

White Paper: Determining When and Where PHM Should be Integrated into Manufacturing Operations

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1 Introduction

The American Society of Mechanical Engineers (ASME) Subcommittee¹ on Monitoring, Diagnostics, and Prognostics for Advanced Manufacturing has produced this white paper to highlight the rationale and key considerations behind the initiative to develop **guidelines** for **when** and **where** manufacturers should integrate advanced monitoring, diagnostic, and prognostic (also known as prognostics and health monitoring (PHM)) technologies within a factory. The proposed guidelines will include recommended best practices to

- (a) identify areas where operational efficiencies can be improved
- (b) define use cases linked to desired safety, environmental, and cost-benefit factors as well as operational improvements
- (c) establish a baseline of current maintenance practices and health-ready capability levels
- (d) implement cost-effective equipment asset condition management (ACM²) strategies and measure their effectiveness in improving operational efficiencies

The goal is to help enterprises of all sizes make informed decisions about the addition and integration of PHM technology into factory equipment assets within existing or new manufacturing operations.

2 The Rationale

PHM technologies were developed by the aerospace, energy, and process industries [1] [11] [12] and are increasingly used within the manufacturing community [2]. PHM can be defined as the discipline focused on monitoring, diagnostics, prognostics, and health management of either products or processes to promote cost effective maintenance strategies [3]. Fortune 500 manufacturers, such as Boeing, General Motors, and General Electric, are leveraging emerging PHM technologies within their maintenance strategies. PHM-related technological advances may be adopted by companies as part of equipment and infrastructure modernization efforts. These technologies are designed to reduce equipment downtime through the early detection of equipment anomalies and prediction of failures associated with machine tools, manufacturing cells, supporting subsystems, systems of systems, and overall manufacturing processes.

Interest in PHM is growing within the manufacturing industry, but there is limited guidance or recommended best practice on **where** and **when** PHM should be integrated to improve manufacturing operations. One metric that is often used to assess manufacturing operations is overall equipment

¹ <https://cstools.asme.org/csconnect/CommitteePages.cfm?Committee=102342234>

² Asset condition management (ACM) can be defined as the unified capability of a manufacturing system (i.e., the asset) to assess its current state of health and use that knowledge to predict when equipment will fail so that preventive maintenance can be performed to maintain system health and meet production operations demand.

effectiveness (OEE). This metric measures an asset's ability to perform its specified function reliably, at desired quality specifications, and on time [4]. This white paper highlights key considerations for addressing how manufacturing problems, or pain points, may be addressed through the implementation of appropriate PHM technologies. This white paper also discusses a proposed functional reference model to assist manufacturers in assessing the current capability levels of their health-ready assets³. This reference model can be instrumental in determining where PHM technology can be best integrated into the manufacturing process.

3 Determining Equipment and Manufacturing Process Pain Points

What is the potential value of PHM for manufacturing? To determine this, it is necessary to assess not only the health of individual equipment but also that of subsystems, work cells, and potentially the manufacturing process. The objective of this collective assessment approach is to associate the value of PHM with OEE to specify and characterize manufacturing productivity based on process and equipment health. A manufacturer typically has a data collection process to measure and monitor the operational (process) parameters that affect equipment availability, productivity, and quality of operations. This historical process data, along with maintenance work requests data, can be used to identify the process pain points that may be ripe for PHM implementation. The aggregated data provide the basis for developing operational use cases that support the manufacturer's objectives and the needs of the various stakeholders (e.g., maintenance, process control, operations management). In some industries, PHM investment returns the most value when the business strategy for its application is clearly identified and when it is combined with an overall strategy to improve operational efficiencies [5].

3.1 Assessing Manufacturing Equipment Health

Monitoring the operational performance of individual pieces of equipment assets that contribute to the most critical functions is the intuitive way to assess what can go wrong in a manufacturing process. It also makes sense to pay attention to production-critical equipment with a history of failures, and those pieces that undergo accelerated usage or excessive duty cycles, have costly repair or maintenance profiles, are lacking redundancy within the process, or are difficult to replace. Some equipment vendors provide health-ready assets with embedded sensors for detecting failures, and some offer comprehensive monitoring strategies (e.g., specification of sensors) associated with the equipment's critical failure modes. In other cases, the equipment-monitoring strategies are known in industry or specified by operators, plant managers, and other domain experts.

Individual equipment health is still largely assessed using relatively simple caution and warning thresholds on sensed parameters. However, advances in PHM technology, coupled with network communications and increased processing power, have made enhanced sensors and analytical strategies for detecting or predicting equipment failures possible [6]. Numerous manufacturing equipment components, from rotating machinery to robotic systems, are more effectively monitored using techniques such as statistical processing, historical trending, the application of physics and empirical models, sensor fusion, event correlation, expert system techniques, and model-based reasoning.

³ "Health-ready assets" are manufacturing systems with the capability to monitor and report their own health.

The assessment of equipment health within a manufacturing process is further improved when the manufacturer takes a “process-centric” view of the equipment’s role. This is particularly important when evidence of an equipment failure is observed from process performance indicators or data obtained across subsystem boundaries or from other locations within the manufacturing process (e.g., upstream or downstream). A process-centric approach complements industry best-of-breed approaches to equipment monitoring by introducing improved awareness of incipient or predicted failures based on the assessment of manufacturing operations performance.

3.2 Assessing Manufacturing Process Health

An assessment of overall process health can produce actionable awareness regarding availability, profitability, quality, sustainability, and reliability of a manufacturing process. This information is also useful for establishing proactive, condition-based, or predictive maintenance strategies intended to keep the process operational, safe, and efficient. Other benefits associated with this process-centric approach include increased digitalization across the manufacturing enterprise and increased access and integration with production, equipment, and process data. Faster processing platforms, increased memory storage, and increased prevalence of distributed computing platforms provide additional opportunities for leveraging computationally-intensive strategies along with model-based prediction and reasoning. These technological improvements make it possible for PHM practitioners to better realize the value of real-time awareness of manufacturing effectiveness based on process performance indicators.

The process-centric approach requires practitioners to consider the following when assessing process health:

- (a) There is an important distinction between assessing a manufacturing process’s functional health and simply describing an equipment asset condition using condition indicator parameters. Manufacturing equipment vendors are relatively adept at identifying condition indicators, and these threshold-based alerts offer manufacturers interested in improving their equipment health assessment capability a great place to start. However, this approach provides limited understanding with respect to process health. When problems arise, there is often an excessive number of uncorrelated low-level alarms, which creates a confusing situation for operators and may misdirect their efforts. The implementation of PHM technology should increase situation awareness, provide contextual intelligence and understanding to managers and operators, and ultimately reduce the time it takes to restore a degrading asset or process to a healthy state by sending accurate actionable data to the users.
- (b) When evaluating the function of each asset within the manufacturing process, consider the impact of its failure on the process and define the monitoring requirements accordingly. In other words, the monitoring strategy for manufacturing equipment should be designed to respond to observed or predicted reductions in the asset’s ability to perform its stated function. This procedure is greatly aided by performing a reliability analysis, such as a failure modes and effects analysis [7] or a reliability-centered maintenance [8, 12] technique, of both the machine and the process. Reliability analysis helps identify the most critical functional failures as well as highlight the observable (and potentially measurable) effects of those failures on the manufacturing process. Ideally, the analysis should be performed over the entire enterprise, since a more holistic approach can generate better insights regarding **why**, **when**, and **where** data should be collected [11]. This approach also helps identify the optimal sensor suite required to unambiguously manage all critical failure modes. In this context, a trade-off between the cost and performance of chosen sensors and the criticality of identified functional failures should be made. The objective

is to determine whether a chosen sensor suite is adequate for providing the desired fault coverage, or whether an identified sensor adds any useful information with respect to equipment or process health.

- (c) In many cases, reliability analyses that have already been performed by the equipment vendor can provide the practitioner with adequate insights. Most reliability analyses attempt to characterize equipment reliability, failure modes, and likelihoods and consequences of failure. However, they rarely provide a functional perspective or consider the process's operational context—things that are helpful when attempting to leverage PHM technology [9]. Nonetheless, if reliability analyses and in-service failure data are available, they should be used in the assessment process.

4 Advancing Maintenance Strategies in an Enterprise

The incorporation of PHM into manufacturing is having a positive effect on equipment and plant maintenance [3]. Maintenance policies have typically been based on the performance of routine maintenance actions that attempt to extend equipment life and minimize the likelihood of equipment failure. Scheduled maintenance and other preventive methods have long been the norm, and maintenance objectives have been achieved through regular equipment inspections and scheduled maintenance at predetermined intervals based on operational time, cycles, units, etc. ACM redirects maintenance policies toward condition-based maintenance (CBM) or predictive maintenance (PdM). These strategies require monitoring and managing of the condition of the equipment assets to avoid disruptions to manufacturing operations due to equipment downtime.

The CBM/PdM strategies dictate that maintenance be performed when certain indicators show evidence of equipment degradation or decreased performance. The objective is to drive maintenance based on the evidence of need while ensuring safety, reliability, availability, and reduced life-cycle cost. In practice, these strategies help to minimize unnecessary downtime by employing “just-in-time” maintenance procedures. ACM can support the maintenance strategies of manufacturers by promoting the appropriate identification of current and desired health-ready capabilities throughout the system and manufacturing process.

4.1 ACM Functional Reference Model and Operational Processes

ACM capability includes the asset health monitoring and data processing functions inherent within the assets. It also includes the data acquisition, integration, contextualization, data exchange, and tools and processes used to manage and restore the asset or work cell to a healthy state. These functional elements are required to deliver a complete ACM solution and drive the operational and economic benefits targeted by a manufacturer.

A functional reference model has been defined in [13] that can be used to characterize where PHM capabilities are required within a manufacturing process (component, subsystem, or work cell) to support ACM. It is important to note that the system functions could be part of inherent design within or external to the asset. The objective is to leverage, as much as possible, the inherent equipment health-monitoring functions to enable the ACM capability.

The cited functional reference model is based on ISO 13374 and the Open Systems Architecture for Condition-Based Maintenance (OSA-CBM) specification [10]. The functional elements include (bottom to top): data acquisition, data manipulation, state detection, health assessment, prognostic assessment, and advisory generation. The ACM core operational processes enabled by the functional blocks are summarized in Figure 1.1-1.

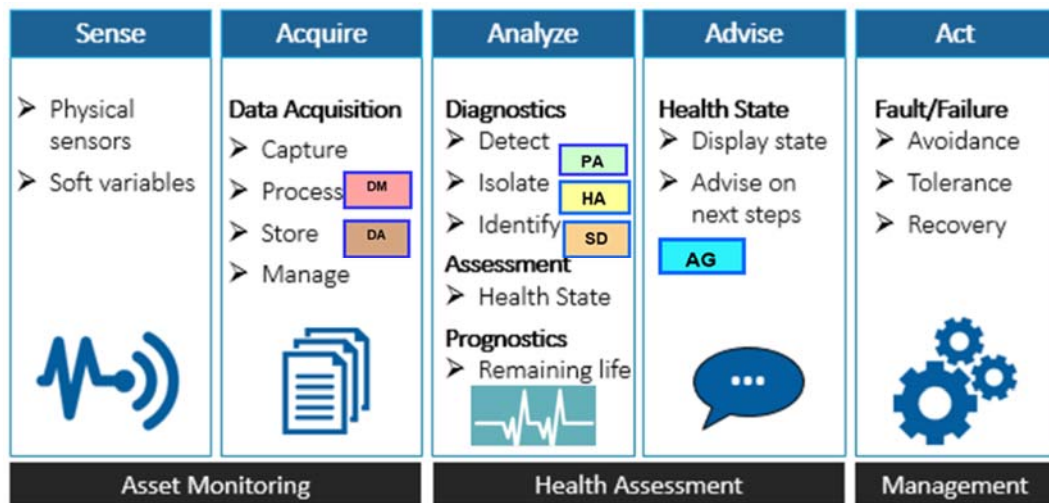


Figure 1.1-1 Asset Condition Management Operational Processes

As shown in Figure 1.1-1, ACM depends on several operational processes. Data from the system's physical sensors and any "soft" (calculated or virtual) performance or control variables available within the system enable the "sense" process. The "acquire" process is enabled by the data acquisition and data manipulation functions inherent in the system design. These include data capture (including spot readings), processing, storage, data management, and data communication. The state detection, health assessment, and prognostic assessment functions either inherent in the system design or external to the system enable the "analyze" process. These functions include fault detection, isolation, identification, assessment of the system's health state, and estimation of the performance life remaining. The advisory generation function, inherent in or external to the system, includes presentation of health state data, prescriptive information, or display advisories, and enables the "advise" process.

Finally, the "act" process uses the information generated in the advise component to initiate actions to return the system to a healthy state or predict allowable control parameters, enabling, for example, the completion of a production run under a (known) degraded state. The goal is to provide a level of autonomous failure tolerance and recovery as well as operator-initiated failure avoidance and preventive maintenance actions.

4.2 Implementing ACM in Existing Manufacturing Operations

The proposed guide to aid the manufacturing community will include recommended best practice guidelines for implementing ACM in existing manufacturing operations. These recommendations include the following:

- (a) Review the manufacturing operations, inclusive of the specific manufacturing processes and the equipment employed to enable these processes, to understand the functional role and interdependence between the manufacturing asset health and the health of the manufacturing process.
- (b) Review maintenance records to understand which manufacturing lines and machines have high frequency of or high-impact failures.
- (c) Meet with maintenance team(s) and process engineer(s) to identify critical failure modes or issues with selected assets and processes.
- (d) Develop the top-priority operational use cases for ACM implementation to determine the feasibility of supporting the initiative using existing equipment health-ready levels.
- (e) Assess process level and quality measurement data, if available, and monitor mechanisms needed for quality-related initiatives.
- (f) Assess the ability to extract data from the control system and the feasibility of adding external sensors to the equipment, if needed.
- (g) Reference past use case experience to assess how difficult it is to implement ACM to improve a process or machine.
- (h) Select the optimum ACM integration approach based on the cost/benefit, anticipated revenue gains, likelihood for success, and cost of the effort to develop, deploy, and sustain the ACM solution.

Ideally, the selected operational use case will have high business value and a high chance for success, but that is not always possible. The business case is usually based on some aspect of OEE that the manufacturer wants to improve, such as reducing unplanned downtime, cycle time, or scrap; improving quality improvement; or shifting maintenance operations to a condition-based maintenance practice.

5 Summary

Based on the current state of PHM technology implementation in other industries, and the points discussed in this white paper, the ASME Subcommittee on Monitoring, Diagnostics, and Prognostics for Advanced Manufacturing was formed to develop guidelines for advancing the implementation of PHM in manufacturing operations. These include a **guide** to help the manufacturing community determine **when** and **where** PHM technology should be integrated within a factory. The guidelines will also include recommended best practices, as discussed in this white paper.

The foundation for the guidelines is a proposed functional reference model based on ISO 13374⁴ and the OSA-CBM⁵ specification [10]. The benefits of using a standard functional reference model include:

- (a) a common methodology for characterizing and revealing the equipment and process health-monitoring functions; and the constraints for the required functional elements listed in Figure 4.1-1
- (b) a common functional reference for determining ACM capability levels
- (c) a reference for applying existing industry standards and developing new ones specific to manufacturing

It should be noted that the proposed reference model can be used, as described in this white paper, to make informed decisions regarding the addition and integration of PHM technology into factory equipment assets—component, subsystem or work cell—within existing or new manufacturing operations in an enterprise of any size.

References

- [1] Roemer, Michael. J., Kacprzyński, Gregory J., Nwadiogbu, Emmanuel O., & Bloor, George. "Development of diagnostic and prognostic technologies for aerospace health management applications." *Proceedings of the IEEE Aerospace Conference* (2001).
- [2] Vogl, Gregory W., Weiss, Brian A. & Helu, Moneer M. "A review of diagnostic and prognostic capabilities and best practices for manufacturing." *Journal of Intelligent Manufacturing* Vol 30, Issue 1 (2019) pp. 79-95. <https://doi.org/10.1007/s10845-016-1228-8>
- [3] Milojevic, Milos and Nassah, Frank. *Digital Industrial Revolution with Predictive Maintenance*. CXP Group, (2018).
- [4] Hansen, Robert C. *Overall Equipment Effectiveness (OEE)*. Industrial Press. (2005) [ISBN 978-0-8311-3237-8](https://www.industrialpress.com/book/9780831132378).
- [5] Thomas Dabney, Luis Hernandez, Philip A. Scandura Jr., and Roger Vodicka. "Enterprise Health Management Framework - A Holistic Approach for Technology Planning, R&D Collaboration and Transition", Proceedings of PHM Society Conference (2008).
- [6] Pavel, R., Iverson, J. C., "Machine Tool Health Characterization using Condition Monitoring and Prognostic Based Technologies", MFPT 2012: The Prognostics and Health Management Solutions Conference, Dayton, Ohio, April 24-26, 2012.
- [7] *Procedures for Performing a Failure Mode, Effects, and Criticality Analysis* (Military Standard), MIL-STD-1629A, Washington D.C.: Department of Defense (1980).

⁴ ISO 13374 is a published standard providing guidelines to support condition monitoring and diagnostics of machines

⁵ OSA-CBM is a standard architecture for communication data within a condition-based maintenance system

- [8] Moubray, John. *Reliability Centered Maintenance, Second Edition*. Industrial Press, New York, N.Y. (1997).
- [9] Walker, Mark and Kapadia, Ravi. "Integrated Design of Online Health and Prognostics Management", *Proceedings of the PHM Society* San Diego, CA, (2009).
- [10] *Mimosa (2013b)*. OSA-CBM 3.3.0. (2013) <http://www.mimosa.org/?q=resources/specs/osa-cbm-330>
- [11] N. K. Verma, R. K. Sevakula, S. Dixit and A. Salour, "Intelligent Condition Based Monitoring using Acoustic Signals for Air Compressors", *IEEE Trans. on Reliability*, vol. 65, no. 1, pp. 291-309, Mar., 2016.
- [12] N. K. Verma, R. K. Sevakula, S. Dixit, A. Salour, "Ranking of Sensitive Positions Based on Statistical parameters and Cross Correlation Analysis" *International Journal on Smart Sensing and Intelligent Systems*, vol. 6, no. 4, pp. 1745-1762, Sep. 2013.
- [13] S. Holland, T. Felke, L. Hernandez, R. Safa-Bakhsh, and M. Wuensch, "Health Ready Components – Unlocking the Potential of IVHM," *SAE International Journal of Materials and Manufacturing*, vol. 9, no. 2, pp. 217-223, May 2016.

Acronyms

ACM	Asset Condition Management
AG	Advisory Generation
ASME	American Society of Mechanical Engineers
CBM	Condition-based Maintenance
DA	Data Acquisition
DM	Data Manipulation
HA	Health Assessment
ISO	International Organization for Standardization
OEE	Overall Equipment Effectiveness
OSA-CBM	Open Systems Architecture for Condition-Based Maintenance
PA	Prognostics Assessment
PdM	Predictive Maintenance
PHM	Prognostics and Health Management
SD	State Detection