8-9-2022

Assessing readiness for implementation of prognostics and health management in small and medium enterprises

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A Thesis
Submitted to the Faculty of
Mississippi State University
in Partial Fulfillment of the Requirements
for the Degree of Master of Science
in Industrial and Systems Engineering
in the Industrial and Systems Engineering

Mississippi State, Mississippi

August 2022

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Date of Degree: August 9, 2022

Institution: Mississippi State University

Major Field: Industrial and Systems Engineering

Major Professor: Linkan Bian

Title of Study: Assessing readiness for implementation of prognostics and health management in small and medium enterprises

Pages in Study: 52

Candidate for Degree of Master of Science

Prognostics and Health Management (PHM) refers to using robust sensing, monitoring, and control to detect, assess, and track system health degradation and failure modes, allowing for enhanced management and operational decisions. The need for PHM within a manufacturing facility has increased due to a variety of reasons, such as the increasing complexity of manufacturing equipment.

A lack of readiness for digital implementations is linked to failure. The literature highlights certain barriers and enablers that can signal whether a technology implementation will be successful, such as management and maintenance employees' desire to change the existing process, an understanding and willingness to take risks with technology, and having employees with the right competencies and motivations.

This thesis identifies barriers and enablers related a successful PHM implementation and develops an assessment tool to identify a company's readiness level as well as recommendations for increasing the probability of success.

DEDICATION

This thesis is dedicated to my husband, J. Brad Fuller, and my children, Emily Paige, Hallie, and Max Fuller. Without their support, encouragement and grace, this work would not have been possible.

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CHAPTER I

INTRODUCTION

Prognostics and Health Management (PHM) is a term that refers to the utilization of robust sensing, monitoring, and control to detect, assess, and track system health degradation and failure modes to allow for enhanced management and operational decisions (Jin et al., 2016; Uckun et al., 2008). In recent years, the need for PHM within a manufacturing facility has increased due to a variety of reasons. The increasing complexity of manufacturing equipment has forced the maintenance community to shift to meet the increased quality and reliability demands (Jin et al., 2016; López et al., 2014). A recent McKinsey report found that these transformations, when done well, can increase asset availability by 5% to 15% and reduce maintenance costs by 18% to 25%. While larger enterprises are typically better prepared to take this next step in their maintenance strategy, small and medium enterprises (SMEs) often struggle and face very different barriers or challenges. Although there is no explicitly defined definition for a SME, the US Department of Commerce defines it as an enterprise employing 500 or less people. This thesis details a research effort aimed at understanding the level of organizational readiness to implement PHM in SMEs. In addition to documenting the challenges that SMEs face when implementing PHM, an assessment tool has been developed to evaluate the current levels of organizational readiness and exiting usage of intelligent maintenance in a SME as well as determine areas for improvement to increase the probability of a successful PHM implementation.

CHAPTER II

STATE OF THE ART

A widespread problem among many SMEs is the ability to successfully implement a PHM system. The literature review shows that PHM is important for SMEs to implement and there are considerable gains that can be realized from a successful implementation, however there are no defined standards or methods on exactly when to do it, where to do it and how to do it although groups of researchers are actively working on those problems. Bradbury et al. recommends that a critical step for most organizations is shifting to a proactive, comprehensive approach to their digital maintenance and reliability strategy. This needs to start with a detailed assessment of the current practices. In this thesis, we (1) identify roadblocks for the implementation of PHM in SMEs, and (2) develop an assessment tool to determine the readiness for PHM implementation for SMEs.

Jin et al. conducted research to understand what level of intelligent maintenance technologies and strategies are being used by the manufacturing community. The results of that survey show that many organizations are considering implementing various condition-based maintenance approaches. Furthermore, most of these manufacturers use a combination of metrics to track part quality, throughput, and overall maintenance effectiveness. Helu & Weiss performed a similar survey and discovered that many SMEs believe they understand the performance of their manufacturing processes until they are presented with data collected from their systems. This generates a strong motivation for the SMEs to explore available opportunities that come with improved sensing, health management, and control. Wang maintains that the key factors needed to achieve stable production are monitoring the health of equipment and optimizing decision making. PHM aims to meet both goals by instituting diagnosis and prognosis.

Currently, PHM tools are highly customized for each enterprise, meaning these tools are not available for off-the-shelf purchasing. Significant effort goes into developing the business case, selecting the right areas for implementation, and incorporating data analytic algorithms and models based on the SME's system. There is no documented right way to do PHM implementation. There are best practices available, but the majority of those are geared toward larger organizations or to implementation of PHM on specific types of equipment/industries (Nguyen et al., 2019) or items such as batteries (Meng & Li, 2019). A research gap exists related to a SME's readiness to implement PHM. Multiple studies outline how to implement advanced sensing and health monitoring for applications ranging from asset level up to asset group as outlined by (Zonta et al., 2020) However, assessing and understanding an organization's readiness to implement PHM studied very little and is a ripe area for further research. Therefore, there is an urgent need for identifying the characteristics that indicate a SME is ready to implement advanced maintenance capabilities such as PHM.

What follows is a detailed literature review of PHM as it relates to SMEs, explaining more about PHM and its impact on the industries, how it can help SMEs, and the implementation challenges and enablers SMEs face. Following the discussion on barriers and enablers, a detailed assessment methodology and case study are presented.

2.1 What is PHM?

PHM has two main functions, diagnosis and prognosis. Adams et al., defines the diagnostic problem as ascertaining the current health state of the process or component and upon failure, determining the element that failed. The prognostic function attempts to estimate the future state, normally specified by the term remaining useful life (RUL). According to Si et al., RUL is defined as the "estimated time until the component or machine either fails or degrades such that it no longer performs its intended function".

PHM for small and medium enterprises (SMEs) remains uncharted territory for the most part. Much of the research is centered around surveys and generalizations about maintenance strategies for SMEs. Although many frameworks exist for implementing PHM, no papers were found that defined a method to assess the readiness of SMEs for implementing PHM. A white paper (Hernandez et al., 2019) published out of the American Society for Mechanical Engineers Subcommittee on Monitoring, Diagnostics, and Prognostics for Advanced Manufacturing hopes to define a roadmap for when and where PHM should be integrated into manufacturing operations. Ideally, the "when" portion will help manufacturers assess their readiness for some level of advanced monitoring of machine health.

2.1.1 Understanding the Relationship between PHM and Industry 4.0

PHM may be a relatively new discipline in the maintenance world, but Industry 4.0 is a commonly used phrase to indicate cyber-physical systems, which is the integration of virtual and physical manufacturing (Lasi et al., 2014). These cyber-physical systems include smart manufacturing, digital manufacturing, cloud manufacturing, Industrial Internet of Things (IIoT) and advanced maintenance strategies (Helu & Weiss, 2016). Condition based maintenance (CBM), reliability centered maintenance (RCM) and E-maintenance have all been developed under the advanced maintenance strategies umbrella (Baglee et al., 2016). These advanced predictive maintenance activities help lay the groundwork for implementing PHM. McKinsey notes that "advanced predictive maintenance (PdM) is one of the most widely heralded benefits of Industry 4.0."

The argument can be made that PHM is a subset of Industry 4.0 due to the digital and physical nature of PHM. Little research has been conducted specifically for PHM implementation; however, Industry 4.0 implementation has been extensively studied and documented for SMEs as well as larger manufacturers. Many of the implementation barriers and enablers discussed in those studies can be applied to PHM, given that PHM is a critical component of Industry 4.0 (Biggio & Kastanis, 2020).

2.2 Impacts/Significance of PHM on Manufacturing and SMEs

According to the Office of the United States Trade Representative, over the past few decades, 30 million SMEs account for nearly two thirds of new private sector jobs, leading to the notion SMEs must do everything in their power to remain competitive and viable. Due to high global competition, SMEs are compelled to improve their performance standards in the dimensions of quality, cost, productivity, product introduction time, and product distribution time. Furthermore, SMEs provide a great many job opportunities and often act as specialist suppliers for parts, components, and sub-assemblies for larger organizations (Baglee et al., 2016).

PHM and other advanced maintenance strategies have been shown to help organizations of all sizes, including SMEs, make more informed decisions regarding the performance and maintenance of their equipment. Adams et al. point out that several studies surrounding PHM in intelligent manufacturing environments have shown that adopting maintenance policies that recommend activities based on machine health have lower operational costs than time based or run to failure policies. Manufacturing has changed drastically and experienced true globalization in the past few decades by moving offshore or re-shoring by bringing it home. Stentoft et al., documents the reasons for the shifts are due to cost advantages, proximity to customers, requirements for local content, need to improve quality, lead time and flexibility.

Maintenance activities have become increasingly important and complex as factory and machine automation increases. For many manufacturers, their production equipment represents much of their invested capital. When these assets begin to degrade or deteriorate, production costs increase, product quality can be reduced, and energy consumption can significantly increase (Baglee et al., 2016). These costs can be more easily absorbed by large enterprises as opposed to smaller enterprises. Traditionally, SMEs have outdated, older equipment that cannot be easily replaced. Baglee et al. further states that SMEs must look beyond the conventional upgrade of machinery, production processes, supply chains, and marketing strategies to remain competitive. PHM can provide insight into asset degradation and help to mitigate the increased cost of production, poor quality, and unintended failures.

It has been shown that organizations utilizing effective maintenance activities more often emerge as winners. Furthermore, quality and maintenance functions are proven to be vital factors in achieving sustainability in an organization (Baglee et al., 2016). There are benefits for using PHM in all stages of system life cycle (López et al., 2014).

Lasi et al. introduces the idea of technological push and application pull as the driving force behind the shift in manufacturing to Industry 4.0. Technological push comes from the increased mechanization and automation, increased digitalization, and continued miniaturization of devices and components. Application pull comes from the market demanding shortened product development times, increased individualization, the need for flexible production, faster decision making, and increased resource efficiency. This shift in manufacturing has resulted in highly automated systems that will benefit from the implementation of a PHM strategy, no matter the size of the enterprise.

The studies discussed in the above sections all detail the benefits of PHM and how implementation of PHM can result in improvements across a variety of business units within the manufacturing world. However, the readiness of a company to implement PHM or any type of advanced maintenance practices is not reported on. Identification of those factors that lead to a successful PHM implementation will provide the basis for the development of the methodology to assess an organization's readiness to incorporate advanced maintenance practices and together satisfy the primary goals of this thesis.

CHAPTER III

UNDERSTANDING PHM IMPLEMENTATION WITHIN SMEs

New technology implementation is a challenging and complex task, fraught with significant barriers, both technical and economical (López et al., 2014). We find that many implementation efforts fail for any number of reasons and the condition monitoring tools often end up unused (Baglee et al., 2016). Adams et al. argue that most of the literature reviews available assume the machine or system for PHM implementation has already been established or identified. There are few publications that cover how to scope the system and determine which asset should be monitored. As Jin et al., 2016 states, many SMEs appear less able or willing to initiate change in their maintenance functions. This points to the notion that many SMEs are risk adverse or do not have the support needed to jump into a new technology, even if it can save them time and money.

Rauch et al., conducted a series of workshops across the world to gain input from SMEs related to smart manufacturing. The goal of the workshops was to understand, from the SME point of view, any specific requirements to implement smart manufacturing. The workshops identified barriers such as lack of support or acceptance by top management, lack of expertise in managing or implementing industry 4.0 technologies, limited numbers of qualified staff or resources for the implementation and execution of new technologies, insufficient facility infrastructure to support new technologies, and perceived risk related to data security.

3.1 Readiness for Implementation

Ali & Miller found that the lack of readiness for digital implementations is linked to failure. The same can be said for many other changes, whether it's policy, cultural, or strategic. Increased readiness leads to increased utilization and increased probability of success. There are factors that can signal readiness, including pressure from both management and maintenance employees to change the existing process, willingness to take risks with technology, sufficient knowledge about the technology, having employees with the right competencies and motivations, and top management support in terms of finances and communication (Haug et al., 2011). Ensuring that an organization is ready and prepared for the implementation will yield a greater chance for success. It should be noted that just because all these factors are present in a SME, it may not be ready for PHM implementation.

Multiple articles were discovered that discuss readiness or maturity assessments for Industry 4.0 or technologies that enable Industry 4.0 (Pacchini et al., 2019; Schumacher et al., 2016; Sony & Naik, 2019), however, no mention of strategies or methodologies to perform an assessment of readiness for PHM implementation were discovered during the literature review. Many papers discuss the barriers for transitioning to Industry 4.0 or implementing an ERP system or other IT system. This lack of assessment availability leads to the assessment methodology discussed in section **Error! Reference source not found.**. The following sections identify some of the barriers that need to be removed or mitigated for a successful implementation, as well as some existing enablers that may allow SMEs to be better positioned for an effective PHM implementation.

3.2 Barriers for PHM Implementation

Based on an extensive literature review, most barriers for implementation can be grouped into four main categories: organizational, resource constraints, technology and data and documentation. This agrees with the results Jin et al. discovered as barriers for why SMEs are not considering advanced CBM/PHM technology. From that survey, cost, human resources, technology support, and organizational readiness were the primary barriers.

Table 3.1 summarizes the barriers identified during the literature review.

Table 3.1 Barriers to PHM Implementation for SMEs

Main Category	Subcategory	Barrier
Organizational	Strategic	SME owners lack long term vision, meaning medium- and long-term strategies such as digitization and PHM implementation are rare in SMEs. (C. Wang et al., 2007)
		They seldom have strategic planning horizons and generally end up resorting to firefighting rather than long term responses. (Baglee et al., 2016)
		CEO involved in and focused on daily operations, rather than strategizing and focusing on development or future growth. (Buonanno et al., 2005)
	Risk	Small and Medium Manufacturers (SMMs) appear less able or willing to initiate change in maintenance functions. (Jin et al., 2016)
	Requirements	SMEs are constrained by lack of knowledge and understanding of the requirements which need to be in place before adopting an advanced maintenance strategy. (Baglee et al., 2016)
	Structural	SMEs typically have less formal organization and communication is close and informal. (Durst & Bruns, 2018)
		Company size influences the key factors, and large firms are generally more advanced than SMEs, particularly with respect to maintenance effectiveness level, maintenance strategy level, profitability level, continuous improvement level, human factor level, and organizational readiness level. (Jin et al., 2016)
		SME face more barriers for change in terms of organizational structure and readiness for innovation. (Jin et al., 2016)
		SMEs have flat organizational structures, riddled with limited resources. Lack the financial resources to have in-house experts or to hold on to the knowledge they gain. (Baglee et al., 2016)
	Financial	SMEs often lack funds for implementing expensive software such as Enterprise Resource Planning (ERP) systems. (Xiong et al., 2006)
		SMEs, hampered by limited funds, are unable to look beyond conventional upgrade of machinery, production processes, supply chains, and marketing strategies. (Baglee et al., 2016)

Table 3.1 (Continued)

Main Category	Subcategory	Barrier
Resource Constraint	Labor	Only 5% of machines in manufacturing facilities are currently being monitored digitally. (Waurzyniak, 2015)
		SMEs experience higher labor turnover rates, where unskilled workers join SMEs for a short period of time and when they are fully equipped with the required skills, leave to join larger enterprises. (Bala Subrahmanya, 2015)
		SMEs often have excessive cost of product development projects. (March-Chordà et al., 2002)
		SMEs typically have limited finances and human resources. (Jin et al., 2016)
		Many SMEs have labor intensive and traditional management practices which leads to inefficiency. (Hashim & Wafa, 2002)
Technology	New technology issues	SMMs have fewer resources and less experience in managing new technologies. (Blili & Raymond, 1993)
		SMEs find it increasingly challenging to navigate the new technologies available. (Helu et al., 2015)
	Ill-Fitting Technology	Technologies have been developed without a good understanding of the capabilities and limitations of the manufacturing environment. (Helu & Weiss, 2016)
	Older/Outdated Technology	Major constraints of SMEs in meeting challenges of competitiveness: inadequate technologies and resources. (Hashim & Wafa, 2002)
		The majority of SMEs rely on outdated technology. (Hashim & Wafa, 2002)
		SMEs struggle to face the challenge of upgrading technology, which is a must have to implement Modern Maintenance Practices (MMP). (Kleindl, 2000)
Data	Analysis	Challenges with implementing machine-level PHM in production factories are still unresolved. How to automatically update the health models due to maintenance activities and obtain enough data in a factory to validate machine-level PHM models. (Jin et al., 2016)
		There is a lack of common data interfaces and protocols, lack of sufficient data to support analysis, and a lack of sufficient security tools to protect sensitive information and intellectual property. (Helu & Weiss, 2016)
	Documentation	Information about the production process is often limited to the know-how of operators without any documentation. Very little documentation is available. (Boden et al., 2012)
		Documentation does not typically include details on how things are implemented. (Boden et al., 2012)
		The production history is created manually by workers. This is a source of data uncertainty. (Snatkin et al., 2012)
		Lack of information and adequate in-house expertise to analyze the data. (Hashim & Wafa, 2002)

3.2.1 Organizational Challenges

By far, the largest group of the four barriers mentioned is organizational challenges. This category is the driving force behind the need to assess an organization's readiness to implement PHM. A common theme among the organizational category is the lack of strategic planning and limited long-term vision (C. Wang et al., 2007). Many SMEs have owners or CEOs that are heavily involved in the day-to-day activities rather than strategizing or focusing on development and future growth in areas such as PHM and digitization (Buonanno et al., 2005; C. Wang et al., 2007). Baglee et al. points out that SMEs rarely have strategic planning horizons, which leads to firefighting rather than determining a long-range solution or response. They just need to get it done now and deal with planning for the next time later. Only later never seems to come.

Structurally, SMEs are less formally organized, and their communication is informal which, compared to large enterprises, puts them at a disadvantage in terms of readiness for innovation (Durst & Bruns, 2018; Jin et al., 2016). Based on the survey performed by Jin et al., company size influences the key factors of maintenance, and large firms are generally more advanced than SMEs, particularly with respect to maintenance effectiveness level, maintenance strategy level, profitability level, continuous improvement level, human factor level, and organizational readiness level. Furthermore, SMEs typically have flat organization structures and limited financial resources (Baglee et al., 2016). This lack of finances does not typically allow for experimenting with expensive software or technologies or for market research that is needed to determine the optimal solution or understanding the requirements that need to be in place before adopting any sort of advanced maintenance strategy (Baglee et al., 2016; Hashim & Wafa, 2002; Xiong et al., 2006).

3.2.2 Technology Issues

The technological issues SMEs face can be divided into two main categories old, outdated technology, and new, confusing technologies. A smaller third category does exist, technology that is poorly designed or ill-fitting. As previously mentioned, SMEs have limited resources available, which means much of their equipment and technology is older or inadequate and in need of upgrading if they want to implement any type of advanced maintenance practices (Hashim & Wafa, 2002; Kleindl, 2000). The literature reviewed for this study revealed that even if SMEs had the resources to procure new technology, they have less experience in managing that technology and it is challenging for them to navigate the variety of options available (Blili & Raymond, 1993; Helu et al., 2015). Further complicating the new technology issue is that many technologies have been developed without first understanding the capabilities and limitations of the SME manufacturing environment (Helu & Weiss, 2016).

3.2.3 Resource Constraints

The literature review showed that resource constraints consist of limited human and financial resources. Bala Subrahmanya found that it is common practice for unskilled workers to join SMEs for a short period of time then jump to larger organizations once they are fully equipped with the required skills. This tactic hinders the SMEs ability to perform skilled tasks such as data quality assessment and pre-processing of data (Omri et al., 2019). Hashim & Wafa point out that SMEs typically have labor intensive and traditional asset management practices with leads to inefficiencies. Additional resource constraints exist but were categorized under different headings. The primary conclusion from this is that SMEs have limited funds, limited skilled workers, and limited time to determine what the best approach is for their company.

3.2.4 Implementation Barriers Related to Lack of Data and Documentation

Two types of data related issues were common throughout the literature review. The first has to do with data that is created or needed to support a successful PHM implementation. This encompasses things like lack of common data interfaces and protocols, lack of sufficient data to support analysis, and lack of security tools to protect sensitive information and intellectual property (Helu & Weiss, 2016). The second type of data issue stems from SMEs lack of controlled or complete documentation. Boden et al. ascertains that information about production processes is limited and is mainly comprised of the operator's know-how. If there is available documentation, it typically does not include details of how things are implemented. Snatkin et al. has found that workers manually create the production history, leading to data uncertainty. For a PHM implementation to be successful, part of the assessment and strategy definition phase includes reviewing the data and making decisions about where to install a monitoring system and developing a business case around that. This is made even more difficult because some experts estimate that only 5% of machines in manufacturing facilities are currently being monitored digitally (Waurzyniak, 2015). Limited, incomplete, or incorrect data can undermine the entire strategy and further add to barriers SMEs already face.

3.3 Key Enablers for Successful PHM Implementation

Baglee et al. performed a comprehensive review of the key enablers that allow SMEs to be successful in the implementation of advanced manufacturing systems, such as PHM. That review, in addition to reviews of other literature, shows that the enablers for successful implementation are broken into several categories: organizational, strategic, operational, and technical.

3.3.1 Organizational Profile as an Enabler

The organizational profile of SMEs is slightly different from larger manufacturers. They typically operate with fewer resources, are less bureaucratic, and have more incentive to be successful (Stentoft et al., 2019). Culture is critically important as well. It is often easier to attain a cultural change in a SME because it is likely to be entirely developed in a single culture, whereas a larger organization may have multiple cultures to manage (Singh et al., 2008). In addition to cultural changes, the employee expertise level and training to better appreciate and understand the idea of CBM/PHM is a fundamental requirement for success (Higgs et al., 2004).

Top management plays a significant role in whether a SME will be successful in the implementation of any new strategy. Management must be committed to the strategy and give support as well as communicate that support (Bengtsson, 2007).

3.3.2 Strategic Planning to Enable PHM Implementation

Strategic planning and a long-term focus should be a goal of any organization. Many SMEs are missing that level of planning; however, they can collaborate with larger organizations which has been shown to have a positive impact on the functioning and overall performance of the SME (Chen & Huang, 2004; Sarmah et al., 2006).

Communication across all levels within the SME is another strategic enabler. Unclear communication or lack of communication regarding the new policy or implementation almost always results in failure (Attri et al., 2014). At a minimum, the maintenance department should be involved in goal setting for the new systems, as they will be responsible for the future fulfillment of those goals (Bengtsson, 2007). Furthermore, any new PHM applications should be linked to the existing maintenance plan (López et al., 2014). This allows for a cohesive approach to understanding the equipment's health status and how the maintenance actions will affect that health status.

3.3.3 Operational Planning Can Facilitate Improved Implementation Odds

In addition to communication and collaboration, a manageable implementation plan, complete with a phased approach will set the groundwork for a successful implementation. The objectives for each phase should be clearly defined and laid out in the beginning. Short term goals with a few long-term goals will help the team get some quick wins, which will encourage continuation of the project. Speaking of timing, as Vrakking points out, the longer an implementation takes, the more likely it is to fail. The success is directly related to the time between the idea generation and its implementation.

As mentioned previously, financial constraints factor into the success in implementing a new strategy. For SMEs, this means the business case rationale is equally as important as the technical viability (Hess et al., 2001). SMEs can set themselves up for success by determining what to monitor in a rational manner. The typical process is to monitor what is easy and available (Parida, 2007). By incorporating a strict business case review, focused on monitoring what is needed to solve the problem, a SME will likely have a cost-effective solution that readily provides the correct data needed for decision making.

3.3.4 Technical Enablers

According to a recent McKinsey report (Bradbury et al., 2018), a fundamental enabler for digital reliability and maintenance is establishing a robust data backbone and management strategy. Data drives all digital processes and decision making. One step beyond gathering the data is analyzing the data. SMEs need to have a comprehensive approach for data integration, rather than the ad hoc approaches typically employed (Baglee et al., 2016).

CHAPTER IV

ASSESSMENT METHODOLOGY FOR DETERMINING ORGANIZATIONAL READINESS FOR PHM IMPLEMENTATION

As part of this research, an assessment tool was developed to verify that the factors from sections 3.2 and 3.3 are in fact barriers or enablers for small to medium enterprises wanting to implement PHM techniques. This assessment is from the organizational standpoint and answers the question "Is the organization ready for this implementation based on their organizational culture, available resources, technology maturity, and documentation and data analysis?" We know certain factors, a data management plan, for example, need to be in place for an implementation to be successful. The conventional approach to PHM implementation is to scope the project, assess costs and benefits, and select the final candidate solution that will be presented to decision makers, without considering the organizational readiness (example: WEAR Methodology, Adams et al.) A gap exists on how to determine the organizational readiness, which should take place prior to the technological considerations.

We know the current barriers many SMEs face such as organizational challenges, technology issues, resource constraints, and data management and research has been done on how to overcome those barriers. Many companies are unaware of their own issues until they are presented with the data showing the problems. The assessment highlights the organization's current maturity level in each of the barrier areas. A score, similar to a Technology Readiness Level (TRL), is assigned for each area of the assessment. A TRL is used to assess the maturity of a technology, with 1 indicating that research is beginning and 9 meaning that the technology has been proven (Mai, 2017). In addition to calculating a score for each area, recommendations for improvement are provided. These recommendations are based on industry best practices as well as research that has been done to show what a successful implementation may look like.

4.1 Assessment Methodology

The assessment is comprised of 54 questions broken into four categories that align with the previously identified barriers for successful PHM implementation: Organization, Resources, Technology, and Documentation and Data Analysis.

To complete the assessment, the assessor answers each question indicated on the assessment sheet. All the questions have “Yes” or “No” answers to enable easier scoring and quick identification of areas of concern. A “Yes” response is scored at 1 point while a “No” response results in 0 points. Once the assessment is complete, the points are tallied for a sub score for each area of the assessment as well as a final score. The final score is the summation of the 4 categories.

Each question also has a comment box where the assessor can add notes related to that specific question. This discussion is not taken into consideration from a scoring standpoint, but it does help determine the recommendations provided to improve the assessment score. For example, multiple “No” responses related to labor resources available to collect and analyze data could be mitigated if the company is willing and able to outsource the data collection and analysis. If the assessor is aware of this willingness, the recommendation becomes related to outsourcing rather than encouraging the company to hire and train resources for data collection and analysis.

There are three readiness levels, High, Medium, and Low, within each category. To determine the intervals for each level, the total number of points achievable for that category is divided by three. The total number of points for each category varies and depends on the number questions in the corresponding category.

Table 4.1 shows the overall readiness level based on the assessment scores and the intervals for each level. Table 4.2 outlines each of the four categories and the associated readiness levels.

Table 4.1 Overall readiness levels

Category	Possible Points
Overall	**54**
Low	0-17
Medium	18-36
High	37-54

Table 4.2 Readiness levels for each category

Category	Possible Points
Organizational	**17**
Low	0-5
Medium	6-11
High	12-17

Category	Possible Points
Technology	**11**
Low	0-3
Medium	4-7
High	8-11

Category	Possible Points
Resources	**14**
Low	0-4
Medium	5-9
High	10-14

Category	Possible Points
Data	**12**
Low	0-3
Medium	4-8
High	9-12

After determining the score for each category of the assessment, general recommendations are provided based on the readiness level achieved for each category. Recommendations based on research are provided for the Low and Medium readiness levels. A category with a high score does not need specific recommendations, the company can support a successful implementation from the standpoint of whichever category the score is associated with. For example, a high score in the organization category indicates that there may be a couple of areas the organization could improve, but overall, from a leadership and organization culture standpoint, the organization is ready to tackle the implementation of a PHM system. The leadership can support an implementation with long term or strategic planning, the organization has a maintenance group with the authority to review and update the maintenance strategy based on new data, and while the idea of a new system may be overwhelming, overall, the organization should be able to move forward successfully.

4.1.1 Organizational Assessment

The organizational category of the assessment centers around the organizational barriers many SMEs face when trying to implement a new technology. These questions highlight how the culture, leadership, and strategic planning can positively or negatively impact the readiness of the organization as it makes changes related to its maintenance strategy. The 17 questions in the organizational portion of the assessment are in Table 4.3

Table 4.3 Organizational assessment questions

Organizational
Does the organization implement any continuous improvement plans?
Does the organization have a dedicated maintenance group?
Does the maintenance group have authority to change any maintenance plans based on new technologies or research?
Does the organization have any equipment being monitored digitally?
Does the organization have regular communication regarding equipment maintenance?
Does the organization have a current maintenance plan?
Has the maintenance plan been reviewed in the past 6 months?
Has the maintenance plan been updated in the past 6 months?
Does the organization have an advanced maintenance strategy?
Does the organization have knowledge about the requirements for an advanced maintenance strategy?
Does senior management have time allocated for strategizing for development or future growth?
Does the organization have any medium- or long-term strategies for data collection or digitization?
Does the organization have strategic planning horizons that allow for thought out responses?
Is the organization open to change in the organizational structure?
Is the senior management involved in or focused on daily operations?
Does the organization feel overwhelmed when investigating new technologies?
Does the organization understand any current capabilities or limitations of the manufacturing environment?

There are 17 points available in this category. This is slightly higher than the other categories, which means the organizational barriers can have more of an impact on the overall readiness for PHM implementation. This highlights how important it is to have leadership support, strategic planning windows, and a willingness to change policies and procedures based on new information or data. Table 4.4 shows the breakout of the three levels of readiness, based on the assessment score for this category.

Table 4.4 Organizational scoring possibilities

Category	Possible Points
Organizational	**17**
Low	0-5
Medium	6-11
High	12-17

In this category, a score of 4 would be considered low and indicates the organization likely faces significant barriers related to their organizational structure, culture, or management. They may have a maintenance plan; however, it may not be updated. The leadership or management of the organization likely does not make time to do strategic planning or may not be open to enacting changes because they are unable to see the possibilities of improvement as they are too mired in the day-to-day activities. When the assessment yields a low score, the organization should implement a maintenance strategy with a plan for regular reviews and updates. Some leadership style adjustments may be warranted, including time set aside for strategic planning for the future, time allocated for investigating new maintenance strategies or plans, and potentially creating or improving a maintenance group and allowing the ability to collect data on critical pieces of equipment.

A medium score of 8 or 9 indicates the organization will have some ability to successfully manage a PHM system implementation. They likely have a dedicated maintenance group with the authority to review and update the maintenance plan. The organization may be monitoring and collecting data on some equipment. The leadership may still be heavily involved in day-to-day operations or may not be allowing time for strategic planning. The maintenance group or organization leadership may not be thinking about advanced maintenance strategies, but rather are still reacting to equipment faults and failures indicated by some minimal level or equipment monitoring. To increase the chances for a successful implementation, the organization leadership should allocate time for strategic planning if that is not happening. This would include short- and medium-term plans for which assets to monitor and what data to collect. The decision on what assets to monitor and data to collect should be based on business case reviews driven by a deep dive into what the critical assets are, and the common failure modes associated with that equipment. Alternatively, if the organizational leadership is planning well and open to change, but the organization is missing more of the maintenance group activities, the recommendations would focus more on developing a maintenance group, maintenance plan and a regular process for reviewing data and updating the plans based on that data.

4.1.2 Resource Assessment

The resource portion of the assessment focuses on the workforce and financial resources an organization has available to implement, use, and maintain a PHM system. The questions also seek to identify the organization's willingness to outsource any of the PHM activities. The resources section also seeks to understand the labor resource structure of the organization by questions on temporary workers and turnover rates. A reliance on temporary workers or having a high turnover rate would negatively impact the ability to implement, use, and maintain a PHM system because there is no continuity of the workforce. As employees leave the organization, they take any knowledge about the equipment, processes, and systems with them, forcing the organization to start over with training someone new. There are 14 questions within the Resources category, as seen in Table 4.5.

Table 4.5 Resource assessment questions

Resources
Does the organization have finances available for implementation of new technologies?
Does the organization have finances available for continued support for new technology implementation?
Does the organization have workforce resources available to assist with implementation of new technologies, such as advanced monitoring equipment?
Will the organization allow external workers to assist in the implementation of new technologies?
Does the organization have workforce resources available to maintain a PHM system?
Assuming a PHM system is put in place, does the organization have a labor resource to analyze equipment failure and maintenance data?
Does the organization have workforce resources available to collect and analyze data, such as equipment failures, from the PHM system?
Will the organization allow external workers to assist in the analyzation of equipment failure and maintenance data?
Does the organization have employees trained in or capable of analyzing data for decision making?
Does the organization have employees trained in or capable of developing an advanced maintenance strategy?
Does the organization experience inefficiencies related to labor intensive management practices?
Does the organization face a high turnover rate?
Does the organization rely on temporary workers?
Does the organization have financial resources available for implementation of advanced monitoring equipment?

With each "Yes" answer being worth one point, 14 possible points are available. Table 4.6 shows how the scores from the assessment are split into categories of Low, Medium, or High. A high score indicated that resources will typically not be a problem when it comes to implementing and maintaining a PHM system. The organization will have financial or workforce resources available or is willing to allow outsourcing of some or all the tasks associated with a PHM system.

Table 4.6 Resource scoring possibilities

Category	Possible Points
Resources	**14**
Low	0-4
Medium	5-8
High	10-14

A low score, 2 for example, would indicate the organization does not currently have resources available to implement a system, utilize the system by analyzing the data, and maintain the system. It would also indicate the organization is not likely to allow outsourcing or be able to fund the outsourcing options. In this case, the organization should undertake a business case review, highlighting which equipment resources need to be monitored, not just the easy ones, and understanding the benefit from that monitoring. It has been mentioned that SMEs can't afford to not monitor their equipment, even when funding or labor resources are tight. Additionally, the organization can evaluate how their resources are currently allocated to free up some labor or financial resources to assist with implementing, utilizing, and maintaining the system.

If the assessment yields a medium score, the organization may have labor resources available or financial resources, but not both. If labor resources are available, they may not be adequately trained in analyzing data or making decisions based on that data. The company may allow outsourcing for PHM system implementation, maintenance, and data collection and analysis and they may have funding for the outsourced labor. The recommendations in this category will depend on which type of resources are available for the implementation project. If labor resources are available, just not trained, training should be provided for those employees. Training should center around collecting and analyzing data to provide information to decision makers as the basis of decisions for future maintenance needs. The employees should also be trained in advanced maintenance strategies so they can implement any changes recommended as the result of analysis of the data. If financial resources are available, the company should investigate outsourcing options for implementing and maintaining the system. Outsourcing can also be used for the data collection and analysis, but it is likely the organization has maintenance employees that can be trained to collect and analyze the data.

4.1.3 Technology Assessment

The third section of the assessment asks questions related to the organization's experience with new technologies and their ability or desire to research and implement new technologies. Additionally, there are questions about the organization's current technology infrastructure and security requirements around data and existing technologies. Understanding how the organization views new technologies and their infrastructure's ability to support these new technologies and systems can help shape the recommendations associated with this assessment section. For example, if the organization does not have a data storage strategy or the ability to store data, any data captured from the PHM system would be lost if not reviewed in real time and would severely hamper efforts to later expand the system. Table 4.7 contains the 11 questions for the technology assessment section.

Table 4.7 Technology assessment questions

Technology
Does the organization investigate new technologies?
Does the organization have experience with implementing new technologies?
Has the organization implemented new technologies using internal labor resources?
Has the organization implemented new technologies using an outsourced contractor?
Does the maintenance group or organization have dedicated time for reviewing and updating maintenance plans based on new technologies or research?
Does the organization have wired data transmission?
Does the organization have any cybersecurity experience?
Does the organization have a backup system for the network to prevent data loss?
Does the organization have a network available for data transmission from sensors on equipment?
Does the organization have recently updated computer systems?
Does the organization have security requirements that prevent wireless data transmission?

Table 4.8 Technology scoring possibilities

Category	Possible Points
Technology	**11**
Low	0-3
Medium	4-7
High	8-11

As with the previous sections, each "Yes" response is 1 point, so there are 11 potential points available in this area. Table 4.8 shows how the 11 possible points are split into Low, Medium, or High score categories.

A low score of 2 or 3 would indicate the organization may not have the technology available to support a PHM system, the organization does not have experience implementing new systems, and the organization may not be up to date on the security requirements for protecting any data they collect. Recommendations for a low score would be centered around evaluating and updating the network that would house the PHM system, investing in a data storage system, researching the use of outsourced labor to implement a PHM system if existing labor resources have little to no experience with implementing new technologies, and understanding any cybersecurity requirements that should be met to protect data being captured.

A score of 6 falls into the medium category and indicates that the company may have some experience with implementing a new technology, may have up to date computer systems and networks for data transmission, and may have sensors on some of their equipment already. To elevate a medium score, the company should evaluate and updates as needed any networks, computer systems, hardware, and security requirements to allow for secure collection of equipment data. Cybersecurity measures should also be implemented to protect any data collected by the company. Small and medium manufacturers are prime targets for hackers and bad actors wanting to infiltrate their systems and collect ransoms (Ponsard et al., 2019). The company should also evaluate the options for implementing the PHM system via internal resources or outsourcing. Both have pros and cons and the ultimate decision on which way to proceed will depend on the organization's resources and willingness to open the door and allow outsourced labor to help.

4.1.4 Documentation and Data Analysis Assessment

The final section of the assessment seeks to determine the organization's status related to existing documentation and data analysis. Are they currently collecting data on their equipment? Do they maintain fault records and analyze them to prevent future faults or failures? Does the organization use any type of process control measures? Many SMEs do not have documentation for their systems or equipment, which makes defining the business case somewhat difficult. Additionally, any data they do have could be limited or incorrect, which is a known barrier for a successful PHM implementation. **Error! Reference source not found.** shows the 12 questions related to documentation and data analysis.

Table 4.9 Documentation and data analysis questions

Documentation and Data Analysis
Does the organization maintain fault records for equipment failures?
Does the organization maintain records for maintenance performed on each piece of equipment?
Does the organization have a standardized process for capturing and documenting machine faults and maintenance?
Does the organization have a resource to analyze maintenance data?
Does the organization have any interest in analyzing equipment fault or maintenance data? (Do they want to do analysis, or would they prefer to outsource that?)
Does the organization allow changes to the existing equipment maintenance plan based on data?
Does the organization have systems or documentation on the production history of each piece of equipment?
Does the organization currently have any process monitoring methods? I.e., SPC? Others? Control Charts?
Does the organization have standard operating procedures documented for each piece of equipment to be monitored?
Does the organization have any expected values documented? i.e., understanding of how the machine should be operating?
Does the documentation include any modifications to the equipment? i.e., has it been updated to reflect the current setup for that piece of equipment?
Does the documentation include any monitoring system implementation?

With 12 possible points, Table 4.9 shows what constitutes a Low, Medium, or High score in this category.

If the assessment yields a Low score, the company does not have the documentation or data in place to successfully implement a PHM system. They are not maintaining records or collecting data related to their equipment and processes, meaning they are not able to change their maintenance plan or production plan based on how their equipment is running.

A score of 5 falls into the Medium score range, indicating that the organization has some level of process control, process or equipment documentation, and data collection. They may be analyzing some of the data or have implemented standard operating procedures for their equipment. The organization likely has some idea of how the equipment and processes should be operating but may be missing some information on how to correct errant processes or faults within their equipment. They may not have complete production, maintenance, or failure histories for their systems.

Table 4.10 Documentation and data analysis scoring possibilities

Category	Possible Points
Data	**12**
Low	0-3
Medium	4-8
High	9-12

Recommended improvements for a Medium score would be to review any system, equipment or process documentation and ensure that it is up to date for how the organization is currently operating. This documentation will be used to help create the business plan so it essential that it is current and complete. If any documentation is missing, that should be completed as well. A system for collecting and reviewing fault or failure data for the equipment should also be implemented. Knowing the types of faults, frequency of those faults and the cost to fix the faults also feeds the business case for implementing a PHM system. The organization should also identify any critical pieces of equipment to help inform the decision of which pieces of equipment to monitor.

CHAPTER V

CASE STUDY

5.1 Company Background

The Center for Advanced Vehicular Systems (CAVS) at Mississippi State University was chosen for this case study due to their desire to improve the management and maintenance of the equipment and machinery within the organization. This assessment focuses on the CAVS machine shop, additive materials lab, and materials testing lab. CAVS has been working to implement more management and control processes related to equipment safety so starting to incorporate more PHM techniques is a natural next step. CAVS has a limited maintenance group for equipment upkeep, however that same group is often needed for additional tasks across the organization. Implementing a PHM system will allow the maintenance group to better plan their activities related to the equipment since they will have more insight in the health of the equipment.

5.2 Assessment Details

This assessment was conducted with the help of the CAVS operations manager. Each of the 54 questions were answered with yes or no and we documented details or conversation about each answer. Upon completion of the discussion portion of the assessment, each section was scored based on the previously identified method, each Yes being worth 1 point, each No being worth 0 points.

5.2.1 Organizational Assessment Results

For the organizational portion of the assessment, CAVS scored a 12 out of 17 possible points, which is in the High category, see Table 4.4 in the previous section. 12 is the lowest possible score in the High range, indicating that while CAVS is organizationally ready to be successful in a PHM implementation, there are areas of improvement that be addressed to further reduce risk and increase chances for a smoother, more successful implementation. Table 5.1 below shows the organizational readiness questions and the scores provided by CAVS.

Table 5.1 Organizational readiness assessment results for CAVS

Organizational	**Yes**	**No**
Does the organization implement any continuous improvement plans?	1	
Does the organization have a dedicated maintenance group?	1	
Does the maintenance group have authority to change any maintenance plans based on new technologies or research?	1	
Does the organization have any equipment being monitored digitally?		0
Does the organization have regular communication regarding equipment maintenance?	1	
Does the organization have a current maintenance plan?	1	
Has the maintenance plan been reviewed in the past 6 months?	1	
Has the maintenance plan been updated in the past 6 months?	1	
Does the organization have an advanced maintenance strategy?		0
Does the organization have knowledge about the requirements for an advanced maintenance strategy?		0
Does senior management have time allocated for strategizing for development or future growth?	1	
Does the organization have any medium- or long-term strategies for data collection or digitization?		0
Does the organization have strategic planning horizons that allow for thought out responses?	1	
Is the organization open to change in the organizational structure?	1	
Is the senior management involved in or focused on daily operations?	1	
Does the organization feel overwhelmed when investigating new technologies?		0
Does the organization understand any current capabilities or limitations of the manufacturing environment?	1	
Total	**12**	

CAVS does not have any equipment that is monitored digitally, however there is a route-based monitoring plan where a technician will check the number of hours on a piece of equipment and perform or schedule any maintenance recommended by the manufacturer. Some of the equipment, namely HAAS branded machines, has information on the condition of the bearings. These bearings are also checked on the manufacturer's timeline.

CAVS does not have an advanced maintenance strategy in place. The maintenance strategy that is in place was implemented in the past few years and is mainly route based, scheduled, or reactive. CAVS is still growing with how to understand maintenance needs and what to do to improve. This also points to why CAVS answered No on having knowledge of requirements for an advanced maintenance strategy. Since CAVS is relatively new to any type of maintenance strategy, it is also not surprising that they don't have any medium- or long-term strategies for data collection or digitization.

Based on the assessment questions that were answered with a no, the following recommendations would apply to CAVS and would help improve their score in this area:

1. Investigate ways to digitally collect data from existing machines. This can be done via aftermarket sensors or by accessing the Programmable Logic Controller (PLC) to collect equipment status data.
2. Research advanced maintenance strategies and determine the needs of CAVS. Not all pieces of equipment may need to have an advanced strategy right away but understanding any bottlenecks or pieces of equipment where unscheduled downtime would cause negative consequences is helpful when deciding which equipment to begin with.

5.2.2 Resource Assessment Results

CAVS received a resource assessment score of 11, with 14 being the highest possible score. As with the organizational results, this is within the High score range, which is 10-14. This indicates that CAVS has the resources necessary to support a PHM implementation. Table 5.2 shows the resource assessment questions along with the scores for CAVS.

Table 5.2 Resource assessment results for CAVS

Resources	**Yes**	**No**
Does the organization have finances available for implementation of new technologies?	1	
Does the organization have finances available for continued support for new technology implementation?	1	
Does the organization have workforce resources available to assist with implementation of new technologies, such as advanced monitoring equipment?	1	
Will the organization allow external workers to assist in the implementation of new technologies?	1	
Does the organization have workforce resources available to maintain a PHM system?	1	
Assuming a PHM system is put in place, does the organization have a labor resource to analyze equipment failure and maintenance data?		0
Does the organization have workforce resources available to collect and analyze data, such as equipment failures, from the PHM system?	1	
Will the organization allow external workers to assist in the analyzation of equipment failure and maintenance data?		0
Does the organization have employees trained in or capable of analyzing data for decision making?	1	
Does the organization have employees trained in or capable of developing an advanced maintenance strategy?	1	
Does the organization experience inefficiencies related to labor intensive management practices?	1	
Does the organization face a high turnover rate?	1	
Does the organization rely on temporary workers?		0
Does the organization have financial resources available for implementation of advanced monitoring equipment?	1	
Total	**11**	

CAVS does not currently have a resource available to analyze any data captured from a PHM system, however an available resource could easily be assigned and trained for that task. CAVS has research being conducted in data analysis and equipment health so training a resource should not be an issue.

CAVS currently allows field service engineers from equipment manufacturers to review the data when they come in for maintenance actions, however that data is manually collected, not provided via a network or remote connection. The networks at CAVS are managed by a separate system administrator so permission would need to be provided if the data from equipment was going to be sent out to an external company for review and analysis.

CAVS has a high turnover rate due to the high percentage of student employees, which can be considered temporary workers. While CAVS has a high number of students or temporary workers, none of those positions are in critical roles, meaning CAVS does not rely on them to get work completed. Although reliance on a temporary workforce is a known issue when it comes to implementing new technologies, the fact that CAVS realizes their students are temporary and strategically does not place them in critical roles, shows that they have already mitigated this potential risk.

Based on the other two questions that CAVS answered with a no response, the following recommendations could improve the score and reduce risk when it comes time for a PHM system implementations:

1. Identify a labor resource that could analyze equipment maintenance and failure data. This resource could begin researching and learning about the different types of potential failure modes for each piece of equipment that will be monitored. CAVS has a research group dedicated to condition-based maintenance, the identified labor resource could begin working with that group to learn more about data analysis related to maintenance and failure data.

2. Investigate the feasibility of allowing an outside organization to assist with analysis of equipment data. Will the systems administrator work with CAVS to facilitate the sharing of the data? How would the organization get the data? CAVS needs to understand what is feasible from a systems administrator standpoint then investigate options for external companies that can work within those constraints. What are the current policies and procedures regarding sharing data and results collected from equipment, particularly data collected during controlled experiments? Is it possible to share the data under the existing policies and procedures, or will they need to be updated? Who will be responsible for creating or implementing the software interfaces needed to share the data? Once these systematic issues are addressed, who will coordinate with the external organization to provide the data and to share the results of the analysis as needed at CAVS?

5.2.3 Technology Assessment Results

CAVS scored a 9 out of 11 on the technology portion of the assessment, which is solidly in the High range of 8 to 11. A score in the High range means that CAVS is comfortable and experienced with researching and implementing new technologies. **Error! Reference source not found.**Table 5.3 details the assessment questions and the responses provided by CAVS.

Table 5.3 Technology assessment results for CAVS

Technology	Yes	No
Does the organization investigate new technologies?	1	
Does the organization have experience with implementing new technologies?	1	
Has the organization implemented new technologies using internal labor resources?	1	
Has the organization implemented new technologies using an outsourced contractor?	1	
Does the maintenance group or organization have dedicated time for reviewing and updating maintenance plans based on new technologies or research?		0
Does the organization have wired data transmission?	1	
Does the organization have any cybersecurity experience?	1	
Does the organization have a backup system for the network to prevent data loss?	1	
Does the organization have a network available for data transmission from sensors on equipment?	1	
Does the organization have recently updated computer systems?	1	
Does the organization have security requirements that prevent wireless data transmission?		0
Total	**9**	

According to CAVS, their maintenance group is relatively small and newly organized, so finding dedicated time to research new technologies and updating a maintenance plan accordingly is not something that is routinely done. The maintenance group does meet every 2 weeks to discuss the activities and plans for the next 2-week period.

As mentioned in the resource assessment, the CAVS network is managed by a systems administrator, who doesn't prevent wireless transmissions; however, they are restricted. Any wireless data transmissions would need to be coordinated ahead of time to determine the feasibility and what restrictions might be in place.

If CAVS were to move forward with a PHM implementation, the following recommendations would increase their chances of a successful outcome:

1. The maintenance group needs to set aside time to investigate any new technologies or research that would be applicable to the equipment at CAVS. Allocating time in an already full schedule is difficult so this may take a bit of strategic planning or the addition of resources to focus on the research. CAVS has many students interested in predictive and condition-based maintenance, one of these resources could work with the maintenance group to understand their pain points or needs and help investigate options to mitigate those issues.

2. If the research performed in the recommendation above yields anything of use, the maintenance group will need to review and potentially update their current maintenance plan. This research and update cycle should become second nature after a few iterations.

3. Like recommendation number 2 from the resource assessment, CAVS will need to discuss any security requirements that may prevent or restrict data collection and analysis activities, such as wireless data transfer.

5.2.4 Documentation and Data Analysis Assessment Results

CAVS scored a 6 out of 12 on the documentation and data analysis portion of the assessment, which is in the medium score range of 4 to 8. This indicates that CAVS can likely address half of the known barriers to implementation of a PHM system but will struggle in some areas unless risk mitigation actions are taken. Table 5.4 shows the assessment questions along with the responses from CAVS.

Table 5.4 Documentation and data analysis assessment results for CAVS

Documentation and Data Analysis	Yes	No
Does the organization maintain fault records for equipment failures?	1	
Does the organization maintain records for maintenance performed on each piece of equipment?	1	
Does the organization have a standardized process for capturing and documenting machine faults and maintenance?		0
Does the organization have a resource to analyze maintenance data?	1	
Does the organization have any interest in analyzing equipment fault or maintenance data? (Do they want to do analysis, or would they prefer to outsource that?)	1	
Does the organization allow changes to the existing equipment maintenance plan based on data?	1	
Does the organization have systems or documentation on the production history of each piece of equipment?		0
Does the organization currently have any process monitoring methods? I.e., SPC? Others? Control Charts?		0
Does the organization have standard operating procedures documented for each piece of equipment to be monitored?		0
Does the organization have any expected values documented? i.e., understanding of how the machine should be operating?		0
Does the documentation include any modifications to the equipment? i.e., has it been updated to reflect the current setup for that piece of equipment?		0
Does the documentation include any monitoring system implementation?	1	
Total	**6**	

While CAVS captures fault and failure data for their equipment, there is not a standard process or capture method for the team to follow. By not having a standard procedure for documenting maintenance faults, it makes it harder to see if the same fault occurs multiple times or if the same piece of equipment is having different faults that may be related to the same root cause. For a PHM system to provide value, effective and efficient analysis of faults and failures needs to happen.

CAVS has production history for some of its equipment but not all. Having the production history can help CAVS understand what was produced on the equipment and what the settings were and potentially link that to any faults or failures that may occur. Since improper settings during part production can lead to equipment breakdowns, having this documentation is important when tracing back to find the root cause of a failure.

CAVS does not currently employ any process monitoring methods. The additive manufacturing equipment at CAVS has this capability to some degree, but it is not being used from a maintenance standpoint. Process control charts would also be part of the equipment production history and documentation and can be used to determine when the equipment started to operate out of control due to tool wear, malfunction, operator error, etc.

CAVS has Safe Work Procedures (SWP) in place for all pieces of equipment, however they do not have Standard Operating Procedures (SOP) in place for each piece. SOPs document how the machine is to be used and what the settings are for each process completed on the machine. Having formally documented SOPs helps to reduce equipment failure due to improper use. Employees using the equipment should also be trained on the machinery and be familiar with the SOPs.

CAVS does not have expected values in documented for their equipment. The expected values provide an understanding of how the equipment should be operating and goes along with the process control procedures. The additive equipment has flow rates and feed rates which are known and tracked; however, the other machines do not have that same documentation. CAVS does follow the equipment manufacturer’s suggested calibration schedule and standards to ensure the equipment stays in tune and is able to produce the parts needed at the tolerances required.

Since CAVS has limited documentation history on their equipment, it's not surprising that, for most of their equipment, they do not have the documentation related to modifications made to equipment reflecting the current setup. CAVS has several Instron tensile testers which are well documented, however, the rest of the equipment in the facility does not follow suit. The modification history and current setup of each piece of equipment is important for a PHM system implementation because the practitioners need to understand what has been done to the machine, so they know what the expected operating values are. For example, modifications made to a car will cause it to run differently that what the manufacturer says. Having that modification history allows the car mechanic to better asses what a problem may be.

If CAVS were to move forward with a PHM implementation, the following recommendations would increase their chances of a successful outcome:

1. Develop a standard process for documenting equipment faults and failures. This can start with a paper form that is used to collect the data; however, an electronic system will make the data analysis easier and reduce errors when transferring from paper into an electronic format.

2. Start capturing production history of each piece of equipment. Like the first recommendation, this can be done with a paper form, but electronic documentation will be easier to search if there is a failure. CAVS will need to determine the parameters that need to be collected which will probably be different for each piece of equipment.

3. Begin using process control procedures. CAVS-Extension regularly offers a 2-day course in Statistical Process Control and requires that students in the class employ control charts for some of their equipment. Control charts can easily be completed and maintained within Minitab or any number of other products.

4. For each of the pieces of equipment that will be monitored, an SOP should be created. Ideally, all equipment will have a SOP, however it is critical for the monitored machinery. These SOPs will need to be reviewed and potentially updated if a modification is made to the equipment. Some manufacturers may have an SOP or something similar already available. Equipment operators will need to be trained using the SOP so that data collected does not have variances due to different operators running the equipment differently.

5. Document the expected values of each piece of equipment. For example, the water jet can cut through thick steel, CAVS should determine the time required to cut a certain distance for a specific thickness. If the time required increases, that may indicate some sort of tool wear or flow issue with the water or abrasive material.

6. Create documentation for the current setup of each piece of equipment, including any modifications that have been made since it was purchased. This setup documentation will also go into the SOP.

5.3 Company Feedback and Results Discussion

CAVS' overall score of 38 falls into the High range of scores (37-54, based on Table 4.1) for readiness for PHM implementation, meaning CAVS should be successful in this implementation, however there would be some risks related to areas where they scored lower. Based on discussion during and immediately after the assessment, we feel that the PHM implementation readiness assessment developed through this thesis adequately reflects CAVS readiness for implementing a PHM system. The CAVS operations manager mentioned that these questions brought up many points that he had not considered before and helped him to realize that some improvements can be made to the way the maintenance group is currently operating.

CAVS found the organization and format of the assessment to be helpful for managing responses based on the recommendations. CAVS believes they can immediately use the recommendations for each section as a list of action items for discussion and planning with the operations team and maintenance team. Overall, CAVS feels "this assessment revealed that we are positioned well to begin taking the next steps towards implementing PHM at CAVS."(McGinley, 2022)

Many specific recommendations were provided for each of the four assessment areas, but some general recommendations hold true for every organization. These recommendations are based on research surrounding the enablers for PHM implementation for SMEs and were mentioned previously in section 3.3 but are important enough that repeating them seems necessary.

1. Management must be committed to the strategy and give support as well as communicate that support.
2. A manageable implementation plan, complete with a phased approach, will set the groundwork for a successful implementation.
3. Incorporate a strict business case review, focused on monitoring what is needed to solve the problem.
4. Establish a robust data backbone and management strategy.

5.4 Assessment Limitations, Lessons Learned, and Future Work

Through the process of developing and completing the assessment and case study, some limitations and areas for future work were noted. For a more thorough and complete assessment, a diverse assessment group should be considered. Talking to different people within the company will allow the assessor to get more diverse answers. Often time, employees with the same mind set will provide similar or the same responses.

A simple score does not always define the current situation at any organization. To help overcome this limitation, the discussion section and comment boxes allow for additional insight into the answers provided during the assessment as well as any current planning requirements or considerations.

An additional limitation to the scored assessment is that all responses are scored equally. More research and case studies would be required to provide more dynamic scoring. This would consider the criticality of each barrier or enabler. For example, a No response to a certain question may not make as big of an impact as a No response to a different question. This would highlight the impact each enabler or barrier have on an organizations readiness to implement PHM technologies.

While performing the case study, we identified several questions that should be reworded to be clearer or to address where a No answer is a good thing and should receive a point rather than 0 points like the other No answers. For example, question 16 on the organization readiness sections asks if the organization feels overwhelmed when investigating new technologies. That question and several others should be either reworded or the assessment should notate that those questions are scored opposite from the rest of the questions. An example of rewording could be "Is the organization capable of investigating new technologies without getting overwhelmed with information?" For the CAVS case study, this new question would yield a Yes answer and would add 1 point to their organizational score. In addition, questions 12 and 13 from the resource assessment should be reworded from "Does the organization face a high turnover rate?" to "Does the organization have a low turnover rate?" and "Does the organization rely on temporary workers?" to "Can the organization function normally without temporary workers?" Question 11 from the technology assessment should be reworded from "Does the organization have security requirements that prevent wireless data transmission?" to "Do the organization's security requirements allow for wireless data transmission?"

One question that was unclear is question 8 from the technology section. The existing question is "Does the organization have a backup system for the network to prevent data loss?". This is unclear because it sounds like the question is asking if there is a backup system for the network, when the question means to ask, "Is the data backed up or stored somehow to prevent data loss?" The case study helped to identify these lessons learned and will allow for a clearer and easier to follow assessment in the future.

CHAPTER VI

CONCLUSION

Many small and medium enterprises (SMEs) struggle with the notion of and implementation of Prognostics and Health Monitoring (PHM) solutions. There are plenty of off the shelf products available, however they are often expensive and assume the organization is ready for this type of implementation. The conventional approach to PHM implementation is to scope the project, assess costs and benefits, and select the final candidate solution that will be presented to decision makers, without considering the organizational readiness (example: WEAR Methodology, Adams et al.) A gap exists on how to determine the organizational readiness, which should take place prior to the technological considerations.

The assessment tool and methodology described in the previous sections allows an organization to review their current state from organizational culture, available resources, technology maturity, and documentation and data analysis standpoints. The assessment helps to highlight areas where risks to the successful implementation of PHM system may lie. The questions from the assessment are based on research into what the barriers and enablers are for SMEs when implementing new technologies, especially Industry 4.0 type technologies.

A case study was performed to verify that the 54 questions developed through research into barriers and enablers of successful PHM implementations for SMEs were able to identify an organization's readiness for this type of implementation. Based on feedback from the organization, the assessment was effective in highlighting risk areas and provided comprehensive recommendations to address the identified risks. While the assessment has some limitations, identified above, such as only providing a simple score, rather than scoring that considers the impact or lack of impact a certain barrier may have on an organization, it does address the gap that many SMEs face when considering a PHM implementation.

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