenance life-cycle decision-making. Essentially, CBM+ leverages technology to be more predictive with maintenance to further enhance operational availability, cost savings, and decision-making ability. In this paper, we reference both CBM and CBM+ intentionally depending on the context in which the term is written. When CBM is addressed, the focus is on monitoring the actual condition of an asset through visual inspections, tests, or analyzing performance data from the onboard sensor capabilities and tools the Marine Corps currently possesses to conduct maintenance and make decisions (HQMC, 2020a). When CBM+ is used, it is emphasizing the use of technology such as embedded sensors and data analytics capabilities that form an ecosystem in the maintenance process as well as referencing the naming convention of a policy or directive.

A. MARINE CORPS’ LEGACY GROUND MAINTENANCE STRATEGY

The focus of this paper is maintenance on ground transportation or motor transport (MT) equipment in the Marine Corps due to CBM+ implementation efforts have primarily been tested on MT equipment. MT is surface transportation using wheeled vehicles and it provides elements of the Marine Air-Ground Task Force (MAGTF) with tactical and logistical support to include transportation of people, equipment, and cargo (HQMC, 2001). Every tactical unit has organic MT capability, but combat service support units have larger inventories and greater maintenance requirements for MT equipment due to their support mission. MT equipment capabilities are expected to operate under all

environmental conditions to meet all assigned missions (HQMC, 2001). Maintenance is a critical logistics function that supports the ability of MT equipment to be operationally ready to accomplish its mission.

Marine Corps units currently conduct maintenance utilizing the MCO 4790.2, *Field-Level Maintenance Management Policy*, to direct their maintenance strategy and maintenance production processes and actions. MCO 4790.2 outlines a preventative and corrective maintenance strategy approach. Preventative maintenance (PM) refers to “maintaining equipment on a regular schedule based on elapsed time or counter reading,” also known as time-based maintenance (TBM) (HQMC, 2016, p. 3-1). Corrective maintenance (CM) is reactive and involves actions to restore equipment to a serviceable condition (HQMC, 2016). Under the corrective maintenance approach equipment is run-to-failure therefore it is unscheduled when a system or component breaks (HQMC, 2020a).

The current primary metrics to measure overall performance in maintenance is maintenance cycle time (MCT) and equipment readiness. In MCO 4790.2, MCT is defined as “the period of time covered from the initiation of maintenance actions until repairs and maintenance records are complete. Maintenance cycle time begins when the equipment is inducted/accepted into the maintenance activity and ends upon the closeout” (HQMC, 2016, p. 3-5). Equipment readiness, also referred to as operational availability (Ao), is the second primary metric to measure maintenance performance. Equipment readiness or Ao is the total number of a selected equipment type possessed and “mission capable” divided by the total possessed. In simpler terms, readiness indicates the materiel condition of an organization’s possessed equipment (MCO 3000.13B, 2020).

B. CBM+ ORDERS AND DIRECTIVES

The DOD realized the value of a CBM+ maintenance strategy from industry and then made its first initiative to implement CBM+ in November 2002 through a memorandum for the secretaries of the Military Departments titled *Condition Based Maintenance Plus*, which was published by the Deputy Under Secretary of Defense (Logistics and Materiel Readiness) (DOD, 2008). In January 2004, the military services nominated programs to serve as lead for CBM+ research; the Marine Corps selected the Expeditionary Fighting Vehicle (EFV) and the Light Armored Vehicle (LAV) (Cutter & Thompson, 2005). These programs informed CBM+ implementation recommendations in

a CBM+ Select Program Survey conducted by LMI Government Consulting in 2005. Subsequently in 2007, the DOD issued DOD Instruction (DODI) 4151.22, *Condition-Based Maintenance Plus (CBM+) for Materiel Maintenance*, which required all Military Departments to implement CBM+ for new weapon system acquisitions while integrating it into existing weapon systems where it was feasible and beneficial (DOD, 2008). Following the DODI 4151.22, the *Condition-Based Maintenance Plus DOD Guidebook* was published in May 2008 to support the Military Departments in their implementation of CBM+ strategy (DOD, 2008). In January 2020, the Marine Corps published MCO 4151.22, *Condition Based Maintenance Plus Order*, to take the next step in implementation (HQMC, 2020a). Most recently, the Secretary of the Navy released a memorandum on May 26, 2022, *Actions to Improve the Department of the Navy Sustainment*, stating, “We must move forward aggressively to adopt and deploy CBM technologies” (Secretary of the Navy, 2022, p. 3).

Department of Defense Directive 4151.18, *Maintenance of Military Materiel*, was published March 21, 2004, and reissued August 31, 2018, in order to reestablish policy and responsibilities associated with performance of DOD maintenance for systems. Change 1 to the directive reassigned the office of primary responsibility for the directive to the Undersecretary of Defense for Acquisition and Sustainment (DOD, 2018a). With a focus on improving the life cycle of military materiel, DOD Directive 4151.18 emphasized the need to adopt corporate business practices that would improve maintenance operations within the DOD. The focus of the practices targeted for adoption was to allow for cost savings, reduced maintenance cycle-time, and increased operational availability through investment in new technologies and corresponding policy updates. Commercial procurements and public-private partnerships were specifically encouraged by the directive to encourage adoption of private-sector practices that would improve the DOD maintenance posture.

The directive highlighted the need to review and implement data-driven reliability models with technology connecting metrics to decision-makers.

Maintenance programs for materiel maintained for the Department of Defense shall facilitate, collect, and analyze maintenance-related reliability data. The programs shall include sufficient analytic capability

for identifying needed adjustments based on operating experience, materiel condition, and requirements for reliability, maintainability and supportability modifications, and changes to training curricula or delivery methods. The programs shall provide maintenance activities as the means for assessing information generated by prognostic and diagnostic capabilities and for taking appropriate maintenance actions. The programs shall also establish and evaluate performance metrics that promote continuous improvement in maintenance, ensuring responsiveness and best value to operating forces. (DOD, 2018a, p. 5)

Over the last couple of years, the Marine Corps has made deliberate efforts to advance CBM+ implementation by establishing a dedicated CBM+ team at Headquarters Marine Corps Installations and Logistics (HQMC I&L) to lead and collaborate efforts with other key stakeholders including industry, academia, Marine Corps Combat Development Command (MCCDC)/Combat Development and Integration (CD&I), Marine Corps Systems Command (MCSC), and the FMF. This was energized by the commandant, General Berger, in April 2020, with the issuing of White Letter 2–20 titled *Achieving Condition Based Maintenance*, which lays the foundation for CBM+ scaling and to fully embrace CBM+ (HQMC, 2020b). The Marine Corps’ initial CBM+ strategic implementation plan entailed three phases occurring between 2020 and 2023 that involved conducting a minimum viable product (MVP) utilizing 10 MTRVs and 10 JLTVs, then expanding the MVP and data scaling to 300 JLTVs and MTRVs across the Marine Corps operational forces, and later expanding CBM+ to other systems (HQMC I&L, 2021).

In April 2020, the Commandant of the Marine Corps (CMC) published a white letter with the subject of *Achieving Condition Based Maintenance*. The letter highlighted the creation of Marine Corps Order (MCO) 4151.22 which established Condition Based Maintenance Plus (CBM+) as a Marine Corps policy. The CMC reiterated this message with a one-page white letter published in February 2020 that addressed the intentional approach with which CBM+ needed to be pursued for implementation. “CBM+ is an industry-proven concept that represents a deliberate shift from reactive equipment repair to a proactive, predictive approach. Simply put, it is maintenance based on evidence of need. ... Getting to this future state will require an organized and sustained effort across the Corps” (HQMC, 2020b). This letter came on the heels of the Marine Corps’ *Condition Based Maintenance Plus (CBM+) Order* published in January 2020 (MCO 4151.22) to

achieve buy-in across the enterprise in an effort for total force implementation (HQMC, 2020a).

The Marine Corps CBM+ order provided directive guidance to initiate the DOTMLPF-P process for CD&I. The process would focus on the methods and processes needed for execution and scaling of CBM+ in the Marine Corps. Commanders, maintainers, and the FMF were directed to MCO 4151.22 for additional guidance and received the following commander's intent:

Achieve the total force implementation and integration of CBM+ concepts throughout the integrated total life cycle framework. This Order will leverage people, processes, and technologies to integrate CBM+ and Reliability Centered Maintenance (RCM) within the Marine Corps' maintenance program to increase operational availability and support to the warfighter. CBM+ includes both hardware and software components... Successful implementation is reliant on data collection and information management practices implemented in accordance with reference (g), and technologies that will provide operational planners, operators, maintainers, maintenance managers, and program managers the right information to maximize the operational availability of MAGTF's PEIs. (HQMC, 2022a, p. 1)

Per the intent, the three pillars for CBM+ are people, processes, and technology, but the primary focus of the order was on data aggregation and acquisition efforts of data logging systems. The heavy focus on technology solutions remained present in the MCO 4151.22 definition of CBM+, which emphasizes the *plus* of CBM+:

To be most effective, CBM+ requires processes, technology, and capabilities that support RCM analysis and maintenance decision-making. These requirements may include but are not limited to: (1) Automated Information Systems (AIS) for maintenance data collection and process analysis, (2) sensors embedded within equipment platforms to provide operators, crew and maintainers enhanced visibility of equipment condition, and (3) portable equipment to conduct external tests and measurements to support RCM analysis. Accordingly, the Marine Corps will acquire or develop Automatic Identification Technology (AIT) and other test, measurement, and diagnostic equipment, and integrate it with existing and emerging AIS to automate and enhance data collection and sharing to support CBM+. (HQMC, 2022a, p. 3)

The order presents data assessment tools as an initial step in CBM+ implementation that will inform processes and procedures rather than a two-way relationship and does not

provide guidance on how processes are meant to be evaluated or updated prior to the arrival of technology solutions. The order provides the following tenets of CBM+, which link closely to change strategies and can potentially be leveraged for strategic communications about CBM+ implementation:

1. Vision - Establishes CBM+ as the department's key strategy for sustaining weapon system readiness at best cost.
2. Strategy, Policy, and Planning - Clear and strong guidance, including policy, strategy, action plans, and road maps at all levels, underlies the successful planning, implementation, and sustainment of CBM+ execution.
3. Organization - CBM+ execution requires a holistic and systematic approach spanning multiple organizations, functional disciplines, and communities.
4. Resources - Sufficient personnel and funding are essential for development, planning, implementation, and sustainment of any systemic effort.
5. Technologies and Tools - Appropriate tools and technologies are necessary to execute CBM+ successfully.
6. Workforce - A workforce trained on basic CBM+ principles is essential.

(HQMC, 2020a, p. 2-16)

Despite the numerous initiatives, policies, instructions, a guidebook, and orders published since 2002, full implementation of CBM+ strategy has not yet been realized. An audit report of the DOD's implementation of predictive maintenance strategies to support weapon system sustainment was completed on June 13, 2022 and highlighted that there are still significant actions required across the Military Departments to transition to a CBM+ maintenance strategy (DODIG, 2022). The report stated that progress has been made but DOD officials did not "develop comprehensive strategic plans," lacked "full visibility of CBM+" projects, and did not "develop training tailored to the appropriate levels in the life-cycle sustainment workforce" (DODIG, 2022, p. 9). Additionally, the DODIG (2022) report identified the challenge of the DOD's transition from a TBM and "run to failure maintenance culture to a predictive maintenance culture" as one of several barriers

(DODIG, 2022, p.9). Other challenges to CBM+ implementation identified in the audit report were a “lack of accurate and usable data and algorithms to make maintenance forecasts,” “lack of a standardized method to distinguish parts removed based on predictive forecasts,” and “limited funding and resources” (DODIG, 2022, p. 9). These findings reveal that there has been a lot of activity, resources, and information published surrounding CBM+, but one of the most significant hurdles is the complete transition from old maintenance practices to newer and more relevant maintenance practices and strategies. There are cultural barriers and organizational inertia factors that need to be identified and resolved.

C. GCSS-MC LESSONS LEARNED

A comprehensive review of the Marine Corps’ adoption of Global Combat Support System–Marine Corps (GCSS-MC) by the Institute for Defense Analyses (IDA) published September 2018 provided many lessons learned that can be applied to the adoption of new information technology systems in the Marine Corps. The initial intent for GCSS-MC was to replace legacy supply and maintenance programs still in active use from the 1970s with the added potential goal of continuing to develop the platform to support all logistics chain management functions for the Marine Corps, including finance and manpower management activities, under a single system (Aronin et al., 2018). Treating GCSS-MC as an all-encompassing enterprise resource planning (ERP) software program for supply and maintenance activities meant a reliance on master databases and simultaneous information updates that would bring with it inherent complexities. As stated in the IDA report,

It is generally not possible for an organization to procure a package of ERP software and simply install it with in-house expertise. Most organizations know they will need outside help but there is no single recipe for how to plan for a conversion, pick the software required, configure that software to perform the needed functions, and transition from current processes to the new set of processes. (Aronin et al., 2018, p. 9)

The IDA report emphasized the importance of having the appropriate processes and people in place to effectively receive and implement new technologies.

Due to the complexities outlined in the document, GCSS-MC required an extended timeline for implementation with multiple releases, updates, and verification of data over

years. The initial Milestone A software procurement approval for GCSS-MC was granted July 2004, but the initial operational test and evaluation (IOT&E) with III MEF was not conducted until May–August 2010, with follow-on adoptions at II and I MEF in subsequent years (Aronin et al., 2018). A key lesson from this case is that there is a significant gap between original consumers for commercial off-the-shelf (COTS) products and the differing requirements the Marine Corps as a consumer would demand. Flexibility in terms of user functionality and interface were necessary for GCSS-MC adoption and will remain requirements for adoption of follow-on information systems. Additionally, the ability to support a detached user is crucial for any systems to be employed in an expeditionary environment that would have either limited or no data connectivity. A mobile capability that could operate on stand-alone systems will also need to be able to support to scale the dynamic demands placed on equipment that often surpass more predictable in repetitive environments in industry. The ability to scale not only applies to the physical equipment such as sensors, but the data processing and analytics capability to make use of the system. This means that transition will be drawn out over an extended period and often simultaneous operation of both new and legacy systems. Complex decisions of how to phase the implementation of an ERP will need to be made.

The report compiled eight conditions for successful implementation for GCSS-MC, the Marine Corps had achieved less than half of those conditions at the time of the report (Aronin et al., 2018). This would read very similarly for the implementation of CBM+ in the Marine Corps and DOD with positive indicators in sustained involvement by senior leadership and willingness to make decisions regarding the implementation of the system, but several negative indicators for successful adoption as well. The Marine Corps would likely be assessed an observable failure regarding the organizational operating model (structure, processes, and policy) aligning with the implementation of a new data system and regarding a strategy that addresses the fundamental root cause of problems with the Marine Corps maintenance cycle. For full implementation of a program, trade-offs need to be made to continue to advance automated information systems: “either military processes must change to be compliant with those in the commercial world or an organization must bear the cost of developing and maintaining custom solutions for their unique but essential processes” (Aronin et al., 2018, p. 12). Lessons learned from the adoption of GCSS-MC

can apply to additional technology integration efforts and provide valuable insights into further Marine Corps organizational change initiatives.

D. CBM+ PRIOR RESEARCH

Whitaker (2019) applied the concept of automated data collection and data analysis to provide real-time monitoring of maintenance conditions for a given piece of ground equipment. The thesis demonstrated that COTS sensing hardware and openly available software can support the data collection and processing requirements necessary to develop an implementable CBM framework for platforms in the Marine Corps. Though the focus of the research was centered on a single statistical model for the Marine Corps Medium Tactical Vehicle Replacement (MTVR) engine, the research demonstrated the utility of data aggregation to identify maintenance trends and improve operational availability of a given component. The research was limited in recommendations for practical implementation, but briefly outlined a CBM “policy that can be used to enhance preventative maintenance methods and decision support capabilities on Marine Corps ground equipment” (Whitaker, 2019, p. v).

It is worth noting that implementation of CBM+ has not garnered universal, immediate success in all organizations that have adopted the maintenance model. Meyer Zu Wickern, in 2018, identified five challenges consistently facing predictive maintenance adoption based on observations in the private sector: “financial and organizational obstacles,” “data source limitations,” “limits of machine repair activities,” “optimization narrowness,” and “sentiment towards challenges and outlook” (Meyer Zu Wickern, 2018). The struggles faced in the private sector echo those of the Marine Corps with GCSS-MC and are cautionary tales to the deliberate nature with which the Marine Corps needs to approach CBM+.

In a study of CBM for land force vehicles for the Australian government, Rajesh and Francis (2012) identified a litany of challenges that implementation of CBM would face. While many of the challenges required technical solutions, multiple challenges arose from organizational inertia and required redress through policy and management solutions. These challenges included cost-benefit analysis that holistically captured CBM implementation; the initial high capital cost; the size of the fleet of vehicles subject to CBM implementation; adoption of transitional technologies while not having an immediate

demand signal for acquisition; changes to maintainer skill requirements; identification of the who, what, and how frequent for data requirements; and the lack of overarching CBM policies (Rajesh & Francis, 2012).

Inroads have been made in the Marine Corps regarding the generation of policy, planning groups to identify data requirements, and the conduct of cost–benefit analysis. However, the size of the fleet of vehicles and the intention of a total force implementation remain concerns for the Marine Corps. Different levels of implementation will need to occur with a judicious approach in targeting and prioritizing platforms that would be candidates for a shift in the maintenance strategy.

Stuetelberg and Thomas (2021) conducted a similar study into industry predictive maintenance best practices that could be incorporated into the Marine Corps. While information technology infrastructure was an area that requires considerable investment for effective CBM implementation, the study emphasized the need for the effective application of ERPs. Substantial attention should be given to how the user will interface and make decisions with the data collected by sensors and how a predictive maintenance approach will require adjustments to manpower, training, and procedures (Stuetelberg & Thomas, 2021). The Marine Corps needs to be methodical in its approach and have a deliberate process for trade-off decision points regarding the retrofitting of legacy platforms with sensing technologies.

Approaches and phases with implementation vary widely in industry. Shin and Jun (2015) defined the approaches for implementation as data-driven, model-driven, and hybrid. There is a balance to be struck between the data-driven approach, which has a heavy dependency on the quality of the operational data, and the model-based approach, which incorporates a physical understanding of the platform (Shin & Jun, 2015). Regardless of the model chosen for implementation, there are common conditions that need to be in place prior to adoption. One of the first conditions is to determine which data needs to be captured and which MCTs are appropriate for a given platform. This data will help inform the decision method for determining which maintenance option is most cost-effective. Therefore, preventative maintenance is still a component of a predictive maintenance strategy. Additionally, a decision needs to be made based on the specific platform as to

whether CBM is effective for a given platform or part since it is not effective in all cases (Shin & Jun, 2015). As identified in Stuetelberg and Thomas (2021), preventative maintenance models may particularly serve better in instances of limited data collection or compilation capability. CBM, as it is adopted on a by-platform basis, will need to be implemented with consideration for the impacts to other maintenance cycles, personnel, and procedures for related systems. In adopting integrated systems, we need to be particularly cautious when considering CBM+ implementation and ensuring execution aligns with the holistic maintenance strategy.

While CBM+ is heavy with data analytics through growing IT infrastructure and cloud-based computing, CBM+ application is more than just a software solution. Experience from USAF program adoptions point to CBM+ as a “maintenance toolbox” that requires cultural change and adjustments to current maintenance inspection models to succeed (Dayton Aerospace, 2018). Individual platforms will require systematic platform-specific approaches to address key CBM+ enablers such as infrastructure and policies.

E. ORGANIZATIONAL CHANGE APPROACH

There are numerous models and frameworks published that can be used to help facilitate organizational change. The approach that guides this analysis of organizational change in the Marine Corps concerning CBM+ implementation is primarily from internationally recognized experts in strategic change and leadership, Michael Beer and John Kotter. Both experts have served as Harvard Business School professors and have conducted extensive research projects, case studies, and written numerous books and articles on the topics of leading change and organizational effectiveness. Their works have proven to help organizations execute successful large-scale change initiatives over the past several decades. The combination and integration of their change models or frameworks provide a practical guide to help the Marine Corps implement change toward CBM+ within the organization.

Michael Beer, in his 1988 *Harvard Business Review* article, *Leading Change*, provides a conceptual formula that outlines the critical dimensions of change that must be considered for organizational change to be successful (Beer, 1988):

$$\text{Amount of Change} = (\text{Dissatisfaction} \times \text{Model} \times \text{Process}) > \text{Cost of Change}$$

Beer's formula describes in simplest terms that for organizational change to be successful, the amount of change required must be stronger and more compelling than the cost it takes to change (Beer, 1988). The "Dissatisfaction" element of the formula relates to the level of dissatisfaction the key organization members have with the status quo of their current state. There needs to be a deliberate effort to increase the level of dissatisfaction with the status quo which can be raised in numerous ways. Beer asserts that information and data about the organization's performance and its environment should reveal the current and prospective problems, and then discussions should be generated to elevate the impacts. "Information about the concerns of employees and their perceptions about how the company is being run can be a powerful tool for creating 'dissatisfaction' among managers" (Beer, 1988). Beer further contends that relying solely on data alone is not sufficient; there needs to be a dialogue about the meaning of the data to reveal underlying assumptions and come to a shared explanation of stakeholder difficulties within the organization.

The "Model" in the formula refers to a vision of the future state of the organization. This includes the behaviors, attitudes, structures, and systems that must be developed for change to occur. Beer stated, "The future state envisioned should reflect the multidimensional nature of organizations" (Beer, 1988). The vision developed needs to connect with the people in the organization and address the numerous dimensions of the organization. It is valuable to have an organizational unit that exhibits the success of the change envisioned to build credibility and be an example for other organizational units to learn from.

The "Process" in the formula recognizes that organizational change takes time to see results. Beer describes, "the process for change is a *sequence* of events, speeches, meetings, educational programs, personnel decisions and other events aimed at helping employees, including top management, learn new perspectives, skills, attitudes, and behaviors" (Beer, 1988). He further emphasizes the benefit of involving people within the organization in developing the processes of change noting that people will become more committed when they are part of creating the solutions. A well-planned process that is shaped by the participation of people in the organization provides a greater chance of successful change.

Lastly, the “Cost of Change” in the formula indicates the losses stakeholders expect because of change. Beer explains typical losses stakeholders experience due to organizational change being power, relationships, rewards, and identity (Beer, 1988). Beer states, “it is the fear of losses that is the cause of resistance to change” (Beer, 1988). Therefore, to achieve successful organizational change a good understanding of the resistance level is necessary to determine the strength in dissatisfaction with status quo, vision, and processes to overcome the cost of change.

Kotter’s 2012 eight-stage process of creating major change reinforces and describes in greater detail the practical application of Beer’s conceptual formula. Kotter asserts that each of these eight process stages needs to be achieved to create enduring change within an organization. Additionally, Kotter’s examination of success stories has revealed two important patterns regarding organizational change. First, in alignment with Beer’s formula, Kotter states that, “useful change tends to be associated with a multistep process that creates power and motivation sufficient to overcome all sources of inertia” (Kotter, 2012, p.22). Second, change must be “driven by high-quality leadership, not just excellent management,” for a change process to be employed effectively (Kotter, 2012, p.22). These two important observations, backed by extensive research, are used to underpin recommended solutions to implementing change in the Marine Corps. Figure 1 is a summary table of the eight-stage process as well as an in-depth description that will guide recommendations.



Figure 6. John Kotter's 8-stage process for leading change. Source: Kotter (2012).

A key factor of effective change that is often overlooked or underappreciated is the *heart of change* (Kotter & Cohen, 2002). Most change initiatives in large organizations place the heaviest focus on policy, process, structure, operations, data, and analysis and not enough on things that appeal to emotions and inspires people in the organization to act and change. John Kotter and Dan Cohen, understood the significant value and importance of connecting with people's emotions to spark behavior change and action that leads to success, so they wrote a book called *The Heart of Change* and an accompanying field guide. Change can be very hard, therefore successful transformation cannot solely be accomplished by structural and operational changes within the organization, but people's behaviors also need to change (Kotter & Cohen, 2002). Changing behaviors requires

intentional focus on connecting with people and providing them a compelling vision that positively impacts them and the organization as a whole in the long run.

The Heart of Change outlines two approaches to change: “analysis-think-change” and “see-feel-change” (Kotter & Cohen, 2002). Most companies in the business world and in military or governmental organizations lean toward “analysis-think-change” methods. However, the “see-feel-change” method which targets people’s emotions caused behavior change more so than “analysis-think-change.”

In a 2021 published book by Kotter titled, *Change: How Organizations Achieve Hard-To-Imagine Results in Uncertain and Volatile Times*, he dives into the science of change and how that impacts success (Kotter et al., 2021). After extensive research and observations of hundreds of companies Kotter states, “Without sufficient communication of a rational and emotionally compelling case for change, it was nearly impossible to achieve buy-in that inspired and mobilized the action required to drive and sustain difficult changes” (Kotter et al., 2021). He goes on to say, “We have seen that the most successful large-scale change efforts start with a clearly articulated, compelling, and emotionally inspiring opportunity.” A key concept emphasized in Kotter’s study on change, is the focus on communicating the opportunities that the change provides. This opportunity seeking communication reinforces a compelling vision to initiate and maintain momentum for behavior change which leads to holistic organization change.

F. 3D MARINE LOGISTICS GROUP CBM+ IMPLEMENTATION

The Commanding General for 3d Marine Logistics Group (MLG) published the *3d MLG Condition Based Maintenance Plus (CBM+) Implementation Report* 14 October 2022 (3d MLG, 2022). The report captured the results of modified maintenance induction processes for “D” Table of Authorized Materiel Control Number (TAMCN) equipment at 3d MLG over the previous year in concert with a policy waiver. The policy waiver will be later referred to in our paper as an exception to policy (ETP), for MCO 4790.2 granted by the Deputy Commandant Installations and Logistics (DC I&L) and provided detailed data and recommendations for process improvements. In the absence of immediately available technology that supports CBM+ efforts, the 3d MLG CBM+ strategy focused on people and process improvements. An example of 3d MLG’s improvements was the removal of non-value-added administrative steps in the maintenance cycle which minimized

maintenance costs, reduced maintenance cycle time, and improved production. Change effort successes were measured in improvements to the maintenance downtime, preventative maintenance monetary costs, labor man-hours, and days in the administrative maintenance process as seen in Table 1.

Goal Name	Measurable Points	Pre-CBM+ Avg	Goal	Post-CBM+ Avg
Balance Maintenance Effort	CM Days Deadline	44.25 Days	30-70 Days	24.2 Days
	PM Cost	\$ 85K	\$ 75K	\$ 32K
	PM Man-Hours	3176 Hours	2,150 Hours	83 Hours
Reduce Days in Shop	DRIS to SR Close	103.56 Days	50-70 Days	27.46 Days

Table 3. Executive summary results 3d MLG 2022 report. Source: 3d MLG (2022).

The report was able to display year-over-year improvements in MCT, days in shop, and days deadline as a result of CBM+ process improvements. Figure 2 presents the trends in maintenance cycle from 2017 through 2022.

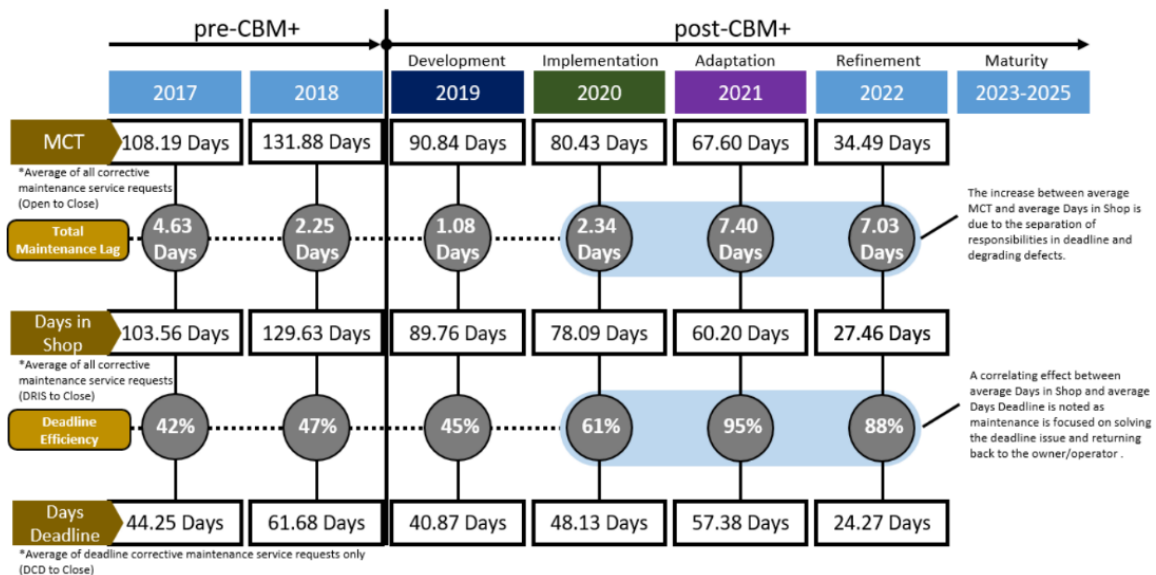


Figure 7. 3d MLG Pre-CBM+/Post-CBM+ CM Data Metrics. Source: 3d MLG (2022).

The 3d MLG report identified lessons learned and provided recommendations for scaling efforts to be adopted in the Marine Corps. Key takeaways from the report include

the importance of capitalizing on incremental gains, incorporating stewardship/ownership in CBM+ implementation efforts, adequate communication about and training for changes to the maintenance strategy, and engagement with leaders to ensure changes are adopted.

While the 3d MLG ETP period only applied to D TAMCNs at a single major subordinate command (MSC), the improvements and efficiencies achieved through process change and people development, reflect a functional approach to CBM+ that is primed for incorporation at the enterprise-level. In his endorsement on the report, the Commanding General for 3d MLG, Brigadier General Adam L. Chalkley, advocated that, “3d MLG has marked out a trail for the enterprise to follow to achieve the future state of maintenance in more minor distributed elements. Additionally, 3d MLG CBM+ implementation demonstrates that immediate positive results will occur when embraced by the service” (3d MLG, 2022). The lessons learned from 3d MLG are revisited in the fourth and fifth chapters of our paper.

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IX. METHODOLOGY

We reviewed Marine Corps policies, practices, and organizational structure to identify key roles, information flows, and policy directives in the maintenance community that influence maintenance decision-making and CBM+ implementation. We furthered our understanding by interviewing military and civilian SMEs within the FMF, supporting establishments, and other DOD organizations. We identified and synthesized themes and patterns in the information collected. Then we conducted thematic analysis to identify barriers to and opportunities for change within the Marine Corps maintenance community. An organizational change approach and a theoretical concept of successful change principles informed our development of recommendations for implementation to lead to effective CBM+. The major steps of the methodology were:

1. Identify key roles based upon Marine Corps structure and SMEs associated with each role.
2. Review relevant guidance and policy procedure documents.
3. Conduct interviews with SMEs to address research questions.
4. Capture trends from SME responses.
5. Synthesize and analyze (based on organizational change models).
6. Identify significant barriers to adoption (thematic analysis).
7. Make recommendations for implementation.

A. CBM+ KEY STAKEHOLDERS

CBM+ implementation requires the actions and decisions of several stakeholders throughout the Marine Corps organization from Headquarters Marine Corps (HQMC) down to unit level commanders, staff, maintainers, and operators. Marine Corps requirements are generated from office of Combat Development and Integration (CD&I), directed by a lieutenant general acting in the capacity of Deputy Commandant (DC) CD&I. With respect to CBM+, there is a Materiel Readiness Branch, Logistics Combat Element Integration Division, that facilitates and creates the requirements documents. These requirements documents influence and drive the policy and acquisitions decisions. Policy

is established at the HQMC level, therefore policy concerning maintenance in the Marine Corps is published within the HQMC Installations and Logistics (I&L) office directed by a Lieutenant General acting in the capacity of DC I&L. Acquisitions is the responsibility of Marine Corps Systems Command (MCSC), commanded by a Brigadier General. In October 2022, a CBM+ Program Office was established to support the implementation of CBM+ by procuring the technology and equipment necessary to fulfill the CBM+ requirements published by CD&I.

Key stakeholders in the Marine Corps operational forces include the Marine Expeditionary Forces (MEF), primarily the Commander and G-4 leaders; the Major Subordinate Commands (MSC) which include the Divisions, Marine Logistics Groups, MEF Information Groups (MIG), and the Marine Aircraft Wings (MAW). Additionally, leaders, key staff, and maintenance personnel resident in the regiments and battalions contribute to the success of CBM+ implementation and execution. The MEF G-4 and staff are responsible for directing actions within the MEF to improve the materiel readiness which includes close coordination with weapon system program offices for guidance as well as disseminating policy direction to subordinate commands. It will be vital for the MEF G-4 to understand the CBM+ vision and proper execution to effectively communicate CBM+ implementation efforts to the MEF leadership and subordinate elements.

B. RESEARCH PARTICIPANTS

Fifteen maintenance and logistics Marines were interviewed during the research process. Interviews ranged from an hour to two hours with select interviewees being interviewed a second time. At the enterprise level, six Marines were interviewed with participation from individuals at HQMC CD&I, I&L, and SYSCOM. At the Major Subordinate Command, two senior Marines and a senior logistics analyst were interviewed. At the operational unit level, six maintenance officers and three maintenance chiefs were interviewed. Interviewees were selected based on prior knowledge and experience with CBM+ implementation efforts within the Marine Corps. Most respondents were selected from 3d MLG and were participants in 3d MLG's implementation process. Participants within 3d MLG were able to juxtapose CBM+ practices with legacy maintenance policies using experiences prior to and after their time with 3d MLG. Interviewees had an in-depth understanding of legacy maintenance strategies and CBM+ implementation.

C. INTERVIEW QUESTIONS

The questions developed for interviews conducted with SME and key billet holders were based on the following two overarching research questions:

- Primary Research Question: What are the key factors impacting CBM+ implementation in the Marine Corps? What decisions and actions can the organization and leaders take to support the management of CBM+ adoption?
- Secondary Research Question: If we make the assumption that technological systems required to implement CBM+ are within reach, what business processes need to be in place to facilitate the CBM+ maintenance strategy?

The below set of questions were asked of all participants:

1. What is your billet and unit? What prior experience or exposure do you have with CBM+ and legacy maintenance practices?
2. How would you define or explain CBM+?
3. Has your unit utilized the CBM+ MCO and guidebook? Is it integrated in your SOPs? If so, how long has it been integrated and how are the concepts employed?
4. How/what do you perceive the overall vision for CBM+ in the Marine Corps? Is it compelling? What do you find compelling about the maintenance strategy?
5. What are the critical drivers for maintenance practices and processes within the Marine Corps? Do the drivers create an effective sense of urgency at your command?
6. What would create a greater sense of urgency for CBM+ adoption? Is the burden of the status quo greater than the cost to change? What competes for focus of effort with CBM+ adoption?
7. How are CBM+ processes being employed within your command? How does this differ from previous commands and adjacent commands?
8. What enabled the implementation of the CBM+ processes?

9. What challenges have you experienced in executing CBM+?
10. What data do maintenance decision makers need to inform improving operational availability? Are we able to harvest that data with current technology and tools? How would condition data need to be presented to leaders?
11. Does CBM+ change how readiness is presented to commanding officers and other leaders within the organization? What understanding do commanders need of CBM+ and the Marine Corps' maintenance strategy?
12. Is there friction in the readiness reporting process that will impede CBM+ adoption? Does readiness reporting need to change and how?
13. Is change to maintenance policies by incorporating CBM+ a disruptive process that impacts operations or is it an incremental change? Is there a tolerance level for disruptive change to maintenance strategy?
14. How do ground units and higher headquarters interact regarding ground maintenance? How are lessons learned and process improvements communicated unit to unit? How are lessons shared and promulgated across the enterprise?
15. How do inspections influence the decision-making process by maintenance personnel and leaders within the organization?
16. What other barriers or change opportunities exist within the organization that could impact the success or failure of CBM+ as a maintenance strategy?
17. What singular change could have the greatest influence on CBM+ adoption?

D. THEMATIC ANALYSIS

Responses from interviewees were consolidated into two overarching categories of barriers and opportunities for change. Under each category common themes were determined based on frequency of response from interviewees and emphasis placed during interview sessions. The themes presented in chapter IV reflect a combination of our interviews and organizational change literature. Our recommendations offer a response to these themes.

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X. FINDINGS AND ANALYSIS

The findings and analysis presented in this chapter are organized into eight major themes that were discovered during the interview and research process. The eight themes are split into two categories; barriers identified and opportunities for change. Analysis of our themes is presented through an organizational change approach as it applies to CBM+ and Marine Corps maintenance strategies. Recommendations related to these themes will be outlined in the subsequent chapter.

A. BARRIERS IDENTIFIED

In our interviews and research four major themes emerged as barriers to CBM+ implementation in the Marine Corps. The first theme was a lack of clear and consistent understanding of CBM+ across the FMF. The second theme was conflict between various orders and policies that delineated Marine Corps maintenance strategy. The third theme identified how inspections heavily influence maintenance actions at the operational unit level. The final theme highlighted the effects competing priorities have on focus and capacity necessary to change maintenance strategies.

1. CBM+ Not Understood Throughout the FMF

Gaps in the CBM+ policy, emphasis on technology solutions, and legacy maintenance practices prevent a clear understanding of the CBM+ vision and maintenance strategy. There appears to be a stove-piping of efforts to adopt CBM+ which has led to a slowing of implementation efforts. Slowed implementation efforts can be tied to an inconsistent interpretation of the vision for CBM+ in the Marine Corps, which varied based on respondents, billets, and duty station. In various parts of the organization, the CBM+ vision is incomplete, not fully understood, or ineffectively communicated throughout the organization. This incongruity is characteristic of maintenance practices in the Marine Corps and was observed in the 3d MLG report.

There was a complete compartmentalization and disassociation of focus of effort, alignment of priorities, organizational cohesiveness, and integration/unification of perspectives in the tactical maintenance effort. This contributes to the proliferation of the layering of additional responsibilities on the maintenance activity serving as an additional maintenance management check and backstop for owner/operator

maintenance. There is an institutional culture of accepting the current maintenance policy without questioning the value process steps in the greater mission of combat readiness, material condition maintenance, and data inputs/capture. (3d MLG, 2022, p. 101)

3d MLG's observation highlights the added administrative burden and requirements placed on maintainers which results from separate and sometimes conflicting visions of the Marine Corps maintenance strategy.

Maintenance officers interviewed expressed that there were different visions of CBM+ implementation in the Marine Corps between HQMC elements and operational units. The most important difference is between a focus on processes versus a focus on technology as the prioritized effort for accomplishing the vision. One interviewee summarized,

So the focus is technology at the high level, and at the 3rd MLG level, my level, it was focused around process and change management, change expectation management, because it's not going to fix you overnight. It's going to take time to get to where we need to be. But I don't think technology is the answer right off the bat. I think we change our process. (Maintenance SME, interview, 2022)

In developing 3d MLG's implementation plan, policies were crafted to nest within the CBM+ implementation intent and provide an obtainable pathway to achieve the vision. The 3d MLG CBM+ implementation report summarized the need for executable policy to address gaps in the enterprise implementation plan.

The policy represents the organization's "what" in terms of the goal and intentions of the program. The policy to be effective must be set at the highest level available. Therefore, 3d MLG had an enterprise policy that stipulated an overarching goal but did not necessarily provide more tactical implementation guidance. 3d MLG carefully built upon the enterprise policy and filled in the gaps focusing on people and processes. (3d MLG, 2022, p. 65)

3d MLG's ability to execute CBM+ implementation was through a focus on people and processes with intermediate guidance by the MSC to enable unit level execution. However, outside of 3d MLG and HQMC, maintenance officers and chiefs agreed that the CBM+ vision is not being successfully communicated throughout the FMF. A maintenance officer interviewee expressed that, "the vision of CBM+ is not being received at the lowest

level. They do not know what CBM+ is” (Maintenance SME, interview, 2022). In most cases, unless a unit is part of a proof of principle, the CBM+ order and guidebook are rarely used or applied to local maintenance practices. Interviewees suggested the lack of knowledge or engagement with the CBM+ vision across the FMF was closely associated to a perceived lack of immediate usefulness (HQMC, interview, 2022). The perception is that CBM+ appears as a technology centered program that will be available in the future rather than a process that can be applied to current practices for immediate gains. Credible feedback from the FMF is not being implemented in policy to further enable implementation. 3d MLG found that,

Changes must be able to be generalized enough to be portable and transferable from garrison to the field and back, as well as capable of implementation across the force both horizontally and vertically. However, interpretation cannot be so general that it becomes ineffective. A balance must be initiated where it isn’t ‘one size fits all.’ (3d MLG, 2022, p. 60)

Changes to maintenance practices and policies in the Marine Corps to implement CBM+ as a strategy must be digestible with clear intent and goals. For change to maintenance strategy to be fully accepted, disruptive thinking needs to be embraced as a part of the culture put forth by the vision for CBM+ adoption. 3d MLG described the relationship between disruptive thinking and CBM+ policy changes as follows:

This analysis has been a catalyst for disruptive thinking among motor transport professionals responsible for accomplishing and sustaining operations. As more Marines are exposed to the science, theories, and principles, we observe a change in how thinking, questioning, and knowledge are incorporated into day-to-day mission execution. The strength of this analysis is best revealed when the Marines no longer accept the established status quo and begin to question the “how” and “why” of the current paradigms with a desire to improve maintenance processes and outcomes. In many ways, this thinking has ushered in a renaissance in maintenance execution re-design for distributed operations and how those techniques/methods influence outcomes. (3d MLG, 2022, p. 100)

A key component of CBM+ that is not currently emphasized in the vision is the empowerment of Marines and operational units to seek creative means to solve complex maintenance problems. 3d MLG identified that for CBM+ to be realized as an effective

ground maintenance strategy there needs to be an environment that encourages Marines to try new maintenance processes with a tolerance to change.

CBM+ implementation rests upon three main pillars; people, processes, and technology. There is a tendency to narrowly focus on technology to the detriment of the attention required for people and process changes necessary to support technology once it is available. Combating existing organizational inertia rooted in legacy maintenance strategy mindsets is a required step prior to the fielding of sensors and analytic tools. The heavy focus on technology, legacy maintenance thinking, and gaps in CBM+ policy impede a clear, unified, and widespread understanding of the CBM+ vision and maintenance strategy.

2. Marine Corps Maintenance Policies Conflict

The current vision portrayed through orders, policies, and directives sets CBM+ apart as a distinct and separate program from current maintenance strategies. Distinct maintenance policies that are not mutually supporting lead to a muted vision and place CBM+ on the periphery of Marine Corps maintenance rather than making it an integrated change effort. Orders directing opposing maintenance strategies currently leave an ambiguous vision for change efforts with no prescriptive means for achieving observable gains through integration into current policies and practices.

The tenets identified in MCO 4151.22 for CBM+ closely reflect the Kotter change model but keeps CBM+ as a distinct and separate policy from the overall maintenance strategy of ground equipment. The distinction requires maintainers to continue to follow maintenance strategies from MCO 4790.2, which does not mention CBM+, RCM, or predictive maintenance concepts as part of the Marine Corps overall maintenance strategy. Rather MCO 4790.2 is highly prescriptive in maintenance processes for the Marine Corps and restrictive in innovative changes to established maintenance practices. For example, “Commanders are not authorized to deviate beyond the minimum established schedule(s) for the conduct of PMCS tasks. When tasks are identified that are either redundant and conditions warrant change Commanders will recommend changes to these tasks to the appropriate program manager via NAVMC 10772 or PQDR” (HQMC, 2016, p. 3-9). The

change process is cumbersome and requires coordination for each individual change with I&L and specific PMs.

Prescriptive maintenance policies such as MCO 4790.2 have not been updated and do not align with current ground maintenance strategy documents for CBM+. This misalignment between orders leads Marines to rely on the legacy policies that provide prescriptive actions. A consistent theme among maintenance officers interviewed was that “the [MCO] 4790.2 does not change, and in fact, the [MCO] 4151.22 doesn’t necessarily provide processes, so even if you were trying to say, the [MCO] 4151.22 conflicts with the [MCO] 4790.2 ... the [MCO] 4790.2 still has a lot of cleaning up to be done” (Maintenance SME, interview, 2022). In 3d MLG’s implementation efforts, the conflict between orders led to the requirement for an ETP to allow for changes to processes associated with MCO 4151.22 to supersede applicable portions of MCO 4790.2. However, exceptions and waivers have limited application and usually require units to proactively seek them. Innovations require an open approach to MCO 4790.2 and an integration of the 4151.22 into the overall maintenance strategy. The 3d MLG report addressed this barrier with the following:

The methodologies of data capture, reporting, and incorporation of executable processes supporting operations need a complete overhaul. (3d MLG, 2022, p. 100)

The MCOs regarding CBM+, MCO 4790.25 and MCO 4151.22, provide definitions for CBM+, but do not present a means for integration into the ground maintenance strategy or a pathway for refinement of existing orders/processes. This lack of means for integration creates an environment where many view CBM+ as a faraway future solution tied to technology acquisitions rather than understanding a shift in maintenance strategy approaches to be executed immediately. Additionally, those that are seeking to move forward with process improvements do not have a clear path to capture process improvements in line with the strategy and disseminate those improvements across the enterprise.

3. FSMAO and Commanding General Inspections Ignore CBM+

Our findings indicate CBM+ is not mentioned in any inspection checklists therefore creating a barrier for CBM+ awareness and execution. Marine Corps organizations put

focus on areas that are inspected and the basis for ground maintenance inspections is the FSMAO inspection checklists and the Inspector General Functional Area Checklists used for the Commanding General Inspection Program (CGIP). The questions in these inspection checklists are drawn from policy documents. The current, FY22 FSMAO inspection checklist and CGIP checklist for maintenance reference the MCO 4790.2 as the primary policy document which inspection questions evaluate. The MCO 4151.22, CBM+ Order, was published in 2020 but is not referenced in any inspection checklist. Units are evaluated based on their compliance with the questions in the inspection checklist, therefore units are naturally drawn to prepare and operate in accordance with those requirements. This has shown to be a significant barrier to CBM+ implementation and will continue to prevent units from experimenting with CBM+ processes and practices.

The 3d MLG report observed that, “leaders were concerned with “passing FSMAO” as a reason not to make changes” (3d MLG, 2022). The impacts of inspections on commanders and units were a repeated concern brought forward in interviews with maintenance officers and maintenance chiefs. Commanders and maintenance personnel are currently evaluated against legacy maintenance policies and are required to conduct burdensome administrative actions to ensure compliance. Until there is a mechanism or policy action to lift these inspectable legacy maintenance requirements, the organizational environment will not be conducive for change to a CBM+ maintenance strategy.

4. Competing Priorities Consume Capacity

Capacity at commands is a product of resources, manpower, and focus that are competed over by a variety of programs. CBM+ implementation has been challenged by other competing priorities which has slowed down the change process. Monetary and manpower resources for new programs within the Marine Corps, and larger DOD, are finite. Per 3d MLG’s CBM+ maintenance approach,

The scope of this program is to address maintenance processes and is limited to the resources already available at the implementing unit. Additional funding, manpower, or extended work hours is not sustainable and therefore cannot be part of the solution set as a matter of routine. The scope of all our efforts centers on low-cost/no-cost solutions, primarily the process of how maintenance is performed, the effectiveness of the maintenance effort, and what maintenance actions are reported as a matter of value. (3d MLG, 2022, p. 10)

3d MLG's ability to execute CBM+ with low-cost/no-cost solutions means that significant time and attention needs to be applied to consolidate gains from CBM+ related people and process improvements. In the current environment, the focus on the Financial Internal Control and Audit Readiness program (FIAR) and passing the audit crowd out efforts to implement CBM+ by putting a drain on time, focus, and manpower resources. Interviewees described the audit as taking the preponderance of focus from policymakers and executors. CBM+ was described as a lesser priority that did not receive the amount of time necessary to implement maintenance strategy changes. The relationship between the audit and CBM+ was overall perceived to be competing for resources and attention (HQMC, interview, 2022).

The limited capacity of units to address administrative requirements has ramifications for the execution of maintenance strategies. Interviews conducted with policymakers reflected that the audit process reinforces many of the non-value-added tasks in the maintenance process, through inspections, that directly inhibit CBM+ improvements and the overall maintenance process (HQMC, interview, 2022). Legacy maintenance practices impact flexibility and burden maintainers which reduces capacity to make improvements. Maintainers do not have time to seek out potential process improvements without means to capitalize and capture gains from existing resources. The relationship between CBM+ and the audit provides an example of how competing priorities require Marines and leaders to place a hierarchy of importance on new initiatives. There are finite personnel, time, and money available to be applied to various initiatives across the FMF. Capacity available for CBM+ integration needs to be maximized to realize meaningful gains across the FMF.

B. OPPORTUNITIES FOR CHANGE

During the conduct of our interviews, four themes emerged from interviews as potential solutions to gaps in CBM+ implementation. The first theme indicates that leaders within the organization need to drive the CBM+ maintenance strategy implementation process. The second theme emphasizes the benefits of temporary waivers of policies that restrict adoption of CBM+ maintenance practices. The third theme is the opportunity to remove non-value-added tasks within maintenance practices to achieve measurable gains.

The final theme is the concept of ownership in the change process and the application of cross-training within operational units.

1. Leadership Buy-In and Advocacy

Commanders must have an awareness of CBM+, understand its benefits, and support the change for unit's to effectively implement CBM+ processes and practices in the organization. The role of leadership in effective implementation echoes Kotter's finding that in successful change stories, change must be driven by leadership (Kotter et al., 2021). During interviews with several maintenance officers, a common theme identified was the weight a commander's support can bring in driving change and creating a sense of urgency (Maintenance SME, interview, 2022). One SME surmised that, "if the Marine Corps wants to fully implement CBM+ and our leadership wants us to do that, we should not have any issues doing it because we write our own policy" (Maintenance SME interview, 2022). Maintenance officers expressed that a commander's interest and advocacy drives urgency more than anything else (Maintenance SME interviews, 2022). Therefore, there is critical importance for commanders throughout the chain of command to understand what CBM+ is and how they can help foster the environment within their units to enable CBM+ success.

3d MLG demonstrated a successful practice in building leadership buy-in and advocacy. Prior to a unit conducting CBM+ implementation, the G-4 staff provided a CBM+ overview brief that equipped commanders and key staff with the understanding of CBM+, the 3d MLG implementation approach, immediate process improvement opportunities, and how to best facilitate successful adoption (3d MLG, 2022). This training to leaders in the organization created greater buy-in throughout the unit and enabled Marines to execute CBM+ processes (Maintenance SME, interview, 2022).

Urgency for CBM+ must be supported and advocated by commanders and leadership in the chain of command. CBM+ technology is not currently a disruptive technology that forces an organization to change which means changes will be incremental in nature. Maintenance officers reflected that since legacy maintenance practices function to meet mission, a sense of urgency would need to be generated by commanders to implement new maintenance practices (Maintenance SME interviews, 2022). Maintenance officers concluded that leaders need to be presented with the relatively low-risk of CBM+

implementation in contrast to the potential high-rewards (Maintenance SME, interview, 2022). There is not a clear understanding of the low-risk relative to high-rewards that will encourage them to seek policy exceptions and drive policy change. Buy-in by leaders across the FMF will generate urgency necessary to accomplish CBM+ implementation efforts.

2. Exceptions to Policy Enhance CBM+ Implementation

Interviews with 3d MLG maintenance officers highlighted the importance of an interim ETP in the ability to implement CBM+ processes and practices in their daily activities. An ETP enabled them to adjust their processes that were not aligned with non-value-added tasks written in the MCO 4790.2. These units were able to explore new approaches in conducting maintenance that improved efficiency and maintenance production (Maintenance SME interview, 2020). Without an ETP, the unit would be steered to follow the inspection checklists which do not mention CBM+ and mandate the maintenance policy actions in MCO 4790.2.

If units work under an ETP, the valid concern is that they will be able to do whatever they want which could cause things to go awry. To help mitigate this concern, there still need to be guidelines and a planned framework for units to utilize to guide their change efforts and experimentation. 3d MLG's CBM+ Order, playbook, and implementation guide are useful tools to guide units in the implementation efforts. These guidance products can be reproduced and distributed to units throughout the Marine Corps to get momentum in CBM+ implementation. It provides standards units can use to give them focus and direction throughout the transition while also allowing healthy modification and experimentation to improve processes in specific contexts.

3. Reductions to Non-Value-Added Maintenance Actions

Non-value-added maintenance actions such as administrative or duplicative tasks waste time and resources in maintenance organizations. Feedback from 3d MLG demonstrated that a deliberate reduction in non-value-added actions creates opportunities to improve maintenance processes and conduct training on CBM+ (3d MLG, 2022). The current maintenance production process requirements listed in the MCO 4790.2 Appendix C, are overburdensome and there are not enough work hours to effectively complete those tasks across the fleet of vehicles in a typical unit (Maintenance SME interview, 2022).

One significant area in which the Marine Corps can reduce non-value-added maintenance actions and get a good return on investment is to modernize preventative maintenance checks and services (PMCS). For motor transport vehicles, a full preventative maintenance (PM) process is required to be conducted annually. According to the technical manual (TM), it will take forty hours to do a PM for one Logistic Vehicle System Replacement (LVSR). It takes twenty hours to complete the PM process for one Medium Tactical Vehicle Replacement (MTVR). These time-consuming processes across the fleet of vehicles within a unit can overwhelm maintenance personnel, negatively impacting their production on other necessary tasks. Annual PMs create significant burden in man-hours, cost, and redundancy across most motor transport platforms (3d MLG, 2022). Additionally, sometimes the PM actions to check serviceability such as disassembly of components on vehicles can cause components to break during the process creating additional corrective maintenance tasks (Maintenance SME interviews, 2022). This is referred to as conducting over-maintenance which causes a greater risk of breakage and increase labor hours.

There are many opportunities for reducing tasks within the various phases of the maintenance process. Figure 3 displays an example of 3d MLG's approach to reduce the acceptance phase from an eighteen to six step process through the removal of non-value-added tasks.

Acceptance Phase

"AS IS" MAINTENANCE PRODUCTION PROCESS IAW 4790.2



"TO BE" MAINTENANCE PRODUCTION PROCESS



NOTE: REDUX FROM 18 STEPS TO 6 STEPS. ELIMINATED STEPS INCLUDE REDUNDANT, NO VALUE, AND/OR STEPS NOT WITHIN CONTEXT OF PERFORMANCE TASKS.

Figure 8. 3d MLG example of maintenance process reduction in the Acceptance Phase. Source: 3d MLG (2022).

Reduction of non-value-added tasks has a compounding effect on readiness, cost, and man-hours. Figure 4 highlights the potential gains that can be realized through process changes that eliminate non-value-added maintenance tasks.

Results for 3d MLG

D TAMCN READINESS		
Pre-CBM+	Post-CBM+	
72% MLG Avg (Aug 2018 – Jan 2020)	86% MLG Avg (Dec 2020 – Apr 2021)	14% increase
D TAMCN Annual <u>FULL</u> PM Cost		
Pre-CBM+	Post-CBM+	
\$1,098,652 (required by TM)	\$216,141 (projected for FY21)	80% decrease
843 assets require full PM	167 assets require full PM	
D TAMCN Annual PM Man Hours		
Pre-CBM+	Post-CBM+	
15,716 (required by TM)	1063.5 (projected for FY21)	93.3% decrease
257 MTVR X 20H = 5,140 Hours	257 MTVR X 1.5H = 385.5 Hours	
184 LVSR X 40H = 7,360 Hours	184 LVSR X 1.5H = 276 Hours	
402 HMMWW X 8H = 3,216 Hours	402 HMMWW X 1H = 402 Hours	

Figure 9. 3d MLG CBM+ D TAMCN Readiness, PM Cost, and PM Man-hours Analysis. Source: 3d MLG (2022).

There is potential to scale these observed benefits from 3d MLG D TAMCN CBM+ process improvements. Figure 5 provides an estimate of the cost and man-hours savings for a MEF with the implementation of CBM+ processes that seek to reduce non-value-added maintenance tasks.



III MEF Projected Results

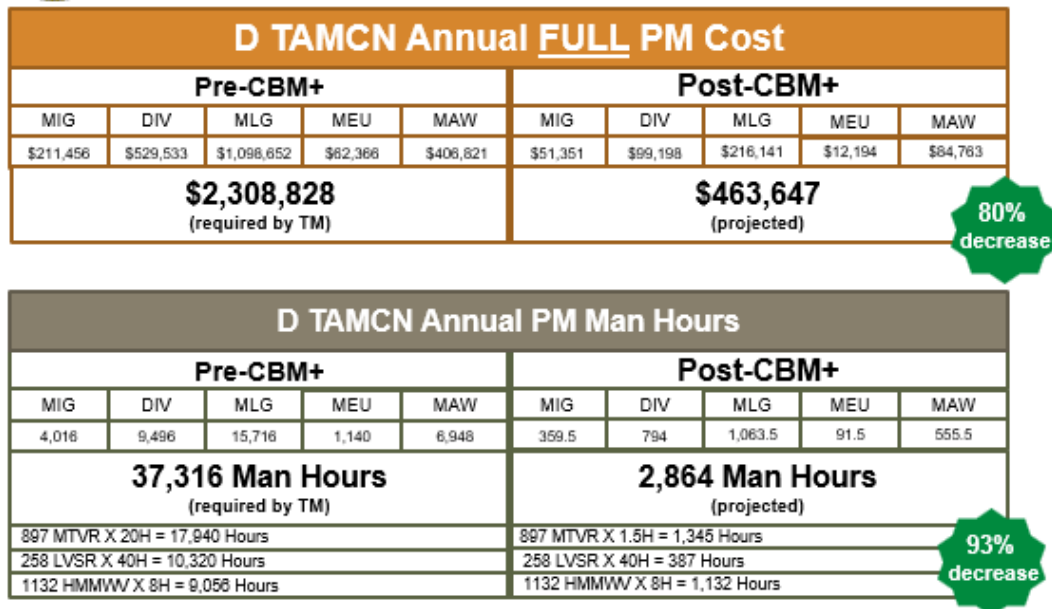


Figure 10. 3d MLG Projection Analysis of III MEF PM Cost and Man-hours with CBM+. Source: 3d MLG (2022).

3d MLG revealed how much time was saved by adjusting the PM process and discovered there is a reduction in man-hours by 50–60% by eliminating redundant annual PM actions that were already covered in beginning, during, after (BDA) and monthly zonal PM checks (3d MLG, 2022). Due to this modification, there was a positive impact on morale for the mechanics. Additional time could be dedicated toward corrective maintenance repairs to improve readiness and operational availability.

These are relatively immediate results that can be realized across the Marine Corps with this one modification in the approach to maintenance with the focus on the true condition of the assets and eliminating redundant actions within the current maintenance process. Readiness can increase, millions of dollars and thousands of labors hours can be saved and applied to higher priority tasks across the force.

4. Cross-Training Operators and Mechanics

The CBM+ focus on identifying the true condition of the weapon system puts a greater importance on operators becoming more proficient at detecting faults or

irregularities in the weapon systems. The “mecherator” (mechanic-operator) concept was developed in 3d MLG which aims to train operators to become more proficient with maintenance actions and train mechanics to better understand operator considerations (3d MLG, 2022). The key benefit of this cross-training is it reduces the amount of time between discovering a fault and getting it repaired. Operators are the first sensors that can detect a problem and identify the condition of a vehicle, so being equipped with basic operator-level maintenance skills can be a force multiplier to make repairs as required while reducing the burden on trained mechanics. Operators possessing the responsibility and maintenance skills to conduct operator-level maintenance such as lights, fuses, door handles, and other degraded actions, can free mechanics to focus time and effort on conducting restorative deadlining actions that only they are authorized and trained to execute.

This concept directly supports the Marine Corps concepts of stand-in forces, expeditionary advanced based operations (EABO), and distributed operations. To operate effectively under those operating concepts, the Marine Corps will need more versatile Marines that are equipped with more skill sets to increase survivability, maintainability, and lethality. CBM+ encourages this cross training in daily operations which will build a more flexible Marine and overall unit that can solve maintenance problems forward with greater confidence.

The 3d MLG report proposed the consolidation of certain military occupational specialties (MOS) that align within maintenance performance roles (3d MLG, 2022). Though there is potential for MOS realignment and changes to training, the key takeaway is the benefit that cross-training provides as a capability multiplier in austere environments. Restrictions on the type of maintenance conducted by certain MOSs and echelons by level should be reviewed and lifted where possible. This will assist in a key finding from the 3d MLG report that, “increased responsibility for the owners/operators provided stewardship at the tactical level improved the material condition of the assets, thereby increasing operational availability” (3d MLG, 2022, p. 21). The FMF putting greater emphasis on operator-mechanic cross-training provides numerous advantages for the Marine Corps and better prepares the people and process for CBM+ implementation.

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XI. RECOMMENDATIONS

Change is difficult and often comes up against a lot of resistance. Effective change requires a multi-pronged approach that leverages existing and new resources to make change happen. These recommendations are based on that understanding and consider the numerous lines of efforts and areas of opportunity that can be leveraged to facilitate CBM+ implementation in the Marine Corps. To build sufficient momentum to change maintenance strategies, various organizational entities and initiatives are required to act in alignment with the CBM+ vision. Organizational change is a dynamic and continuous process therefore these recommendations provide only a portion of the overall change effort. This chapter provides some key recommendations that the Marine Corps should explore in the implementation of CBM+ throughout the enterprise.

A. ALIGN CBM+ WITH FORCE DESIGN 2030 AND TALENT MANAGEMENT 2030

A sense of urgency should be built for CBM+ implementation by communicating to the FMF how it supports the current CMC priority initiatives. Since 2019, the Marine Corps' highest priority has been force design to meet the current and future threats (CMC, 2019). In March 2020, the CMC published Force Design 2030 (FD2030) which provided an argument for change, vision, and expectations of the force design effort. Significant innovation and experimentation have occurred to meet the FD2030 requirements, and there will continue to be adjustments over the next several years (CMC, 2022). As FD2030 has gained momentum, the Commandant has placed equal emphasis on the priority of Talent Management 2030 (TM2030) which supports the objectives of FD2030 (CMC, 2021). Included in this document, along with CPG 2019, is the importance of talent retention. The CMC's Planning Guidance states, "Retention of the most talented individuals within the institution is critical" (CMC, 2019). Talent retention is essential to the maintenance community to maintain high levels of readiness.

Shifting from executing maintenance utilizing the MCO 4790.2 that includes many time-consuming and non-value-added maintenance actions toward CBM+ that seeks to reduce non-value-added tasks and improve operational readiness can directly impact maintenance workforce behaviors, attitudes, and retention. The maintenance community

has historically been known to work long hours consistently and still trying to keep up with the demand while seeking to adhere to time-consuming policy requirements (Maintenance SME, interview, 2022). Excessive policy requirements that are difficult to achieve on top of a heavy workload causes added stress and frustration at the mechanic and mid-level manager positions. These are Marines that the Marine Corps needs to retain to mature the force and maintain high talent Marines. The longer the Marine Corps executes legacy maintenance practices, the harder it will be to retain talented Marines in the maintenance community.

A CBM+ implementation initiative across the FMF can instead leverage the young maintenance Marines to help improve maintenance processes in alignment with CBM+ practices which will help gain their buy-in as well as reduce labor hours in the long run. 3d MLG CBM+ implementation efforts have sparked innovation, ideas, and a renewed energy in the junior enlisted workforce (3d MLG, 2022). The junior enlisted maintainers are seeing increased results in maintenance production, equipment operational availability, with reduced labor-hours and redundant tasks. Leaders will have a greater ability to retain Marines that are experiencing these positive impacts than Marines that are operating in an inefficient maintenance process environment. CBM+ implementation can help retain critical Marines and experienced maintainers with the ability to innovate which will enhance CBM+ application. The emphasis on CBM+ benefits to FD2030 and TM2030 objectives should be communicated throughout the FMF to build a greater sense of urgency to change maintenance strategies.

B. ESTABLISH A CBM+ GUIDING COALITION

The purpose of a CBM+ guiding coalition is to, as a team, guide, coordinate, and communicate CBM+ implementation throughout the Marine Corps. Creating a guiding coalition is the second stage of Kotter's change process (Kotter, 2012). A CBM+ guiding coalition should consist of Marines and civilians throughout various levels of the Marine Corps organization. This includes representatives from the battalion-level to the MEF-level, key supporting establishments, and headquarters elements such as I&L, CD&I, and MCSC.

The guiding coalition should be directed and led from the owners of the Marine Corps maintenance policy and strategies to have the sufficient level of authority and

responsibility to initiate and approve enterprise policy change. In the Marine Corps' context that would reside in LPM, Materiel Readiness and Management Branch, in I&L. The members of this guiding coalition need to possess the knowledge, competence, credibility, commitment, will, and drive to get CBM+ maintenance strategy executed throughout the Marine Corps. The deliberate development of this coalition will be critical to the speed, efficiency, and effectiveness in which CBM+ is implemented. This guiding coalition will be a key strategic communication tool to empower broad-based action as well as be a role model for the attitudes and behaviors that are necessary for CBM+ execution. If individuals in this guiding coalition are not fully bought into CBM+, it will create added friction, barriers, and slow down the implementation process. On the other hand, if the guiding coalition consists of highly talented and well-respected individuals from the youngest Marine to senior-level Marines and civilians, then there is potential for accelerated momentum during implementation. There are four key characteristics that Kotter deems to be essential to effective guiding coalitions which are position power, expertise, credibility, and leadership (Kotter, 2012). These four characteristics within the coalition will help give it enough power that is necessary to combat the forces of inertia.

There is potential to use existing tools within the Marine Corps policy refinement process, such as the Total Life Cycle Management Cross Functional Team Model, for a CBM+ guiding coalition. MCO 4000.57A, *Marine Corps Total Life Cycle Management (TLCM) of Ground Weapon Systems, Equipment and Materiel*, established a cross-functional governance structure to support the direction and execution of the total life cycle management strategic framework (HQMC, 2009). This governance structure consists of an executive board, a corporate board, cross functional teams (CFTs), and integrated project teams (IPTs). The CBM+ CFT would be chartered to provide oversight for policy improvements, provide metrics for implementation efforts, and communicate overall Marine Corps ground maintenance strategies as a permanent entity.

When this CBM+ CFT is formed, led by I&L LPM, integrated planning teams (IPTs) can be scheduled quarterly, semi-annually, or annually to help shape the initial CBM+ maintenance vision and strategy across the enterprise. Kotter supports this sequence of creating a guiding coalition with power and expertise to lead change, then getting them together to work as a team to create a vision and develop executable strategies to achieve

that vision. A CBM+ vision is already written, but it will need to be refined and shaped with the contribution of a guiding coalition to create buy-in and communicate it in a more effective way to the enterprise (Kotter, 2012). Each commodity manager will likely have different planned actions and milestone timelines based on the complexity, variety, and understanding of CBM+ application on specific systems. These IPTs can be a tool to help shape the correct vision and an executable strategy to achieve that vision.

During the early stages of the CBM+ guiding coalition, there should be a higher frequency of IPTs to build the necessary understanding, communication, and momentum to develop a sound strategy and achieve early gains. Additionally, members of the CBM+ CFT can capitalize on the annual commodity symposiums, conferences, or operational advisory groups (OAGs) to discuss and advance CBM+ maintenance strategy in each of the commodities and throughout the enterprise. Establishing a guiding coalition is needed to sustain the change process and will bring the right players to the table to ensure policy and orders are updated to reflect the intent of CBM+ implementation.

C. REFINE AND COMMUNICATE CBM+ VISION

We recommend the CBM+ CFT provide an updated CBM+ vision that associates with FD2030 and empowers units to seek out improved maintenance practices and provide bottom-up refinement to the CBM+ CFT. A directed review and update effort of the MCO 4790.2 should integrate CBM+ strategies and provide commanders guidance on latitude to implement innovative concepts. While MCO 4151.22 provides the overarching narrative for CBM+, the order needs to be incorporated as a part of MCO 4790.2 to reflect that CBM+ is a key component of the Marine Corps maintenance strategy moving forward.

A necessary component of communicating a compelling vision is ensuring that the vision, as presented, is achievable with measurable and observable gains. Kotter's sixth stage, generating short term wins, emphasizes planning for observable improvement in performance (Kotter, 2012). The *3d MLG CBM+ Implementation Report*, endorsed 14 October 2022, demonstrates the success of policy as measured by CM days deadline, PM Cost, PM Man-Hours, and DRIS to SR close (3d MLG, 2022). This can be translated into improved readiness, cost effectiveness, improved use of manpower, and reduced administrative burdens. Measurable improvements in MCT, cost effectiveness, and man-

hours provides CBM+ advocates with compelling evidence for presenting CBM+ to leaders across the FMF.

Technology, the “+” in CBM+, is a long-term enabler for the predictive aspect of CBM that will be contingent on the acquisition process, updates to current equipment sets, and will likely be piecemeal. Many of the short term wins available for changing the way that the Marine Corps conducts maintenance exist in maintenance processes and behavior changes. Intermittent updates to policy, technical manuals, and inspectable criteria will enable capturing and disseminating lessons learned in a meaningful manner to encourage future change actions. This leads into the consolidation of gains and production of more change that Kotter emphasizes in stage seven of *Leading Change* (Kotter, 2012).

A strategic communication plan needs to be developed to promulgate the vision of a CBM+ maintenance strategy as well as build the knowledge and education of the force on CBM+ practices, processes, and benefits. Kotter observed in studying organizations going through change that, “without sufficient communication of a rational and emotionally compelling case for change, it was nearly impossible to achieve buy-in that inspired and mobilized the action required to drive and sustain difficult change” (Kotter et al., 2021). Existing strategic communications capabilities need to be leveraged to push CBM+ vision and narrative throughout the force for CBM+ change efforts to take root in the organization. MCSC has an Office of Public Affairs and Communication (OPAC) which can be used to broadcast actions the different program offices are doing with CBM+ and RCM. Every MEF has a Strategic Communications and Operations (COMMSTRAT) company that can support CBM+ implementation through strategic communication. OPAC can provide MEF COMMSTRAT with messaging and narratives related to CBM+. Additionally, units within the MEFs having success or discovering effective CBM+ processes and practices can feed COMMSTRAT ideas to broadcast throughout the force. Deliberate and frequent broadcasting will build greater awareness of CBM+ which can lead to educating the force faster and generation of more innovative ideas. A CBM+ strategic communication plan will expedite the exposure of CBM+ maintenance strategy throughout the force helping to advance implementation at a faster rate.

D. RESOLVE CONFLICTS BETWEEN MAINTENANCE POLICIES

The military's standard top-down pushing of policy and change is not the most effective way of creating change in this generation and cultural context. It is still necessary to have the high levels or policy approvers of the organization to establish an initial policy direction and outline a strategy, but that can be enhanced over time from bottom-up refinement when there is a new initiative introduced to the organization like a CBM+ maintenance strategy. There is an opportunity with CBM+ implementation to drive change within the Marine Corps in a different way that aligns with many of our goals and initiatives for FD2030 and use a method that has been proven successful in private sector organizations. The Marine Corps has an opportunity to capitalize on and leverage the knowledge and skills throughout the organization to build buy-in and shape the policy from up and down the chain of command.

To enable change to the Marine Corps maintenance strategy and adoption of CBM+, operational units need to be empowered to seek out process improvements and opportunities to apply CBM+ practices. The restrictive nature of present orders and constraints placed by required non-value-added maintenance actions present obstacles to Marines seeking to update processes to incorporate CBM+ principles. We recommend creating an environment that fosters short-term wins through ETPs and enhancing gains through consolidation of maintenance orders in a single volumized policy document.

1. Institute Exception to Policy During the Transition to CBM+

A Marine Corps-wide interim ETP specific to maintenance practices that inhibit the implementation of CBM+ should be published. This ETP will enable units across the Marine Corps to test CBM+ and discover more efficient ways of conducting maintenance that will better prepare them for technology integration. Marine Corps units need to be given time to improve their processes and procedures under a CBM+ maintenance approach prior to the integration of technology to truly maximize its impact. An ETP allows units across the Marine Corps to build momentum for CBM+ which will also provide the force evidence of best practices that can help influence and shape CBM+ future policy. An ETP helps remove some barriers to change and it also provides an opportunity to capitalize on the ideas and creativity of Marines and units across the force. This helps create empowerment at the lowest levels and there will be a sense of ownership within each unit

to drive toward CBM+ using initiative, innovation, and problem-solving. They will need to be given right and left lateral limits within the ETP, but there needs to be some freedom of experimentation to discover the best processes and practices the Marine Corps can use.

A Corps-wide ETP will reduce the friction of a Marine going from one unit under the ETP to another unit that is still operating under the MCO 4790.2 maintenance practices. An interim ETP will reduce potential friction in CBM+ implementation and mitigate frustration within the maintenance community while policy updates incorporate CBM+ strategies.

A large concern for many regarding changing maintenance practices is the potential risks in using an ETP and transitioning to CBM+. The Marine Corps often views risk through two lenses: risk to force and risk to mission. Risk to force ties into the safety of the Marines. During the interviews with experienced maintenance officers, there was a unified agreement that there is low risk in terms of safety and mission with the implementation of CBM+ practices and processes. Due to the low safety risk and risk to mission, a CBM+ organizational change effort is an initiative worth executing across the force to gain speed, progress, and improve the adaptation proficiency of the Marine Corps.

CBM+ implementation can be used as a change model/example/standard for future changes the Marine Corps will need to perform. There will be lessons learned and some failures along the way during this change effort, but the Marine Corps will be further along in performing more modern and effective maintenance practices and the organization will grow from the adaptation that it required. An ETP during CBM+ implementation will enable a more agile ground maintenance strategy and innovative environment for the FMF.

2. Conduct Volumized Maintenance Order Rewrites and Dynamic Updates

We recommend a volumized rewrite of maintenance orders such as MCO 4790.2, MCO 4790.25, and MCO 4151.22 into a central document that defines a holistic maintenance strategy for the Marine Corps. A consolidated order for ground maintenance strategy will assist in presenting a concise vision of Marine Corps ground maintenance that is inclusive of CBM+. A volumized approach will allow for individual volume updates to capture process improvements over an extended period. Additionally, the structure enables

updating individual process and procedural segments while combining multiple references into a single source document. A deliberate rewrite of orders will also provide measurable targets for implementation by the CBM+ CFT and working groups.

Creating a volumized MCO that clarifies, simplifies, and removes duplicative orders for TLCM and ground equipment maintenance will help solidify the change initiatives into the future. Kotter's eighth stage, *anchoring new approaches in the culture*, identifies the need to codify improved processes and articulate lessons learned (Kotter, 2012). A volumized MCO can be shaped and developed through frequent feedback throughout CBM+ implementation from the FMF in venues such as annual commodity conferences, operational advisory groups (OAG), or integrated planning team (IPT) meetings. To have maintainers' buy-in to CBM+ as the new maintenance strategy, Marines need to see the adoption of innovations through codifying policy changes and incentivizing positive contributions for reducing maintenance downtime. Feedback directly from the maintenance community in the form of innovation challenges will communicate the new view towards maintenance strategy, encourage participation in process improvements, and invest Marines in the implementation of CBM+. The consolidation of feedback into a volumized MCO can help ensure the maintenance strategy best practices and lessons learned during implementation are anchored in the culture through informed and actionable policy.

E. DEVELOP CBM+ EDUCATION FOR COMMANDERS

We recommend incorporating CBM+ and maintenance concepts central to Marine Corps maintenance strategy into training and logistics seminars for leaders. Our interviews make clear that not all commanders are aware or have a good understanding of CBM+. CBM+ education to commanders is a line of effort that needs to be expanded to create a greater sense of awareness and urgency throughout the Marine Corps to implement a CBM+ maintenance strategy. Commanders have a significant number of responsibilities and information that they are required to absorb prior to and upon assuming command therefore there needs to be an iterative and balanced recurrent approach to educating commanders.

All commanders are required to attend a two-week course designed for O-5 and O-6 command-selected leaders called Cornerstone: The Commandant's Combined

Commandership Course. This course is offered twice a year, tentatively in October and April, to help equip commanders for the responsibilities and duties of command. This venue is an opportunity to educate commanders on CBM+ and its benefits before they command. Promulgating a CBM+ information paper is an effective tool to provide commanders and FMF CBM+ awareness and education in an expedient manner. An information paper provides easily digestible content that can be leveraged by unit commanders and staff throughout the FMF to improve CBM+ education and implementation efforts.

After commanders assume command, CBM+ education can be reinforced by the MEF or MSC G-4 materiel readiness symposiums which are typically conducted on a quarterly or semi-annual basis. Additionally, individual unit commanders should receive a more in-depth education on CBM+ maintenance strategy from the MSC CBM+ training personnel to help build greater understanding and be able to get unit-specific feedback on the barriers and opportunities of CBM+ implementation efforts. This individual unit commander education touch point has shown to be a best practice that has created positive momentum in 3d MLG's implementation of CBM+.

Additionally, we recommend integrating CBM+ in the Commander's Materiel Readiness Handbook to improve leaders' familiarity and provide a quick reference to principal components of the Marine Corps maintenance strategy. Feedback from SMEs reinforced that for change to happen within the military, commanders must be invested and willing to adopt changes to the overall maintenance strategy. Limited exposure to maintenance practices or available strategies prior to assuming command reinforces a focus on maintenance to meet inspection or reporting requirements rather than a CBM+ approach. The underlying strategies and implementation of CBM+ as the Marine Corps a ground maintenance strategy should be presented to commanders in a maintenance handbook for commanders. This provides commanders with reference material that will give them the basis for exploring these concepts in their respective commands and encouraging innovation by their Marine maintainers.

F. UTILIZE FSMAO TO SUPPORT CBM+ INTEGRATION

FSMAO is an organization that acts on behalf of HQMC to inspect and analyze units on compliance to orders, policies, and directives. Their mission as indicated in MCO

4400.160 is, “FSMAO conducts comprehensive analyses of logistics functional areas in order to assess compliance with orders and directives and improve overall Marine Corps equipment accountability and readiness” (HQMC, 2013, p.1). The order also states, “The desired end state of a FSMAO analysis is enhanced unit readiness, increased operational availability of equipment, and a comprehensive review of equipment accountability, readiness and reporting, maintenance management...” (HQMC, 2013, p.2).

There are three FSMAO teams in the Marine Corps, FSMAO East, FSMAO West, and FSMAO WestPac. FSMAO teams consist of hand-selected SMEs in the fields of maintenance and supply chain management. FSMAO has the unique opportunity to analyze and inspect every organization in the Marine Corps, which no other entity can do. This unique organization can be leveraged to help facilitate CBM+ implementation throughout the Marine Corps and be a source of feedback for best practices.

FSMAO can be utilized as a key contributor in communicating the CBM+ vision for Marine Corps maintenance through evaluating, training, and consolidating best practices of CBM+ processes. For 3d MLG to capitalize on CBM+, change gains made to maintenance processes, inspections conducted by 3d MLG of subordinate units and checklists were updated to incorporate CBM+. This enabled goal alignment with implementation of CBM+ as a maintenance strategy with individual unit performance indicators. The 3d MLG report described how inspections enabled CBM+ implementation.

3d MLG G-4 provides an inspector to review CBM+ centric processes. This checklist differs from other inspections as it is a knowledge/skills assessment (KSA), meaning key billet holders must be able to show/explain the answer to the question to demonstrate compliance. To be successful, the individual will need to be trained and have incorporated CBM+ into their daily procedural documents. Unit maintenance management sections must include CBM+ type assessments in the internal inspection programs. 3d MLG G-4 also reviews this requirement. (3d MLG, 2022)

Inspections are an enabling force in the maintenance community that reinforce maintenance strategy and processes. Inspection teams assess proficiency and understanding of concepts while providing training and guidance towards corrective actions. These benefits need to be leveraged to solidify CBM+ implementation and maintenance strategy changes.

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XII. CONCLUSION

It is a matter of time before the Marine Corps and the other services fully implement CBM+, the only difference will be the speed and effectiveness with which it happens. There continues to be increased pressure from Congress and the DOD for the services to implement CBM+ and predictive maintenance. Reactive and time-based maintenance as the primary maintenance strategy does not support the future force. Therefore, now is the time to gain momentum by establishing the right foundations to enable CBM+ future success as a ground maintenance strategy.

The foundation to an effective CBM+ maintenance strategy is people executing the right behaviors and processes that will improve maintenance capacity. Making necessary adjustments to get the people and processes working efficiently will facilitate effective technology integration. Technology that is integrated into inefficient processes with people executing poor behaviors will add limited to no value.

The Marine Corps has an excellent opportunity to achieve quick and early gains in the implementation of CBM+ as a ground maintenance strategy by making changes to the people and process aspects that will not require additional resources and funding. 3d MLG's CBM+ implementation efforts has proven to significantly increase operational availability, reduce cost, and reduce man-hours. Gains in the maintenance process were achieved without additional resources and funding. During 3d MLG's implementation, they developed a CBM+ playbook, with the focus on people and process changes, that can be scaled and utilized across the FMF as an enterprise-wide template.

Marines are not empowered within legacy maintenance processes, outlined in MCO 4790.2, to execute CBM+ practices. The maintenance production process outlined in MCO 4790.2 enforces redundant and non-value-added tasks that are negatively impacting the operational availability of equipment, increasing cost, and increasing man-hours. This legacy maintenance strategy does not align with the Commandant's priorities for FD2030/TM2030. The Marine Corps will have a harder challenge encouraging quality maintenance Marines to re-enlist if they continue executing non-value-added tasks mandated in the legacy maintenance strategy. Leaders can also increase Marines'

motivation to reenlist by improving efficiency and effectiveness of maintenance practices and allowing young Marines to contribute to change solutions that improve the Marine Corps. The Marine Corps has an opportunity in transitioning to a CBM+ ground maintenance strategy by tapping into the ideas, innovations, and creative problem-solving capabilities of Marines to better the organization at relatively low risk. Any movement or forward progress in CBM+ implementation is good for the Marines and the organization.

Our recommendations emphasize areas of opportunity for the Marine Corps to generate urgency, empower broad-based action, and solidify CBM+ as a ground maintenance strategy. An effective communication strategy that reinforces the CBM+ vision needs to be presented to Marines that encourages a proactive approach. The management of the CBM+ vision and implementation efforts should be under the supervision of a CBM+ cross-functional team that would serve as the permanent guiding coalition. Organizational change requires a guiding coalition to put forth a consistent vision and sustain a sense of urgency in the organization. Our recommendations are not final solutions for CBM+ implementation, rather they point to available organizational tools within the Marine Corps and organizational change approaches. Our recommendations provide options for leaders and policymakers to drive CBM+ implementation.

This paper is primarily focused on the early wins the Marine Corps can achieve in implementing CBM+ as a ground maintenance strategy with respect to people and processes. People and process are foundational to maintenance strategy and there are immediate actions the Marine Corps can take without additional resources and funding to advance CBM+ implementation. Capitalizing on these opportunities and generating early wins has the potential to create the necessary momentum and maintenance practice foundation for technology integration. CBM+ cannot be treated as just another program; it needs to be holistically integrated into the ground maintenance strategy. Enterprise-wide integration of CBM+ as a ground maintenance strategy plays an important role in enabling logistics as the pacing function for the Marine Corps and supports FD2030/TM2030 objectives.

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