Proceedings of the ASME 2016 International Manufacturing Science and Engineering Conference
MSEC2016
June 27-July 1, 2016, Blacksburg, Virginia, USA

MSEC2016-8783

THE CURRENT STATE OF SENSING, HEALTH MANAGEMENT, AND CONTROL FOR SMALL-TO-MEDIUM-SIZED MANUFACTURERS

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KEYWORDS
Sensing, control, diagnosis, prognosis, SME

ABSTRACT
The development of digital technologies for manufacturing has been challenged by the difficulty of navigating the breadth of new technologies available to industry. This difficulty is compounded by technologies developed without a good understanding of the capabilities and limitations of the manufacturing environment, especially within small-to-medium enterprises (SMEs). This paper describes industrial case studies conducted to identify the needs, priorities, and constraints of manufacturing SMEs in the areas of performance measurement, condition monitoring, diagnosis, and prognosis. These case studies focused on contract and original equipment manufacturers with less than 500 employees from several industrial sectors. Solution and equipment providers and National Institute of Standards and Technology (NIST) Hollings Manufacturing Extension Partnership (MEP) centers were also included. Each case study involved discussions with key shop-floor personnel as well as site visits with some participants. The case studies highlight SME's strong need for access to appropriate data to better understand and plan manufacturing operations. They also help define industrially-relevant use cases in several areas of manufacturing operations, including scheduling support, maintenance planning, resource budgeting, and workforce augmentation.

INTRODUCTION
The role of sensing, monitoring, and control in any system is to observe data, use the collected data to determine the system's state, and apply the generated knowledge to optimize and/or improve the system's performance. To better meet these goals, the development of sensing, monitoring, and control for manufacturing systems has progressed from human oversight to more sophisticated sensor-based monitoring systems [1]. In-process, sensor-based monitoring systems are considered an essential means to meet increasingly tightening requirements on the precision, quality, and performance of manufacturing processes [2-3]. In addition, the growth and accessibility of digital (i.e., information and computer-based) technologies for manufacturing has provided industry with new opportunities to collect and use data to improve the control of engineering and production systems [4-5]. These technologies have the potential to improve the competitiveness of manufacturing by reducing cost, improving productivity, ensuring first-pass success, and augmenting existing capabilities in the workforce.

Smart manufacturing, digital manufacturing, cloud manufacturing, cyber-physical systems, the Industrial Internet of Things (IIoT), and Industry 4.0 are some of the terms that have been used to describe the increasing use of digital technologies in manufacturing and industry in general. Despite the various terms that exist in the literature, these areas of research and development have several common themes. First, all describe some form of interoperability between systems across the product lifecycle (from design to end of life) and the manufacturing enterprise (from the shop floor through the supply chain) [4-6]. Second, this interoperability enables the generation of actionable intelligence through the efficient and effective use of collected data and information. Finally, the generated intelligence supports decision making through improved monitoring, analytics, modeling, and simulation.

One area of manufacturing that has benefited from digital technologies is prognostics and health management (PHM). A recent industry survey found that maintenance and machine performance are two of the most important benefits of the Industrial Internet of Things [7]. While PHM is typically considered in the context of process, equipment, or system health and maintenance, it is a broader field that encompasses performance measurement, condition monitoring, diagnosis, and prognosis [8-9]. The goal of PHM in manufacturing is to apply robust sensing, monitoring, and control to best respond to planned and unplanned changes in the performance of manufacturing systems [9]. Meeting this goal requires sensing and control strategies integrated across the manufacturing enterprise that can generate and respond to high-quality intelligence on the current performance of production systems.

There are a number of digital technologies and standards that have been introduced that support one or more requirements of PHM. Liang et al. [3], Gao et al. [10], and Teti et al. [11] provide a thorough summary of much of the research and development of these solutions and highlight relevant examples in the market. The market contains software solutions that support manufacturing operations management by monitoring shop-floor data and providing dashboards that display metrics and key performance indicators (KPIs). Some of these solutions also include platforms that provide additional intelligence based on the collected shop-floor data, such as classifying productive and nonproductive periods for equipment. Examples of these software include System Insights VIMANA, TechSolve ShopViz, FORCAM Force, and Memex MERLIN [12-13]. In addition, some manufacturers have designed their own software solutions, such as ITAMCO's QUPID system, which is a mobile application that captures and provides operational information to shop-floor personnel [12]. Each of these solutions leverages the MTConnect standard, which is an open-source standard that enables interoperability between shop-floor devices, equipment, and applications [14].

Even though digital technologies are increasingly available and accessible to manufacturers, they are not yet extensively used in industry. For example, some experts have estimated that only 5 % of machines in manufacturing facilities are currently being monitored digitally [13]. Part of the problem is that manufacturers have found it increasingly challenging to navigate the breadth of new technologies available to industry [5]. This difficulty is further compounded by technologies developed without a good understanding of the capabilities and limitations of the manufacturing environment. This is especially true for small-to-medium enterprises (SMEs), which have typically been an underserved market segment. The goal of the research presented in this paper is to enable the development of PHM solutions appropriate for industry by describing industrially-relevant use cases. To describe these use cases, we first study existing manufacturing operations through a series of case studies to identify the relevant needs, priorities, and constraints of industry. Our focus in these case studies is on performance measurement, condition monitoring, diagnosis, and prognosis.

CASE STUDY APPROACH

We designed the case studies presented in this paper to target three research areas. First, we wanted to describe the equipment, infrastructure, and configuration of manufacturing systems common in industry. Second, we wanted to identify the common metrics and best practices used by industry in their sensing, health management, and control activities. Finally, we wanted to define the common problems, failures, and bottlenecks for manufacturing processes, equipment, and systems. These case studies distinguished between large and SME manufacturers so that we could better capture the often substantially different considerations specific to each environment. We have presented the results of case studies conducted with SME manufacturers in this paper. SME manufacturers were defined as those organizations with less than 500 employees [15]. Jin et al. [16] have presented more information about the case studies conducted with large manufacturers.

Case-study participants were primarily discrete manufacturers that used subtractive processes and operated within a variety of industrial sectors, including aerospace, automotive, chemical, energy, mining, personal care, petroleum, pharmaceutical, and shipping. The participants were grouped into three classifications based on workforce size and role within the supply chain: small contract manufacturer, medium contract manufacturer, and original equipment manufacturer (OEM). Contract manufacturers (sometimes referred to as "job shops") are outsourcing organizations that contract with other companies to produce parts owned by the customer. OEMs are organizations that produce parts owned internally or by a parent company. In addition to SME manufacturers, the case-study effort also included solution and equipment providers and National Institute of Standards and Technology (NIST) Hollings Manufacturing Extension Partnership (MEP) centers that work with the SME manufacturing community.

Interactions with prospective case-study organizations typically began with an introductory telephone call to present the objectives of the effort and discuss any potential concerns. We followed this initial interaction with more detailed discussions with key shop-floor personnel (for manufacturers) or appropriate engineering personnel (for solution and equipment providers and NIST MEP centers) that focused on:

- Metrics and key performance indicators (KPIs)
- Maintenance activities and strategies
- Best operational practices and examples of successful improvement efforts
- Methods used to monitor, respond to, and improve interactions with suppliers

The goal of these conversations was to identify the common approaches used by the organization being studied as well as the critical drivers and limitations that motivated these approaches. The discussions did not include any predetermined questions and were allowed to evolve as the participant preferred to better understand the greatest concerns for SME manufacturers even if those concerns fell outside of the scope of this study. Site visits and detailed facility tours were conducted for a subset of participants based on availability. These visits focused on further demonstration and explanation of specific systems, issues, and challenges highlighted previously during the discussions. We followed up with participants as needed to clarify previous discussions.

Table 1. Description of three generic SMEs that reflect the SMEs considered by the case studies.

	Contract Manufacturer		**Original Equipment Manufacturer (OEM)**
	Small	**Medium**	
# of Employees	25 total (25 on shop floor)	150 total (100 on shop floor)	100 (75 on shop floor)
Sales Revenue	$5 million	$20 million	$50 million
Industry Sectors	Automotive, Food, Personal Care, Pharmaceutical	Aerospace, Chemical, Energy, Mining	Chemical, Petroleum, Pharmaceutical, Shipping
# of Part Numbers Managed	5000 (≈50 % under active contract)	5000 (≈20 % under active contract)	100000+

CASE STUDY FINDINGS

We present the findings from the case studies by describing a generic SME within each classification group. Table 1 provides an overview of each of the three generic SMEs. The findings for each generic SME has been developed by aggregating the data generated from the case studies. We select this approach to highlight the overall themes we encountered instead of issues specific to one organization.

Small Contract Manufacturer

Table 2 provides a summary of the findings for the Small Contract Manufacturer (referred to as "SCM"). The SCM has the smallest workforce and lowest sales revenue of the three generic SMEs. It also usually earns the smallest margin per part given the need to remain cost competitive in the market. The SCM's small workforce is employed fully on the shop floor and typically in multiple roles. This flexibility leans the workforce and addresses a significant challenge the SCM shares with all SME manufacturers: finding good operators and machinists. This challenge is especially problematic for the SCM since it needs a relatively diverse set of skills given the variety of contracts it may win, but it often lacks the resources to train and retain talent. In fact, the SCM knows that larger manufacturers poach its talent to avoid having to invest in finding and training employees. This is a significant disincentive for the SCM to invest its limited resources in advanced manufacturing technologies.

The need for flexibility is paramount for the SCM when considering equipment needs. Table 1 highlights the relatively diverse set of industry sectors served by the SCM. It also shows the relatively large number of distinct part numbers that the SCM must manage, which is driven by the need to bid on a large variety of contracts to ensure a steady flow of business. The SCM has more machines (35) than employees to provide as wide a range of manufacturing process capabilities as feasible, such as milling, turning, grinding, electric-discharge machining, stamping, and forming. These machines are also of varied age and equipment make since the SCM purchases equipment with the best value relative to capabilities regardless of the vendor. The SCM also has inspection capabilities primarily in the form of hand tools, such as calipers and gauges. It would like to procure a coordinate measuring machine (CMM) eventually to allow it to bid on more lucrative contracts, such as those in aerospace, which require certification and traceability. Each employee is assigned to two-to-three machines to ensure that somebody is always available to run any machine as needed.

The SCM uses some software resources to support its operations. Cost and a lack of in-house expertise are generally the two largest considerations when the SCM invests in software resources, and so these resources tend to be standard packages with relatively limited capabilities and features. Solidworks is the computer-aided design (CAD) package used in the SCM, and part programming is often completed manually. For those machinists willing to use computer-aided manufacturing (CAM) packages for programming, there is a strong preference for MasterCam, but the SCM does not currently have licenses for all of its staff. The SCM also uses DBA Manufacturing to support manufacturing resource planning (MRP), but there is interest in switching to E2 instead since the SCM believes that E2 better fits its needs. In either case, the SCM relies on manual entry of data to keep its systems simple to use and maintain.

Table 2. Summary of generic Small Contract Manufacturer.

Operational Characteristics	• Emphasis on flexibility and broad skill set in workforce • Diverse equipment of varied age and capability • Limited resources that favor simple solutions
Metrics and Key Performance Indicators	• Gross margin • Basic utilization • On-time delivery
Maintenance Approach	• Primarily reactive • Limited preventative
Supply Chain Interactions	• No tracking or monitoring
Primary Business Challenges	• Workforce development • Equipment availability
Primary Technology Interests	• Dashboards that quantify performance • Detailed operational information • Estimation support
Primary Technology Concerns	• Potential disruption to operations • Lack of in-house expertise to deploy and maintain solutions

Gross margin is the most important metric that the SCM tracks even though flexibility tends to be its most important asset. Gross margin is profit as a percentage of revenue. Basic utilization (i.e., the ratio of the time that equipment is in cycle to total time) is also important, but the SCM often runs at ≈70 % utilization at best since some machines may not be needed for the current set of work. Both metrics reflect the SCM's ability to maximize its efficiency when faced with limited resources and the need to deliver a large variety of parts. On-time delivery is another important metric that the SCM uses to understand customer satisfaction since speed tends to be an important part of a winning contract and successful customer interaction that leads to future business.

Despite its emphasis on gross margin and equipment utilization, maintenance is not an area where the SCM invests heavily. The labor challenges faced by the SCM prevents it from developing a dedicated maintenance staff. Instead, the SCM relies primarily on a reactive maintenance strategy that is bolstered by some preventative maintenance based on the equipment vendor's guidelines. The staff are often unable to recognize deficiencies in performance or other characteristics that indicate an increased risk of failure, which leads to a relatively high occurrence of downtime events. Every downtime event requires external support since the SCM's staff lack the training to respond to and resolve many maintenance issues that occur.

The increasingly competitive marketplace for the SCM has forced it to reconsider many of its operational strategies in order to boost its gross margin and equipment utilization. To do so, the SCM must overcome its two primary business challenges: workforce development and equipment availability. The SCM believes that technological advances in sensing, health management, and control can augment and improve the capabilities of its staff. While many of the SCM's technology interests are relatively "low-hanging fruit," such as dashboards that quantify employee performance and encourage improvements, other interests fall within active areas of research in digital manufacturing. For example, the SCM wants to use data and information from all of its systems to quantify the operational status of its equipment and provide intelligence that explains why its equipment may not be running at peak performance. Such knowledge can improve its preventative maintenance capabilities by identifying machines that require attention as well as support capital investment decisions to replace machines nearing the end of useful life. It can also support estimation activities by examining how well the SCM meets its production targets, which can improve the SCM's ability to bid appropriately for new contracts.

New opportunities presented by digital and PHM technologies have encouraged the SCM to explore ways to address its varied business interests. It has begun to network six of its 35 machines in a project with a solution provider who has provided a dashboard that presents basic operational information, such as machine cycle and basic utilization. As the SCM expands these capabilities, its biggest concern is any disruption to its operations as its machines and systems are upgraded to accommodate this new technology. This is an especially large concern for the SCM since it must rely on external support to deploy and maintain these technologies. Interestingly, cybersecurity is not a large concern for the SCM because it does not deal with overly sensitive information (e.g., export-control work). However, this could also be due to a lack of experience with cybersecurity.

Medium Contract Manufacturer

Table 3 provides a summary of the findings for the Medium Contract Manufacturer (referred to as "MCM"). Unlike the SCM, the MCM provides more specialized services (in terms of manufacturing process capabilities provided to customers) and tends to have a more focused strategy when bidding for contracts. The MCM in this example focuses on machining metal components that require relatively large work volumes in excess of 64 m^3. Even though the MCM serves different industry sectors and manages a relatively large number of part numbers (as shown in Table 1), the types of parts that the MCM produces are typically very similar because of the MCM's specialized capabilities. These capabilities and its larger workforce size provide the MCM with a higher sales revenue than the SCM, however the margin per part can be small, especially if the MCM does not bid appropriately for a contract. In general, though, the market pressures tend to be

Table 3. Summary of generic Medium Contract Manufacturer.

Operational Characteristics	• Specialized manufacturing process capabilities • Standardized equipment and systems • Engineering, maintenance, and administrative support
Metrics and Key Performance Indicators	• Basic utilization • Start time versus in-cycle time • Rework cost per direct labor hour • Part-program conformance
Maintenance Approach	• Primarily reactive • Limited preventative
Supply Chain Interactions	• No tracking or monitoring
Primary Business Challenges	• Equipment availability • Process planning and scheduling • Workforce culture
Primary Technology Interests	• Condition-based maintenance • Near-real-time supervisory monitoring and control of shop-floor operations • Estimation and scheduling support
Primary Technology Concerns	• Lack of common data interfaces and protocols • Cybersecurity requirements • Low data volumes for analysis

lower on the MCM than the SCM since far fewer organizations can provide comparable services to customers.

The MCM's specialization allows it to also focus on more targeted training for its workforce and less varied processes and equipment. The MCM has dedicated engineering, maintenance, and administrative staff in addition to its operators and machinists on the shop floor. All of its fabrication equipment are either three- or five-axis machining centers with large work volumes. This equipment is made by one of three vendors who specialize in this type of equipment, and all of the equipment uses the same type of controller. The MCM is a big proponent of standardization to avoid any issues that can arise with heterogeneous systems and interfaces and to enable its staff to work with multiple machines. However, standardization of this sort also creates unique problems for the MCM. First, the MCM is locked into a limited choice of equipment, which can significantly raise the cost of capital investments. Second, the MCM must seek specific skills in its workforce, which can complicate the already difficult process of hiring talent for all SMEs. Finally, the size and specialization of its equipment forces a high burn rate (or cost to run the equipment in excess of income) when the machines experience downtime: $225/hr on average. This high burn rate drives many of the operational decisions of the MCM as well as its strong interest in health management.

Another significant difference between the SCM and MCM is the MCM's ability to devote resources towards software to support its operations. Here again there is a strong preference for standardization in the choice of software. Solidworks and MasterCAM are the CAD and CAM packages of choice, respectively. The MCM also uses E2 to support MRP, but it is interested in exploring other software options since it would prefer a more customizable MRP option. The MCM also has a strong interest in investing in other productivity resources, such as the various MTConnect-enabled solutions discussed in the Introduction. Because of its standardized systems, these types of productivity solutions become much simpler to deploy within the MCM's facility. However, the MCM still has to contend with the challenges posed by manual data entry when using any productivity solution.

The MCM tends to focus its monitoring efforts on more detailed metrics and KPIs that influence gross margin. The two most important metrics are basic utilization and start time versus in-cycle time (i.e., the percentage of cycle time that the machine is in process as opposed to setup). Two other metrics that the MCM has started to track are rework cost per direct labor hour and part-program conformance (i.e., the percentage of time that a part program is not modified by the operator or machinist). The interest in all four metrics is tied to the high burn rate of the MCM's equipment. Given the relatively high cost to run its equipment, the MCM wants its equipment to produce chips with minimal delays due to setup, maintenance, failure, rework, or needed modifications to part programs.

The MCM lacks a sophisticated maintenance program despite its interest in health management and its dedicated maintenance staff. It relies primarily on reactive maintenance and a "band-aid" approach because of the extremely high costs associated with unplanned downtime. These costs have incentivized preventative maintenance in the past, but the MCM's staff never fully embraced these strategies because of a belief in their high cost. Currently, though, maintenance has grown to become the biggest cost for the MCM as it has experienced unexpected failures every few days that usually last one or more days. These failures are almost always due to a traditional machine fault (e.g., bearing failure) and can be expensive to resolve given the specialized nature of the equipment. Machine calibration has also started to become a significant issue as the MCM's equipment ages. For these reasons, the MCM is reintroducing preventative maintenance, training its operators and machinists to observe events that indicate machine faults and failures, and starting to collect and track maintenance data for its machines. The MCM has also started to explore options for condition-based maintenance and scheduling support to minimize the frequency and impact of unexpected downtime events.

The MCM also faces other significant planning and labor issues that it hopes can be resolved using improved sensing, health management, and control. For example, the MCM relies on tribal knowledge for estimation, which has resulted historically in underestimates that can be up to 200 % below the actual cost. Part of this challenge can be traced back to maintenance problems, but the MCM also believes that it may be due primarily to modifications that machinists make to part programs (which can be caused by poor programming or inexperience in machining) as well as general cultural issues within its workforce. The MCM does not yet have the data needed to understand its estimation issues fully, but they would like to provide their engineering and shop-floor staff more information from near-real-time supervisory monitoring and control systems for shop-floor operations. Specifically, they are interested in productivity solutions that build upon existing technologies, which capture basic utilization and cost, and add detailed information to explain why equipment may not be productive. They are also interested in dynamic scheduling resources that allow them to respond to operational changes. The MCM believes that both solutions can support their efforts to address their cultural problems and keep their workforce engaged. For example, the MCM's engineering and management staff has observed that productivity decreases when the shop-floor staff believe that there is less work in the queue. By having the ability to reliably schedule work beyond two weeks of operations, the MCM hopes to incentivize higher productivity from its staff. Previous efforts focused on rework highlight the potential of these solutions for the MCM: rework was reduced by 50 % when the MCM tracked rework and highlighted poor performance.

Existing improvement efforts emphasize the biggest concerns that the MCM faces when deploying digital manufacturing and PHM technologies. Many of these concerns are due to the obstacles created by networking systems that lack common data interfaces and protocols. Even though it standardized much of its equipment, the MCM's equipment and software resources do not connect well with each other. Internal cybersecurity requirements further complicate data interoperability. Interoperability issues also extend to licensing: vendors who provide product-lifecycle management (PLM) and/or enterprise-resource planning (ERP) solutions have not been receptive to supporting the MCM's efforts to network its existing systems. Instead, these vendors demand that the MCM invest in new software packages that the MCM lacks financial and technical resources to deploy. Even if it resolves all of these issues, the MCM often lacks sufficient data to support analysis because of the relatively low volumes of unique parts that it produces. This is a common problem for all contract manufacturers and underscores the need for appropriate verification and validation tools for digital and PHM technologies and solutions.

Original Equipment Manufacturer

Table 4 provides a summary of the findings for the Original Equipment Manufacturer (referred to as "OEM"). The OEM has the highest sales revenue of the three generic SMEs presented in this paper, but it has a relatively lean workforce (see Table 1). It can have a smaller workforce than the MCM because it is more specialized than the MCM. Instead of delivering parts based on types of manufacturing capabilities, the OEM produces all of the components for five product lines. This is why the OEM manages a large number of part numbers: each component has its own set of part numbers, but overall product variation is minimal and created only because of differences in size and material. Product variation is even smaller in other OEMs that produce only one component of various sizes for a parent organization. The volume for each part number is low in both situations since the OEM typically produces parts to order.

Similar to the MCM, the OEM's specialization allows it to invest in machining centers from one of three vendors. The OEM prefers standardization across all of its equipment, but it has shifted from one vendor to another over time to balance costs relative to capabilities. All of the OEM's equipment use the same type of controller to allow its staff to work with any machine. The OEM's specialization and resources also allow it to organize its equipment into a number of cells with targeted automation so that it needs fewer operators and machinists. One negative consideration for the OEM is that its equipment can be very expensive to operate and maintain. For example, the OEM has purchased an entire inventory of spare parts that it stores in a separate warehouse because of the difficulty in securing needed parts quickly. It is for these reasons that the OEM is extremely interested in developing additional maintenance and health management capabilities.

Because it has more resources than the two contract manufacturers, the OEM can provide additional operational support to its shop-floor personnel. It employs dedicated engineering, maintenance, and administrative staff, and it purchases more sophisticated software packages when needed. For example, the OEM uses SAP for ERP support and has invested in a few of the MTConnect-enabled tools described in the Introduction. Its CAD and CAM packages are Solidworks and MasterCAM, respectively, since this is the preference of its engineering and shop-floor staff. The OEM has also invested in a tooling management system so that it can track and optimize its tooling costs, which are another large expenditure.

The primary metrics that the OEM tracks are basic utilization and process efficiency, which is a measure of the setup and run time for a job relative to a standard part. Both choices are motivated by the relatively high cost to run its equipment. The OEM also tracks its customer satisfaction by monitoring delivery and lead times and conformance to estimation (i.e., ratio of actual to estimated cycle time for each process step). All of these measurements are complicated by the large work in progress (WIP) that the OEM must manage: it usually has 400 to 600 orders in its facility as WIP because it is the sole producer of its products. Also, the OEM currently relies on manual input of data, which delays its information by one day, but it is currently working to network all of its systems to automate data collection. The OEM hopes to automate data collection across its supply chain to improve existing processes that support the traceability requirements on its products. However, it would like to ensure that data shared across the supply chain is strictly controlled to protect sensitive information and intellectual property.

Table 4. Summary of generic Original Equipment Manufacturer.

Operational Characteristics	• Very specialized: produces five lines of the same product • Standardized systems based on cost and capability • Engineering, maintenance, and administrative support
Metrics and Key Performance Indicators	• Basic utilization • Process efficiency • Delivery and lead times • Conformance to estimation
Maintenance Approach	• Primarily preventative • Strong interest in predictive
Supply Chain Interactions	• Minimal based on traceability requirements
Primary Business Challenges	• Equipment availability • Scheduling • Foreign competition • Workforce development
Primary Technology Interests	• Predictive maintenance • Automation • Dynamic scheduling • Near-real-time supervisory monitoring and control
Primary Technology Concerns	• Lack of common data interfaces and protocols • Cybersecurity requirements • Low data volumes for analysis

One role of the OEM's primary metrics and KPIs is to manage the maintenance and health of its equipment. The OEM relies on preventative maintenance broken down into daily, weekly, and monthly activities managed by its maintenance staff. Larger overhauls of its equipment occur every few years based on the vendor's specification and with the vendor's assistance. As we have mentioned previously, the OEM would like to invest in predictive maintenance capabilities. It has conducted several equipment studies to understand common failure modes, but these studies have yet to yield enough data to support operational decision making. It has also trained its operators and machinists to provide anecdotal data about the state of its equipment. The OEM is ready to invest in solutions to collect more maintenance data, but it would like support to decide what data to collect and how to collect it so that operations are minimally disrupted. Like all SMEs and manufacturers in general, the OEM would like to avoid "big data" since it does not have the expertise or resources to manage it. Ultimately, the OEM shares the MCM's hopes that advances in digital manufacturing and PHM technologies yield near-real-time supervisory monitoring and control systems that can explain why equipment is or is not running productively.

The OEM also faces other significant challenges in addition to maintenance. Increasing competition from foreign companies making similar products has forced the OEM to focus on ways to reduce changeovers and increase equipment utilization to cut costs. These demands are made more difficult by the fact that the OEM makes products to order, which creates small batch sizes (typically less than 10). These factors have further motivated the OEM to collect data from its production systems. It would like to use this data to generate dynamic scheduling capabilities that allow it to respond quickly and effectively to changes in the performance of its systems (e.g., due to unexpected downtime) as well as the market or supply chain. They also want to use this data to address existing labor challenges. Like the contract manufacturers, the OEM finds it difficult and expensive to hire and train talent. They often lose trained operators and machinists to large manufacturers because they cannot compete on wages. The OEM hopes that advances in digital manufacturing and PHM technologies can promote automation in ways that simplify operations for and augment the skills of its staff. One extension of these capabilities that the OEM has started to explore is the application of data interoperability across the product lifecycle (also referred to as the "digital thread") to understand the accuracy of their expectations about their operations. For example, the OEM would like to know if decreases in product quality are due to errors in design, planning, or manufacturing; the typical assumption is that quality issues are created by manufacturing, but this can hide other opportunities to improve the overall product design and manufacturing process.

Despite the promise of new manufacturing technologies on the market, the OEM has had several concerns when deploying these solutions. First, the OEM has had to face obstacles created by a heterogeneous mix of production systems just as the MCM. The lack of common data interfaces and protocols has required additional time, resources, and expertise to navigate, and the OEM believes that it will need on-going support to maintain these technologies since its in-house expertise is relatively light. There are also significant cybersecurity concerns for the OEM, especially since the OEM would like to interact with its supply chain as well. If these issues are resolved, the OEM still faces data challenges created by the relatively small batch size. Like the MCM, the OEM has found it difficult to generate sufficient data for analysis and decision making, which again highlights the need for verification and validation tools.

USE CASE EXAMPLE

There were several shared themes observed during the case studies despite the noted differences between the three SME classifications. Perhaps least surprising of these themes was that many (if not all) SMEs believe that they fully understand their performance until they are confronted with real data and information from their systems. This process often motivated further introspection from the SME and generated a strong motivation to explore the opportunities presented by improved sensing, health management, and control. The initial interest tended to focus on relatively straightforward areas of performance, such as equipment utilization. This interest usually then grew into a desire to add detail and context that enables the SME to identify specific operational events and explain why these events occur. The state-of-the-art solutions in the field, such as the software described in the Introduction, have started to develop these types of capabilities. In addtion, other interests included prognostics and predictive maintenance and dynamic scheduling, which was often perceived as the natural use case for digital and PHM technologies for manufacturing. Several existing standards and technology efforts have started developing to support these areas. For example, standards, such as MTConnect, OPC UA, Automation ML, and MQTT, have started to generate enhancements that support machine-to-machine (M2M) communication, data interoperability, and other capabilities needed for prognostics and predictive maintenance and dynamic scheduling.

The themes described previously all highlight potential use cases that can be used to advance and develop digital and PHM technologies for manufacturing. Appropriate use cases are critical to generate reference datasets and protocols, test scenarios, and verification and validation tools that enable solution providers to address industry's needs and manufacturers to evaluate various technology alternatives. Six areas for potentially impactful use cases emerged from the case studies:

- Planning and scheduling support
- Maintenance planning and spare part provisions
- Request for proposals
- Resource budgeting (e.g., capital investments)
- Workforce augmentation
- Automation

A general use case example that features several of the areas defined above is an automated workcell that accepts raw material and produces a finished part. The workcell could contain multiple machine tools for cutting operations and robots for pick-and-place operations. These components would be coordinated with each other based on the measured performance state of all components by an overarching control system. This control system would route materials dynamically based on the measured current state and performance of the system as well as input from design, engineering, suppliers, and other actors across the manufacturing enterprise.

To simplify the use case, the workcell would focus on one milling operation in a larger process chain. All of the machine tools would be identical three or five-axis computer numerical control (CNC) machining centers at varying stages of degradation. The machining centers would be of moderate age (five to eight years) and include a standard set of peripheral components common in CNC equipment, such as coolant and lubricant systems, cutting fluid systems, chip conveyors, tool crib, pallet changer, and multiple internal sensors for the control. Common faults and failures that we would expect include spindle or axis bearing failure, motor failure, tool breakage, and machine calibration errors. Only one robot would be used for pick-and-place within the workcell. The robot would require supporting hardware and software systems, such as a controller, end-effector, sensors, safeguards (e.g., light screens or pressure mats), and human interface. Even though robotic systems are typically robust, common faults and failures that we could expect include gear and motor failures.

The workcell would also interact with an operator and several external systems critical for its operations. One operator would be in charge of the entire workcell, but this operator's role would be primarily to ensure that the workcell maintains a predetermined level of performance. For example, the operator would conduct maintenance activities on all or a portion of the workcell when indicated by the control system. Solidworks and MasterCAM would be the CAD and CAM systems, respectively, used by the engineering support staff. E2 (or another similar software solution) would provide scheduling and MRP support. In addition, a simple MTConnect-enabled productivity solution would be deployed in the workcell that connects to operational information from the equipment controllers.

The performance of the workcell would be determined by a set of metrics and KPIs common to SMEs. Examples of metrics and KPIs include basic utilization and/or equipment availability, workcell throughput, workcell efficiency and/or conformance to estimation (i.e., actual to estimated cycle time), and rework rate. These metrics and KPIs could be calculated from a variety of data sources, including operational information from machine and robot controllers, engineering systems (e.g., CAD, CAM, and product lifecycle management systems), and additional shop-floor sensors. Further research would need to be conducted to verify the appropriateness of these data sources.

SUMMARY

The case studies conducted in this research highlight opportunities for and barriers to the deployment of digital and PHM technologies for SME manufacturers. Strong interest exists in the community, especially for basic equipment performance, but there is hope that advances in sensing, monitoring, and control will provide operational support that enables predictive maintenance and dynamic scheduling. Other potentially impactful areas for further research include maintenance planning and spare part provisions, request for proposals, resource budgeting, workforce augmentation, and automation. Large barriers remain, though, that can limit the deployment of digital and PHM technologies in manufacturing. Four barriers repeated by most of the SMEs interviewed for these case studies where:

- Lack of common data interfaces and protocols
- Lack of sufficient data to support analysis
- Lack of sufficient security tools to protect sensitive information and intellectual property
- Potential disruption to operations

While demonstration and clear return-on-investment are all necessary to educate industry about advanced manufacturing technologies, further research is needed to enable industry to overcome the barriers above and make full use of new digital and PHM technologies. Much of this research should focus on developing heterogeneous system-of-systems approaches that can connect various shop-floor systems together and with design and inspection. Advanced sensing and monitoring are needed to understand the highest-value data and information so that manufacturers avoid the challenges of big data (especially the volume and variety of data) and any disruption to operations. Reference datasets and verification and validation tools are needed to help develop tools that meet the needs to industry. New paradigms are needed that enable the use of generated intelligence to better control design and manufacturing processes. Finally, standardization is a critical part of ensuring that these technologies can be used successfully by all manufacturers. Appropriately defined use cases are needed to address these research questions. Such use cases will allow manufacturers to realize the full potential of digital and PHM technologies.

ACKNOWLEDGMENTS AND DISCLAIMER

The authors would like to acknowledge Ron Pieper, TechSolve, and Genedge Alliance for their exceptional support during these case studies. This paper would not be possible without the participation of the many SMEs involved in this effort. Certain commercial systems are identified in this paper. Such identification does not imply recommendation or endorsement by NIST. Nor does it imply that the products identified are necessarily the best available for the purpose.

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