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ASSET CONDITION MANAGEMENT: A FRAMEWORK FOR SMART, HEALTH-READY MANUFACTURING SYSTEMS

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ABSTRACT

Unscheduled downtime in manufacturing systems can be a major source of lost productivity, profits, and, ultimately, reduced process quality and reliability. However, the incorporation of asset condition management (ACM) into manufacturing systems offers an approach to improve equipment and plant operations by providing real-time condition awareness, system diagnostics, and estimates of future health to enable predictive maintenance. ACM is a framework for assessing the current and future state of health of a manufacturing system and integrating that knowledge with enterprise applications to meet the demand of production operations. In manufacturing systems, successful operations rely on the ability to maintain production assets at their optimal working levels to optimize operations and system performance. Some large corporations have made great strides in incorporating smart technologies to enhance their asset management strategy; however, small- and medium-sized enterprises (SMEs) face distinct challenges. One of the key challenges is that most SMEs do not have the wherewithal to invest in new machines nor is there standard guidance on how older machines can be integrated into an ACM solution, so that their end-to-end manufacturing process can be optimized from a health management point of view. This research presents a framework for ACM to facilitate its introduction into manufacturing systems based on their "health-ready" capabilities. Specifically, an ACM system architecture is defined for manufacturing systems, the health-ready principles and capability levels from the aerospace and automotive industries are adapted to the manufacturing domain, and the results from outreach efforts to the manufacturing community are discussed.

Keywords: Health-Ready Capability Levels, Health State; Smart Manufacturing; Diagnostics; Prognostics; Predictive Maintenance

NOMENCLATURE

ACM	Asset Condition Management
CBM	Condition-Based Maintenance
HRCS	Health-Ready Components and Systems
ICD	Interface Control Document
IIoT	Industrial Internet-of-Things
IVHM	Integrated Vehicle Health Management
PdM	Predictive Maintenance
PHM	Prognostics and Health Management
O&M	Operation and Maintenance
OEE	Overall Equipment Effectiveness
OEM	Original Equipment Manufacturer
OUC	Operational Use Case
RCM	Reliability-Centered Maintenance
RUL	Remaining Useful Life
SCADA	Supervisory Control and Data Acquisition
SME	Small- to Medium-Sized Enterprise

1. INTRODUCTION

Many machines are still reactively maintained or are operated in run-to-failure modes of operation [1]. Such an approach can result in the waste of time, cost, and resources. More advanced maintenance strategies include condition-based maintenance (CBM), reliability-centered maintenance (RCM), and the combination thereof, CBM-Plus. Continuous monitoring of an asset's condition to facilitate CBM, can help reduce unscheduled downtime and allow maintenance to be scheduled

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during a financially-opportune time with minimal impact on production operations [2]. CBM has been found to be a sustainable alternative to reactive and preventive maintenance practices [3]. At the very basic level, RCM leverages the detailed study of failure and degradation mechanisms for critical systems to appropriately schedule maintenance actions to enable the reliable operation of these systems and meet user needs. While CBM is a laudable goal, a deeper understanding of the RCM principles has done much to improve maintenance practices across many industries. One notable industry is the aerospace sector where RCM is used to determine maintenance requirements based on the analysis of the likely functional failures of components, equipment, subsystems, or systems having a significant impact on safety, operations, and life cycle cost.. Combining RCM and CBM principles, also known as CBM-Plus, is gaining traction as the U.S. Department of Defense has required its suppliers to follow this strategy [4].

In recent decades, the growth of computing power, the increased use of automation, and the advanced capabilities of sensor technology has facilitated the emergence of the Industrial Internet-of-Things (IIoT) and smart manufacturing. Readily available data has also allowed researchers to apply artificial intelligence and machine learning techniques to manufacturing applications as well. With the shift towards smart manufacturing systems, decision-makers in the factory can go beyond CBM and apply prognostics and health management (PHM) to avoid failures and sizable disturbances via predictions [2,5]. However, several challenges remain in the implementation of PHM and even more so for small- to medium-sized enterprises (SMEs), which represent the vast majority of manufacturers in the United States [6]. For example, legacy equipment likely do not have the digital capabilities that are designed into newer machines to offer plug-and-play solutions for process monitoring. Additionally, SMEs may lack the in-house expertise needed to implement and sustain smart manufacturing technologies [1] and may not have the personnel or financial resources to invest in new machines. A major challenge across manufacturers, however, is that they "lack a standard process and methodology for using [PHM] technologies on the shop floor" [7].

SAE JA6268: Design & Run-Time Information Exchange for Health-Ready Components is a standard that was recently developed to help reduce existing barriers to the successful implementation of Integrated Vehicle Health Management (IVHM) technology into the mobility sector [8]. This standard introduces the concept of "health-ready components and systems (HRCS)." HRCS, in the aerospace and automotive domains, are components that monitor and report their own health (at run-time) so that the health management of the entire aircraft or vehicle can be achieved. For the system to achieve this integrated behavior, JA6268 advocates that the supplier needs to work closely with the system integrator during the design phase to provide sufficient amount of (design-time) information to accurately assess the component's health via a higher-level "reasoning" system on the vehicle. This SAE standard has two primary objectives: (1) to encourage the introduction of a much greater degree of IVHM functionality in future vehicles at a much lower cost, and (2) to address intellectual property concerns by providing recommended design-time and run-time data specification and information exchange alternatives to help unlock the potential of IVHM [8].

This paper presents a framework to facilitate the characterization of an Asset Condition Management (ACM) system based on the "health-ready" capability of the manufacturing assets. ACM has been defined as "*the unified capability of a manufacturing system (i.e., the asset) to assess its current and future state of health and integrate that knowledge of the system state of health with enterprise applications to meet production operations demand*" [9]. This unified capability takes the form of a framework whose goal is to help manufacturers introduce IIoT technologies and advanced maintenance practices into their operations to improve the awareness of a system's health state, reduce asset downtime, and improve productivity and product quality. In this way, operation and maintenance (O&M) can be optimized and the useful life of the system can be extended. The objectives of this research were as follows: 1) define an ACM system architecture for manufacturing systems, 2) adapt the SAE JA6268 principles and Capability Level definitions to the manufacturing industry, and 3) reach out to the manufacturing community to obtain feedback on the key artifacts developed for ACM.

2. ASSET CONDITION MANAGEMENT

The first objective of this research was to define a PHM architecture reference for manufacturing systems. This research effort referenced prior work done in the aerospace and automotive industries [8,10,11] and PHM research for the manufacturing industry [2,7,12]. During this research, the use of "Asset Condition Management" was proposed for the manufacturing industry, since asset management can be recognized and interpreted by the manufacturing community without prior knowledge of PHM. Moreover, the concept behind ACM was introduced to attendees of the ASME Standards Subcommittee Meeting on Advanced Monitoring, Diagnostics, and Prognostics for Manufacturing Operations, held at NIST in May 2019. Several attendees expressed their interest in ACM to better understand its potential and how it could help their manufacturing operations.

ACM has been defined as "*the unified capability of a manufacturing system (i.e., the asset) to assess its current and future state of health and integrate that knowledge of the system state of health with enterprise applications to meet production operations demand*" [9]. ACM can support an enterprise in advancing their maintenance strategies by promoting the appropriate identification of current and desired "health-ready" capabilities throughout the system and manufacturing process. In this context, *"health-ready assets" are manufacturing systems or subsystems with the capability to monitor and report their own health*.

Maintenance practices for manufacturing equipment are based on activities that attempt to extend equipment life and reduce the likelihood of equipment failure. Scheduled and other "preventive" maintenance strategies have been the norm –

achieving maintenance objectives through regular equipment inspections and scheduled maintenance at pre-determined intervals based on operational time, cycles, units, etc. [1]. ACM aims at moving maintenance more towards Condition-Based Maintenance or Predictive Maintenance (PdM) strategies, where it makes sense. In some assets, the preventive and run-to-failure strategies may be enough to meet the enterprise business objectives. CBM and PdM maintenance strategies require the monitoring and management of the condition of the manufacturing equipment to avoid disruptions in operations due to equipment downtime. The objective of ACM is to drive maintenance when it is needed to ensure safety, reliability, availability, and reduced life cycle costs. In practice, these strategies help reduce unnecessary downtime by employing "just-in-time" maintenance procedures.

2.1 A Physical Hierarchy for Manufacturing Systems

To decompose the complexity of manufacturing systems, a physical hierarchy is defined ranging from an enterprise to a component level as represented by Figure 1. Weiss et al. [13] previously described the functions of the entities at each of the levels in terms of activity diagrams, and identified the monitoring and PHM functions at each level. The operational metrics related to PHM at each level flow up to be aggregated at the top level to get an overall picture of the health of the entire system.

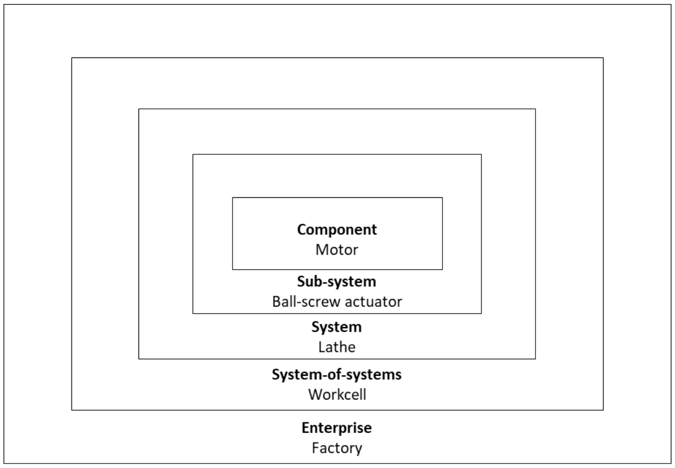

FIGURE 1: THE PHYSICAL HIERARCHY OF MANUFACTURING SYSTEMS

Examples of a physical entity are provided in Figure 1 for each category. At the highest level is the enterprise, which can represent a factory or the larger environment in which the factory operates, such as a collection of factories connected by logistic chains. Next is a workcell or a production line (a system-of-systems). In this case, the "System" is represented by a lathe, and the downstream "sub-system" is a linear actuator. The actuator consists of several components such as the ball-screw, the motor, the motor controller, the tool assembly, etc. Components can be further broken down into sub-components, but for illustrative purposes, the "Enterprise" to "Component" levels are shown in Fig. 1. Also, as has been pointed out by Weiss et al. [13], this is a relative hierarchy. If the focus is at a different level, a component might well become a system, such as what might happen for a motor original equipment manufacturer (OEM).

To understand how one key element of ACM may work in this context, consider the function of estimating the health of the ball-screw actuator. Let us assume that measuring the slew-rate of the actuator is enough to adequately assess one aspect of the actuator health (e.g., the time it takes for the actuator to slew from one position limit to the other and back is enough to determine the health of the system). As all components age, the slew rate increases for the same motor command inputs. By trending this rate, one can calculate a metric indicative of the health of the actuator.

In this example, it is assumed that the slew rate is measured in the computer by measuring the time it takes for the actuator to travel between limit switches. This means that the signals from the switches must be acquired, sampled and encoded, then transmitted to a computer where the analysis is done. Some physical elements are very clear in this implementation. The limit switches are key sensing elements, as are their companion data acquisition electronics, which includes the A/D convertors, for example. In this embodiment, it is assumed that digital data is further transmitted to another central computer for analysis. It is quite conceivable that in another embodiment, the analysis is done in the same location that data is acquired. Such distributed architectures will become more common as distributed computational systems become more feasible with advanced technology, such as higher throughput and faster communications. We present this example, because a lot of interest has been generated in recent decades on the health management of electromechanical systems such as the linear actuator in the mobility sector. This is mainly because of the increase in electrification both of automobiles and aircraft. This trend will continue, and the manufacturing sector can make full use of it to increase its ACM capabilities. To situate this example in the ACM context we compare this with what would be done traditionally in monitoring an actuator of this kind, which is next to nothing! Any estimate of the health of the actuator would be inferred from other parameters further downstream. In a highly ACM-capable manufacturing system, the parameters from the actuator itself will be monitored and its health directly measured. This would be fed to a higher system health management function that would use this lower level intelligence to assess the health of the entire system. The more integrated these capabilities are, the higher the level of health management capability we would assign the system.

2.2 ACM System Architecture Reference

Leveraging sensors and "health-ready systems" in the ACM framework calls for practitioners to focus on identifying and defining information that must be exchanged between the levels in the physical hierarchy or between lower-level components, sub-systems and the higher-level system functions. Hence, data transfer will occur between three tiers: a) Production Assets, Sensors, and Health-Ready Systems, b) Data Acquisition, Contextualization, Integration and Exchange, and c) Enterprise

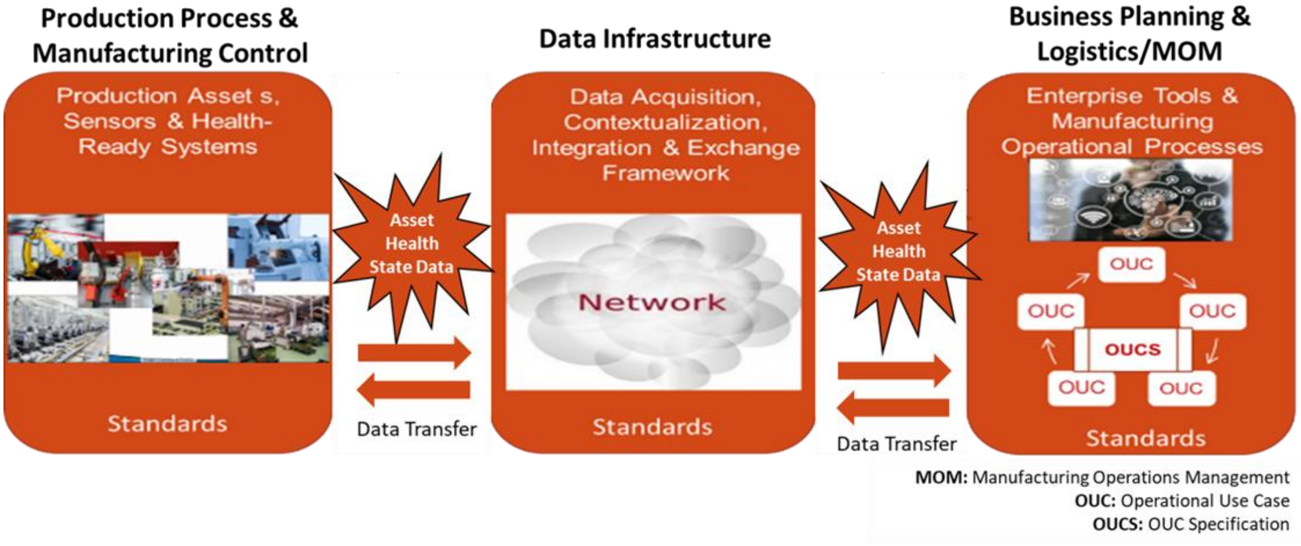

FIGURE 2: AN OVERVIEW OF THE ACM SYSTEM ARCHITECTURE

Tools and Manufacturing Operational Processes (see Figure 2). The ACM system functions can be integrated with the ANSI/ISA-95 Level 0-1-2 functions (production process and manufacturing control) to enable the automation of equipment health data. Knowledge of the equipment state of health may then drive efficiencies and the effectiveness of Level 3-4 (manufacturing operations management and business planning and logistics) functional operations including Maintenance Operations, Production Operations, Quality Operations, Plant Production Scheduling, etc. The ANSI/ISA 95 series of standards address the integration of the enterprise operations with the manufacturing control system [15]; this approach aligns quite well with the concept of ACM.

The Data Acquisition, Contextualization, Integration and Exchange functions can be local (to the specific equipment or process), distributed (e.g., across the factory), or cloud-based (i.e., across the enterprise). The operational use cases (OUCs) express the specific business purpose for using the asset health state data captured by the system; they are used to convey user-specific needs and drive ACM system functional requirements. For example, from an operational perspective, the specific value-added a maintenance department expects from the capability for assessing the individual equipment health, the health of subsystems or workcells.

The objective of this “top-down” approach is to associate the value of ACM with overall equipment effectiveness (OEE) to specify and characterize manufacturing productivity based on equipment and process health. OEE is a commonly used metric across many manufacturing facilities that indicates performance based upon measured productivity, quality, and availability metrics and measures [14]. OEE can be derived at multiple levels of the manufacturing hierarchy, from the enterprise level down to the equipment level. The OUC specification also drives the communication between the business and ACM development teams and provides a way to represent user requirements that align with the operational business requirements. They should be specified in non-technical language and enable ordering, grouping, and prioritization. Also, the use case specification is the primary input for user acceptance testing as well as the development of test cases. Nevertheless, the specific architecture solution depends on the motivating factors driving the need for ACM, the existing infrastructure, and the economics of the situation.

Note that a system implementation may utilize all or a portion of the health-ready functions inherent in the production assets. The reason is that some sensor parameters and lower level diagnostic codes are representative of symptoms and are manifested in higher-level health-state indications. Specifying how each layer in the system produces or uses the data available for exchange was outside of the scope of this research, but future work should leverage existing standards and recommend how data capture, processing, and exchange within and between the architecture tiers should occur for ACM in greater detail.

3. HEALTH-READY CHARACTERIZATION

Historically, manufacturing equipment maintenance policies have been defined based on maintenance actions that attempt to extend equipment life and minimize likelihoods of equipment failure, e.g., preventive maintenance strategies relying on scheduled tasks. ACM can support an enterprise in advancing its maintenance strategies by promoting the appropriate identification of current and desired “health-ready” capabilities throughout the system and manufacturing process.

Starting with data capture, an ACM practitioner characterizes each process or function using technical specifications and interface control documents (ICD). The specific functions and processes depend on the design and implementation of the ACM capabilities considering the physical scope (e.g., the system, sub-system or component level) and the type of equipment involved (e.g., new assets with advanced monitoring capabilities or legacy equipment without them). For example, a certain component might have perfect data acquisition capability, i.e., it can reliably deliver the appropriate data to an acquisition system for a health assessment. This data capture system would buffer the data, convert it as needed and deliver it to the appropriate receivers for further processing (e.g., by a downstream SCADA system). The assessment might end at this point, or, for a more complex sub-system, data processing might be included in the health assessment as well. Such a sub-system might have built-in data normalization and parameter correction, and have the capability of providing such normalized data to the more advanced ACM functions further downstream.

All diagnostic and prognostic analysis systems need to work with processed data. Accordingly, most PHM systems have built-in normalization routines to filter noise and correct for different operating conditions. This way, data under different operating conditions can be compared. In the aerospace domain, for example, this would include correction for standard day conditions, and varying loading factors. The functions or processes involving state detection, health assessment and prognostics assessment might not be very advanced. In fact, it is expected that most assets will not have prognostics capabilities (i.e., capabilities to predict future health states). But for some smarter components, there may be limited ability to assess the current state of health, especially in terms of detecting anomalies and faults. With historical data and analytics, the ability to extrapolate the estimates and to assess remaining useful life (RUL) may also be provided, which would generate the data needed for predictive maintenance. Future efforts will involve some measures of validation.

3.1 Health-Ready Capability Levels

Adapting the SAE JA6268 IVHM Capability definitions [8], a proposed approach for establishing ACM Capability Levels for smart manufacturing systems was developed. The definitions consist of a progression of ACM Capability Levels (from Level 0 to Level 5), which are based on functional aspects of the asset's inherent capabilities:

- **Capability Level 0 - Limited Failure Indicators:** Asset maintenance is prompted by either scheduled preventive maintenance or inspections, when the asset operator is alerted by failure indicator lights or gauges conveying limited awareness, or when the operator observes a performance issue.

- **Capability Level 1 - Diagnostics**: Asset is equipped with diagnostic functions. Maintenance personnel gain diagnostic insight by viewing or extracting operating parameters and/or diagnostic information from the asset. Simple (e.g., relatively high-level) fault isolation information is available.

- **Capability Level 2 - Asset Monitoring**: Asset is equipped with the ability to automatically capture data, possibly store the data, and diagnose based on intelligent algorithms. A key characteristic is that data can be used to monitor real-time performance or to capture performance history over time for subsequent analysis. More detailed fault isolation information is available.

- **Capability Level 3 - Prognostics**: Asset operator and maintenance personnel are provided with alerts of impending faults, listing severity levels, along with estimated RUL, and recommended fault remediation and maintenance actions.

- **Capability Level 4 - Comprehensive ACM**: Asset operator and maintenance personnel are provided with diagnostics and prognostics information at the enterprise level with alerts of impending faults listing severity levels, RULs, and recommended fault remediation and maintenance actions. Limited logistics recommendations may also be provided. This would include resource allocation, resource scheduling, and spare part locations, which may be used to support transportation decisions for tools and material.

- **Capability Level 5 - Self-Adaptive ACM**: ACM capability is integrated with asset control and enterprise management to automate logistics and maintenance scheduling based on available information, resources, and costs. Assets can be automatically (or manually, based on automated advice) reconfigured and repurposed to deliver acceptable performance in the presence of asset or process degradation, with detailed advice on fault remediation and system maintenance.

A key transition occurs between Level 2 and Level 3, where prognostics and predictive analytics are brought to bear to significantly enhance the ACM capability. Moreover, as the levels increase, the maintenance practices shift. For example, maintenance at Level 0 would occur after an inspection or failure. At Level 1 and 2, scheduled maintenance would be coupled with CBM (driven by diagnostic functions) but limited predictive capabilities would be available. At Levels 3 and 4, maintenance would rely on predictions of the asset's condition (i.e., predictive or CBM). Lastly, Level 5 applies CBM with logistics optimization and adaptive process control. Referring to the example of the ball-screw actuator, typical systems are at Level 0 with little or no diagnostic capability. The monitoring of the slew rate as described above would constitute a basic information source that could be used to develop capability at Level 1 or 2 depending on how the information is used. With more sophisticated algorithm that trends the slew rate over time and extrapolates it to estimate RUL, we may even be able to get Level 3 capability. To get to higher levels, the system-wide monitoring and assessment capability must be in place so that the information from the actuator can be used for more than just prediction but also automated maintenance scheduling, etc.

3.2 The Health-Ready Capability Levels in Practice

The outreach to manufacturers was conducted via a survey that was developed and deployed in Qualtrics, as well as one-on-one interviews. The guidelines presented in Sections 2 and 3 incorporate the changes made following the feedback from the outreach efforts. In all, feedback was obtained from six manufacturing entities including four SMEs, one OEM, and one manufacturing trade association.

After being introduced to the ACM definition and the health-ready capability levels (including details about the data acquired and the maintenance practices at each capability level), manufacturing entities were asked which health-ready capability level was achieved by most of their assets and the highest level achieved by their assets. While most assets operated at a Level 2, one manufacturer did operate equipment that achieved a Level 5 as shown in Figure 3. The asset that achieved a Level 5 was a CNC machine tool that had advanced monitoring and control capabilities used for precision manufacturing operations. The machine could self-calibrate based on real-time conditions and optimize the life of the ball-screw, bearings, and rails. In the case where "I don't know" was selected, the manufacturer was an OEM and was unaware of the highest capability level achieved by their suppliers.

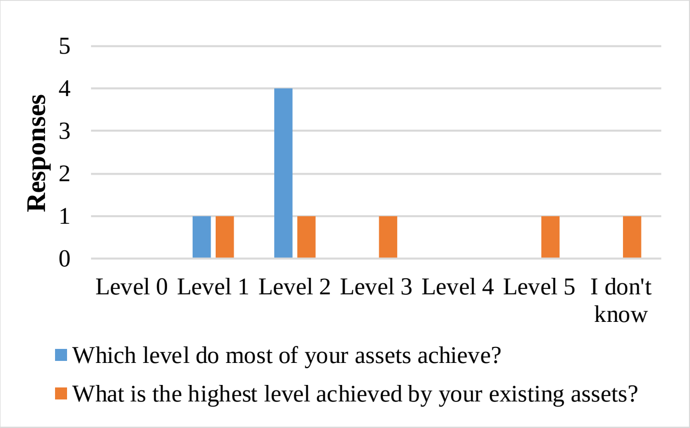

FIGURE 3: ACM CAPABILITY LEVELS OF EXISTING ASSETS; SUMMARY OF RESPONSES FROM THE MANUFACTURERS (EXCLUDES THE TRADE ASSOCIATION).

To further investigate how these assets were maintained, the manufacturers were also asked who the individual or organization was that maintained the assets at the highest level. Table 1 shows the results for all surveyed manufacturers. While routine maintenance was often performed by internal personnel, the supplier of the asset, component, or technology was also a key contributor to maintenance activities as summarized in Table 1. The latter played a key role in maintaining the asset at Level 5 where more sophisticated tasks and deeper knowledge of the asset were necessary.

TABLE 1: THE INDIVIDUAL OR ORGANIZATION THAT MAINTAINED THE ASSET(S) WITH THE HIGHEST ACM CAPABILITY LEVEL AT THEIR FACILITY.

Health-Ready Capability Level	Individual or Organization Maintaining the Asset(s)
Level 0	Not Applicable
Level 1	The supplier of the asset, component, or technology
Level 2	Internal personnel (e.g., technician)
Level 3	The supplier of the asset, component, or technology
Level 4	Not Applicable
Level 5	Internal personnel for routine maintenance and the supplier of the asset for calibration and annual checks.

4. CONCLUSION

Key challenges for SMEs to advance their maintenance strategy include not having the wherewithal to invest in new machines nor standard guidance on how older machines can be integrated into an ACM solution, so that their end-to-end manufacturing process can be optimized from a health management point of view. Legacy equipment may not have the digital capabilities that are designed into today's smart machines, but that does not mean it is impossible to extract high-quality, meaningful data from these assets. Many SMEs may not be realizing the full benefits of ACM because they have older machines and the traditional approach assumes that there is no health-ready capability within the assets. That is, it is assumed that these (legacy) machines don't have the needed sensors to track data or the necessary capabilities to easily connect the assets to a central repository. By retrofitting these systems with sensors and data acquisition units, they may be brought into higher ACM capability levels without excessive investments; the benefits derived from enhancing the capabilities can far outweigh the costs.

The ACM framework offers an opportunity to extend the useful life of manufacturing systems, such that waste and resource consumption can be reduced. It is not the intention of this research to suggest that all manufacturers should maintain their assets at a Level 5. Instead, with the framework in hand, manufacturers can benchmark which health-ready capability level their assets achieve. By comparing the capabilities achieved by alternative systems, they can optimize their decision-making based on the factors that are most critical to their factory or enterprise; for example, the value added, the resources consumed, and the ability to meet their customer's demand.

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