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INCORPORATING PREDICTIVE MAINTENANCE BEST PRACTICES INTO MARINE CORPS TRAINING AND OPERATIONS

Stuetelberg, Mitchell B.; Thomas, Jonathan R.

Monterey, CA; Naval Postgraduate School

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INCORPORATING PREDICTIVE MAINTENANCE BEST PRACTICES INTO MARINE CORPS TRAINING AND OPERATIONS

December 2021

By: Mitchell B. Stuetelberg
Jonathan R. Thomas

Advisor: Eva Regnier
Co-Advisor: Bryan J. Hudgens

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The Marine Corps currently utilizes a traditional time-based strategy for ground equipment maintenance, conducting preventative maintenance at specified time intervals and corrective maintenance when failure occurs. In 2020, the Marine Corps initiated the transition from this maintenance strategy 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. Hypothetically, CBM+ will generate increased cost-savings, reduce man-hour requirements, and improve operational availability for Marine Corps ground systems. Using a case study methodology, this project highlights best practices within the commercial mining, railroad, and heavy equipment industries by interviewing maintenance professionals and supplementing these discussions with existing literature. We then used a thematic analysis across five themes: organizational structure, asset classification, information technology (IT) infrastructure, data management, and maintenance decision making. By highlighting commonalities across the cases and evaluating best practices, we drew three key conclusions. First, some Marine Corps ground systems are not CBM+ compatible. Second, significant upgrades to existing maintenance infrastructure are necessary. Finally, CBM+ should be used as a decision-making framework to maximize cost-savings and combat readiness.

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Mitchell B. Stuetelberg, Captain, United States Marine Corps
Jonathan R. Thomas, Major, United States Marine Corps

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Approved by: Eva Regnier
Advisor

Bryan J. Hudgens
Co-Advisor

Bryan J. Hudgens
Academic Associate, Department of Defense Management

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ABSTRACT

The Marine Corps currently utilizes a traditional time-based strategy for ground equipment maintenance, conducting preventative maintenance at specified time intervals and corrective maintenance when failure occurs. In 2020, the Marine Corps initiated the transition from this maintenance strategy 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. Hypothetically, CBM+ will generate increased cost-savings, reduce man-hour requirements, and improve operational availability for Marine Corps ground systems. Using a case study methodology, this project highlights best practices within the commercial mining, railroad, and heavy equipment industries by interviewing maintenance professionals and supplementing these discussions with existing literature. We then used a thematic analysis across five themes: organizational structure, asset classification, information technology (IT) infrastructure, data management, and maintenance decision making. By highlighting commonalities across the cases and evaluating best practices, we drew three key conclusions. First, some Marine Corps ground systems are not CBM+ compatible. Second, significant upgrades to existing maintenance infrastructure are necessary. Finally, CBM+ should be used as a decision-making framework to maximize cost-savings and combat readiness.

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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	Graphic 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

EXECUTIVE SUMMARY

A. INTRODUCTION

The Marine Corps is currently transitioning to a condition-based maintenance plus (CBM+) strategy from a time-based maintenance (TBM) strategy where preventative maintenance (PM) is conducted at specified time intervals, and corrective maintenance (CM) is conducted when a failure occurs. 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, software and systems, and activities that are currently in place to support a TBM strategy. To potentially alleviate, or at the least identify some of the growing pains and systemic changes associated with transitioning maintenance strategies, we analyzed several companies across different industries to identify how they are implementing a CBM or predictive maintenance (PdM) strategy and what aspects of their approach can best inform the Marine Corps' CBM+ strategy implementation.

B. METHODOLOGY

Throughout our research, we contacted numerous maintenance professionals across multiple industries to determine if their respective industry or experience with CBM was suitable for further analysis. This process resulted in us selecting the mining, railroad, and heavy equipment industries for further research as these industries shared the most meaningful similarities with how and where the Marine Corps operates and maintains ground equipment. Once selected, we used the multiple case study methodology (Eisenhardt, 1989; Yin, 2009) to highlight best practices and identify commonalities across the different industries.

C. ANALYSIS

We then used a thematic analysis across five themes: organizational structure, asset classification, information technology infrastructure, data management, and maintenance decision making to further compartmentalize key findings. The five most pertinent findings are bulletized 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.

D. CONCLUSION

In the context of the Marine Corps, successful CBM implementation should provide the service with the tools to inform commanders with pertinent equipment information such as projected breakdowns during the period of operation, estimates on maintenance costs following operations, and risk to mission or risk force if specific pieces of equipment are, or are not employed in support of an operation or exercise. It is not very likely that the Marine Corps should, or would be able to copy industry perfectly; however, the Marine Corps' implementation of a CBM+ strategy needs to be very methodical, accounting for the five ideas detailed above at the least. Additionally, the service will need to examine the numerous trade-offs and process adjustments that a CBM+ strategy will entail. In these instances, the Marine Corps needs to retain a clear-eyed vision of the CBM system as a whole to best reap the benefits of this maintenance strategy.

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Yin, R. K. (2009). *Case study research: Design and methods* (Fourth edition). SAGE.

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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 organization 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 the 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			
	Reactive	Proactive		
Category	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, semiannually, annually, or bi-annually. As preventative maintenance is conducted, usage information retrieved manually from the equipment odometer or hour gauge 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 and 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. The 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 and is primarily composed of flying squadrons with limited ground formations that provide aviation support such as refueling, runway maintenance and 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 possesses 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 prior to 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 greatly 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 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 incredibly narrow in focus. Therefore, to better understand 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 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) where 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 Östman's research on data management complements the two articles detailed above through the distinction between monitoring data and trending data. Through citing previous scholarship, Soderback and Östman 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 Östman identified that in order to be able 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 Östman 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 difference 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 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 abnormalities 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.

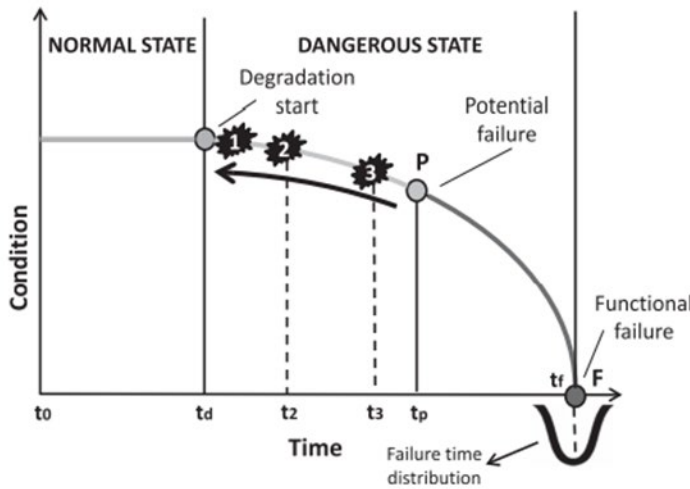

Figure 2. Prevention Failure (P–F) Curve. Source: Bousdekis et al. (2020)

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 most 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 that are 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 the fact that the service will need to have the correct type of IT systems that provide enough information to make informed maintenance decisions in order to achieve an adequate ROI above that of the current TBM maintenance strategy.

In addition to having the appropriate systems in place, 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 the interoperability. To ensure that systems are interoperable with one another, specialists that will be utilizing that system needed 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, there is a large amount of scholarship that 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 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 three case studies focused on the commercial mining, railroad, and heavy equipment industries. Case studies on mining, railroad, and heavy equipment represent a purposeful sample (Eisenhardt, 1989), as they 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, these criteria are similar to the Marine Corps' ground assets, suggesting they are relevant for comparison when examining CBM or PdM strategies and implementation. Additionally, these industries have utilized a CBM or PdM strategy longer than the DOD and have achieved a greater level of maturity and practical experience. We excluded aviation from our case selection, because although both commercial and military aviation utilize a CBM/PdM strategy, aviation and ground assets differ significantly. 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 our sample industries 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 more 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

Our interviews followed broadly recognized procedures (e.g., Eisenhardt, 1989; Yin, 2009). We identified our interview participants purposefully primarily based on their occupation and role within their given company or industry and we contacted them via LinkedIn, existing student/advisor networks, and through referrals from other individuals. Once contacted, we introduced our 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, we asked participants 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. Our questions focused on 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 we gathered during the interview process. All audio recordings were then transcribed to be referenced in the future to enable effective case development. The interviews lasted between 45 to 90 minutes and we contacted interviewees subsequently to elaborate on any information that was of additional interest or unclear during the initial interview session (Yin, 2009).

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 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). Multiple, comparative case studies (Eisenhardt, 1989; Yin, 2009) allow for within-case analysis, but importantly, they also enable additional comparative analysis to help explain possible variance between the case processes or outcomes (Eisenhardt et al., 2016; Langley & Abdallah, 2011). To examine our topic to the required degree of depth, participant interviews were supplemented with 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 (e.g., Eisenhardt, 1989) 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.

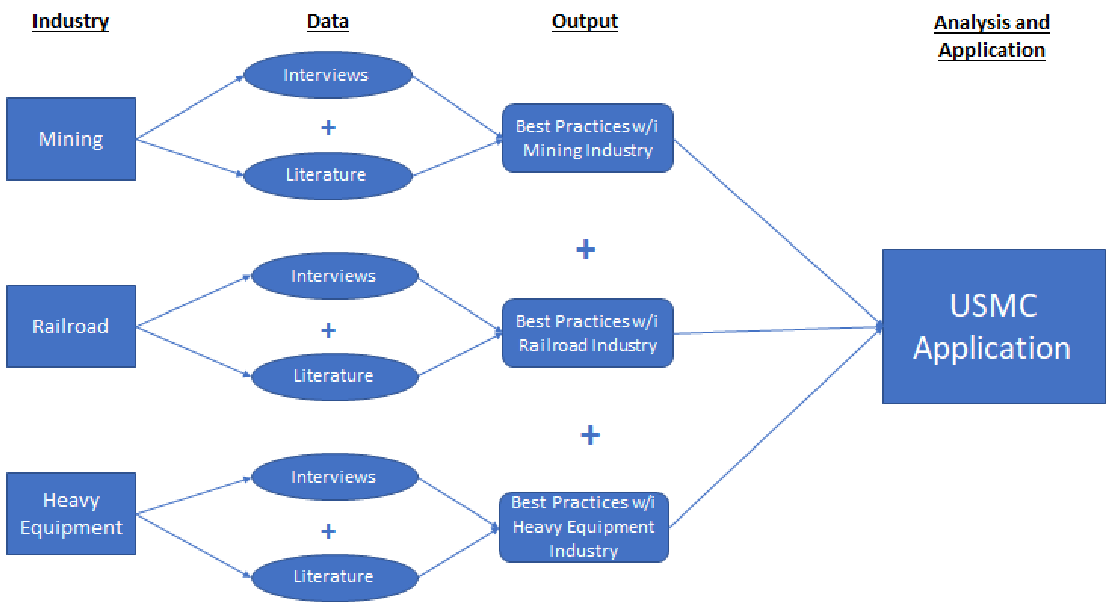

Figure 3. Process Flow Chart Detailing Case Study Construction as They Apply to the Marine Corps' Application of CBM+

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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 in Figure 4.

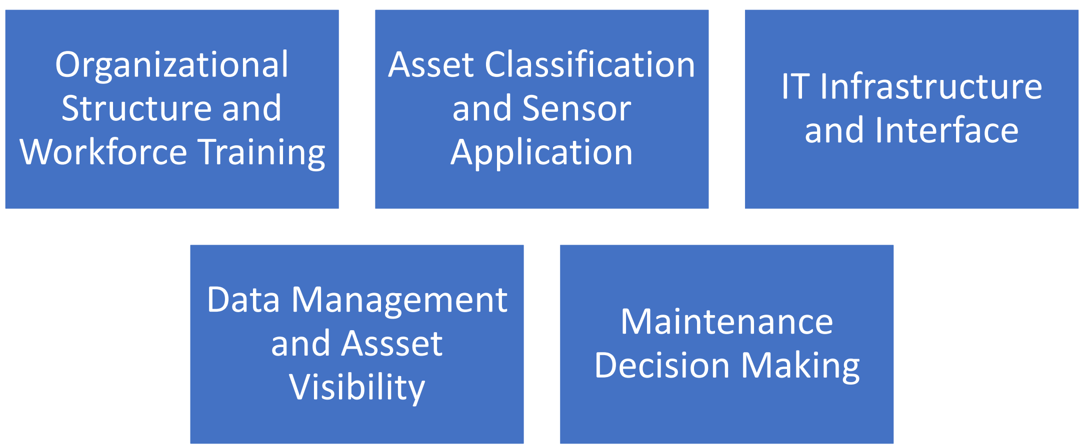

Figure 4. Themes of Analysis

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 of 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 the visibility of equipment health within the organization without incurring additional expenses or information latency that is commonly associated with an 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 that of the cost to actually 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 marker 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). If a secondary or tertiary sensor detects that a malfunction or fault on the primary sensor is occurring, then 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 scientist and maintainers to achieve visibility of all networked assets to include sensor banks at entire mines, to that of 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 program called Microsoft Azure that is 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, have the ability to view a specific asset and monitor specific metrics while that piece of equipment is conducting operations. The ability for them 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 plans 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 contributing 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 number 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 that are powered by diesel-electric engines and also 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 which allows 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 gage if failure is imminent or not. If failure is determined to be imminent based on inspection, the part will be replaced. If the component is expected to have a reasonable remaining life as determined by the inspection which is informed with usage data, it is left in place for reassessment at the next inspection period or until it is operationally run to failure. With regards to direct sensor application, Union Pacific is active in using sensors to both track milage and hours on the whole of the locomotive fleet as well as examine individual components (Participant 2, personal communication, July 30, 2021). In this model, Union Pacific uses networked sensor suites on the actual locomotives, to include sensors on each of the locomotives 16 power assemblies, as well as 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 a 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 strategy the company currently utilizes. 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 view any historical data within that two-year window instantly (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 work station. 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 in 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 the 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 an operation that is very lean 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) whom 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 from 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. (Participant 3, personal communication, August 23, 2021).

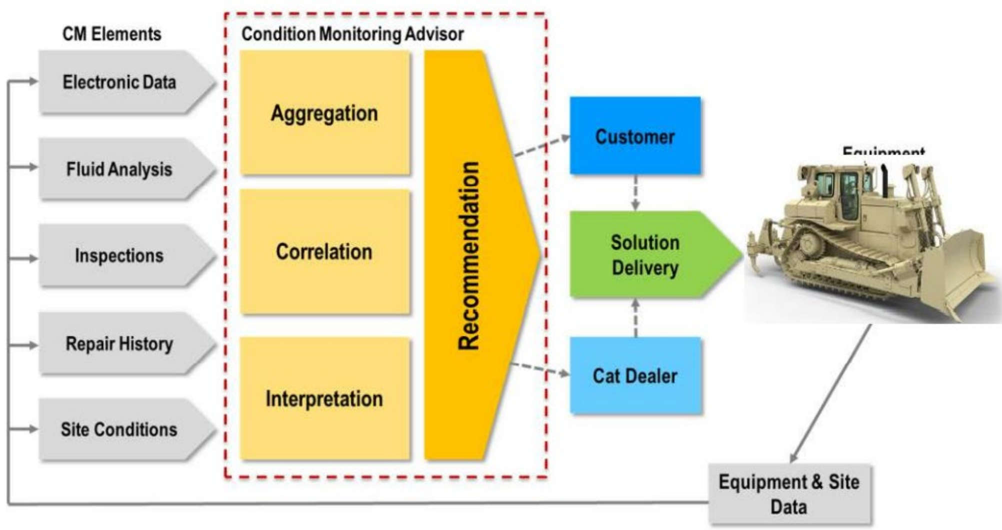

Figure 5. Caterpillar Condition Monitoring Elements and Condition Monitoring Advisor Work Flow. Source: Participant 3, personal communication, August 23, 2021, slide 6.

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, 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 very 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 called the Condition Monitoring Dashboard which enables the Fleet Monitoring Center, Caterpillar dealers, and customers to monitor the condition of equipment 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 customer's 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. If inspections are not being completed to the desired standard or recommended time interval, 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 that 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, if a customer does not purchase Caterpillar's condition monitoring services, then neither Caterpillar nor the customer will have 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 did state 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 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 an 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 all utilize similar strategies in determining 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 are 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 either reducing costs or increasing their revenue stream, or result in increased safety, then it is generally not worthwhile to utilize a CBM/PdM strategy on that asset or component. As our Caterpillar respondent noted, this analysis is a deliberate effort during a potential client's consultation period to determine what equipment should be monitored to ensure their ROI was maximized.

b. ***Discussion:*** During the transition to CBM+, not all assets and components within the Marine Corps ground fleet will need to have sensors installed or be maintained under a CBM approach. While the context, and equipment usage may differ between industry and the Marine Corps, determining what are high-cost driver components and what are 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 maintenance 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 that the cost-effectiveness and complexity of retrofitting existing equipment is not a viable option in most 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 to only acquire systems and platforms that were already compatible with their existing IT infrastructure. By using compatible programs Freeport-McMoRan is able to 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 that had 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 to accommodate an older or not as technologically inclined work force.

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 is completed. 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 increase 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 the 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 handwritten 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 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 attempting 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 to 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 then 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 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 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 capture what we deemed to be most relevant to this endeavor, and highlight 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 being 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 continuingly 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 handwritten 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 milage, 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 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) and 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, a similar rationale as detailed above is recommended for the prioritization of CBM+ compatible acquisition programs with an 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 affected 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 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 affected 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 easy 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 changes 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 the 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 guidelines 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 the 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 (hardwired 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 an 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 selectivity target certain high use, high breakdown assets for CBM+ compatibly 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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