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Conducting a metering assessment to identify submetering needs at a manufacturing facility

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Abstract:

Submetering the energy consumption of processes, systems, or equipment at a manufacturing facility can provide insight into the energy efficiency and productivity of its operations. With the growth of the “Big Data” market and increasing number of submetering options, collecting data is not a challenge; collecting data that can result in actionable information leading to energy savings is a challenge. Further, as manufacturing is in the midst of the smart manufacturing and industrial analytics revolution, developing optimal submetering strategies is of increasing importance, especially if submeters are being installed as a retrofit to an existing facility/process. In particular, small to midsized manufacturing (SMM) facilities will require technical assistance to fully avail of submeter data and join the smart manufacturing revolution.

This paper presents a metering assessment as a method to identify the optimal use of submeters and applications of the collected data at a manufacturing facility. The metering assessment consists of temporarily submetering energy uses to identify future metering needs. The metering assessment involves gathering data on an energy use(s) over a finite length of time, conducting analysis of the data to better understand energy consumption characteristics of the energy uses, and developing an optimal permanent submetering strategy. Through the metering assessment, a facility can better identify uses for submetered data before installing permanent submeters, thereby limiting the collection of extraneous data. Further, the facility can avail of smart manufacturing opportunities by installing submeters as a retrofit and using the collected energy data to inform operational decisions in real-time.

The benefits of conducting a metering assessment are presented using an example from a SMM metal tube manufacturing facility. The results from a metering assessment conducted at the facility resolved outstanding operational issues while also identifying where permanent submetering could improve productivity. Through applying the metering assessment at an SMM facility and identifying uses of submeter data, this paper illustrates the type of technical assistance required to bring the benefits of smart manufacturing and industrial analytics to SMM facilities.

Keywords: Industrial analytics; smart manufacturing; big data; metering assessment; submetering; small to midsized manufacturing

1. Introduction

Submetering within a manufacturing facility can be an effective method for monitoring and improving operations and reducing energy consumption. Submetering consists of measuring and collecting energy-related data of a process, system, or equipment at a regular interval. It is also at the center of the smart

manufacturing and industrial analytics revolution. Smart manufacturing, as defined by the American Council for an Energy-Efficient Economy, is “the integration of all facets of manufacturing, regardless of level of automation, and all the individual units of an organization, for the purpose of achieving superior control and productivity” (Rogers, 2014). Submetering enables the integration and use of real-time energy data from various processes and systems to inform operational decisions and improve productivity.

The challenge with submetering is not in collecting energy-related data, but in empowering a manufacturing facility to use the data to make productivity and energy efficiency improvements. For example, in a survey conducted of manufacturers globally, industry identified the need for tools to manage production processes with respect to energy efficiency. Specifically, integrating real-time data from the facility floor to optimize energy efficiency and reduce energy consumption was identified as a need (Bunse et al., 2011).

There are numerous potential uses of submeter data including improving energy efficiency, reducing energy consumption, and improving the productivity of a manufacturing facility. One example is early detection of system or equipment faults (Armstrong et al 2006, Norford et al 1999). Another is non-intrusive load and energy efficiency monitoring (Agamloh et al 2005). Submeter data can also inform decisions on selecting the appropriate electric utility rate structure. As described by Wang and Li (2015), the energy cost savings from switching from a flat-fee rate structure to a time-of-use structure will depend on the alignment between peak hours and production schedules (Wang and Li, 2015). Alignment can be ensured through the use of data collected from submeters to inform production planning.

Submeter data can also be used to monitor activity on the manufacturing facility floor. Vijayaraghavan and Dornfeld demonstrated the use of electric power data to identify events within a machine tool process, such as spindle start-up, changing spindle speeds, and idle periods. The authors have proposed a software framework that would support energy decision making by evaluating energy consumption and operational data from machine tools and identifying events within a manufacturing process (Vijayaraghavan and Dornfeld, 2010). Similar profiles could theoretically be developed for manufacturing equipment or processes to better understand its energy consumption characteristics and drive energy cost reductions and energy efficiency improvements (Kara et al., 2011, Li et al. 2011, Li and Sun, 2013 ,Pechmann et al., 2011, Vikhorev et al., 2013).

Submetering data can also be an integral part of a continual improvement-based energy management system (EnMS), such as ISO 50001 (ISO 2011). The EnMS establishes a structure, including processes supported by the necessary internal resources, to better understand energy consumption at a manufacturing facility through integration of data collection assets, such as data from submeters. As an example, data from metering systems is required to develop facility-specific energy performance metrics. In a case study at a biomedical facility, submetering was required to develop energy performance indicators specific to the facility’s operations. The energy performance indicators supported by submetered data allowed for continuous monitoring of key energy uses, as well as benchmarking and continuous improvement in their energy efficiency. Monthly data collection or high-level performance indicators (i.e. facility wide metrics such as energy consumption per unit of product)

did not provide the temporal resolution or granularity required for continuous monitoring of key systems (O'Driscoll et al., 2012; O'Driscoll et al., 2013a).

Strategies for integrating submeters and other data collection assets into an energy management system have been proposed (O'Driscoll et al., 2013a, Vikhorev et al., 2013, Dorr et al., 2013). Vikhorev et al (2013) suggest that connecting continuous measurement of energy data at the industrial process level to business performance can support raising “energy awareness”, or insight into how energy use and consumption impacts business overall at the facility. The authors propose a strategy for an advanced energy management system that uses submeter data to identify events during production and calculate key performance indicators in real-time enabling data-driven operational decisions. The connection between energy consumption and units of productivity is central to understanding the energy performance of a facility. An optimal submetering strategy within the context of a continual improvement-based EnMS will both quantify energy consumption and provide insight into productivity.

These examples of using submeter data to drive real-time data driven decision making illustrate the role of submetering in transforming a traditional facility into a smart manufacturing facility. Smart manufacturing and industrial analytics are being seen as defining characteristics of the next industrial revolution. Pictures of robotic automobile assembly facilities are this revolution's icons. However, for small and medium manufacturing (SMM) facilities the challenges and opportunities are less grand but perhaps more important. Implementation of smart technologies must normally be done as a retrofit and proper analytics are different from facility to facility and even system to system. Additional challenges faced by SMM facilities to adopting smart manufacturing and making use of industrial analytics include: unavailability of staff resources to focus on energy considerations, short return on investment requirements for energy efficiency projects, and energy costs viewed as being fixed or sunk. Technical assistance in these areas is necessary to accelerate implementation. Thiede et al (2013) presented a methodology that incorporates data infrastructure and analytics into a continual improvement-based EnMS in a manner that is appropriate for SMM facilities. The authors identify several challenges to developing such a methodology including: 1) determining the correct frequency at which to collect data 2) determining if permanent or single measurement is required and 3) developing a facility-specific methodology. The authors also stated that energy and production data should be integrated in a production management scheme.

In addition to identifying the best uses of the data and turning the data into actionable information, several obstacles emerge when deciding how best to implement submeters. Many are paradoxical in that they are difficult to resolve without collecting data. Facilities may be reluctant to finance metering installations because the resulting energy savings are difficult to predict. A survey conducted at 100 U.S.-based 3M manufacturing facilities identified gaining management approval, justifying costs, financial constraints, and unknown return on investment as barriers to installing submeters (Tutterow et al 2011). Further, identifying metering requirements including the type of meter to install, meter locations, and the frequency at which to collect data is a challenge. There are several metering options, and the selection of the appropriate meter will depend upon the end use to be metered, the desired accuracy, installation cost, sampling rate, intrusiveness, communications, and other characteristics (O'Driscoll and O'Donnell 2013). Similarly, permanent submetering may not be required if temporary

metering can resolve outstanding facility issues. Without overcoming these challenges to submetering, many facilities will be left out of the smart manufacturing revolution.

This paper presents a metering assessment as novel method to identify the optimal use of submeters and best uses of the data in a manufacturing facility. The metering assessment allows a facility to gain a better understanding of the value of data acquisition at a specific facility before installing permanent submeters. This improves on the common practice of installing permanent submeters without a “trial” period, and relying on generic information about manufacturing operations to determine submetering location, frequency, and applications of the resulting data. By conducting a metering assessment before installing permanent submeters, several challenges associated with installing permanent submetering can be addressed, including: developing financial justification for permanent submetering, developing a facility-specific permanent submetering protocol, and identifying if temporary or permanent submetering is required. Unlike other approaches, the approach presented here balances the need for collecting data within a facility, with practical considerations such as the ability to use the collected data to inform productivity and energy related decisions. Finally, the metering assessment allows for existing facilities to become “smart” through retrofitting submeters. The paper uses the example of an SMM facility to demonstrate the value of the metering assessment, including the type of technical assistance and data analysis required to bring the smart manufacturing revolution to SMM facilities.

2. Metering assessment method

For the purposes of the metering assessment presented, permanent submetering is defined as submeters that are left in place and provide data that is reviewed by facility staff. Temporary metering is defined as submeters that are installed for a discreet duration of time. The purpose of a metering assessment is to install temporary submeters to:

- 1) Identify potential energy uses and physical properties to submeter permanently:
Energy uses to potentially meter can include equipment, systems or processes contributing significantly to energy costs, bottlenecks in production processes, or Significant Energy Uses as part of implementing an ISO 50001 EnMS. Meters can collect a variety of energy-related data on physical properties including electric power, pressure, flow rates, temperature, humidity, vibration, and light intensity.
- 2) Identify potential uses for the data:
Identifying potential uses for the data before installing submeters will lead to optimizing data collection such that only actionable information is collected. Actionable information leads to identifying opportunities to improve facility operations. This can include reducing energy costs, improving system reliability, increasing product throughput, or improving product quality. Performance metrics, such as energy performance indicators, and the supporting production information required to support their development, may also be identified as a result of evaluating potential uses of the data. Performance metrics can be used to ensure facility operations are within normal or expected bounds.

- 3) Develop submetering guidelines to improve facility performance (e.g., energy, productivity, financial, environmental):

Submetering guidelines outline how data will be collected. Aspects to consider include the frequency of data sampling, location of meters, and type of data to collect. This will depend on the actionable information sought. For example, if electric power is being metered in order to monitor contribution from a piece of equipment to the facility's electric demand, the frequency of sampling will be related to the methodology used by the electric utility to calculate facility demand. The meter will be placed on the electric supply of the equipment, and voltage and amperes will be collected. Metering guidelines will also include coordinating data collection with other meters collecting complimentary information (e.g., coordinating data from a flow and temperature meter in order to calculate the energy content of hot water), meter accuracy requirements, meter resolution, and use of existing automation or control assets to meet data needs.

Figure 1 outlines the general steps of a metering assessment and provides an example of each step using a scenario where a facility is interested in understanding the energy use characteristics of its systems and processes (e.g. contributors to demand, peak/off-peak electricity consumption, start-up loads).

Figure 1: General steps of a metering assessment protocol and example

A metering assessment should begin by identifying issues related to energy consumption, productivity, or costs that can be resolved with the acquisition of energy data. As noted in the literature, energy data can be used to identify maintenance issues before they occur, monitor activity on the production floor, identify the utility rate structure that best matches facility operations, or in support of a continual improvement-based EnMS (e.g. map energy flows, identify energy consumption characteristics of major equipment, better understand facility energy consumption characteristics).

Once the issue(s) which may potentially be resolved with energy data are identified, all existing data assets should be collected, including utility bill data, energy consumption measured through control devices (e.g., variable frequency drives), and other meters collecting energy-related data (e.g., pressure, flow, temperature within a fluid or air distribution system). Additionally, data on simple measures of physical output (e.g. units shipped, tons produced) corresponding to the time period of energy data collected should be gathered. This data will help to place the energy data within the context of the facility's operations and develop energy performance indicators.

After leveraging all existing data assets, data gaps can be identified. Data gaps will be specific to the results of the previous steps. For many facilities, this may include energy consumption monitoring at the process level. With the data gaps identified, a protocol for conducting the metering assessment can be developed. The specific-protocol and guidelines for conducting a metering assessment depends on the facility's desired outcomes from the metering assessment and the extent of the data gaps. However, some general strategies are identified here. Meter locations should be chosen to optimize data collection; extraneous data may overwhelm the facility, whereas insufficient data will make the assessment ineffective. For example, power metering at the electric panel rather than at each individual component of packaged equipment may be ideal for understanding process energy consumption characteristics. For thermal metering requirements, a single BTU meter may be appropriate wherever there is a change in enthalpy (e.g. supply and return on a hot water loop, or between thermal energy consuming processes). Meters should also be installed to monitor the equipment or process for a sufficient period of time such that multiple cycles of each operational mode (e.g. full production, idling, off) can be monitored. This will allow for definitive and statistically valid conclusions to be drawn from the metering assessment.

The data can be collected either in real-time over the internet or stored locally to the data acquisition unit. While less convenient, storing locally may enable easier metering set-up. If stored locally, data storage capacity may become a factor limiting the frequency and duration of data collection. If collected in real-time over the internet, data storage capacity will most likely not be a concern. However, access to internet can be challenging in plant settings. If overcome during the metering assessment, then any internet access issues can be addressed in the permanent submetering guidelines.

Data analysis should be performed with an understanding of both energy efficiency fundamentals and the operations on the plant floor. The selection of software package will depend on the amount of data to be collected and the type of analysis being performed.

Finally, identifying the needs and guidelines for permanent submetering will depend on the outcome of the analysis. A benefit of the metering assessment is that further continuous metering may not be necessary, or can be minimized. Opportunities for using real-time energy data to inform facility operations are good candidates for permanent submetering.

To illustrate the use and benefits of a metering assessment, an example is provided where a metering assessment was conducted to resolve outstanding operational issues and also to develop a methodology

to monitor production at a SMM site. The facility in the example had specific questions regarding the contributing factors to its high electric costs.

3. Example of a metering assessment

A metal tube manufacturer sought to better understand the factors contributing to high electric demand charges and monitor production in real-time. The primary energy consuming equipment, and subsequently the primary contributors to the facility demand, were four mechanical press brakes ranging from 25 hp to 100 hp used to bend large sheets of metal into a tube (for reference, the 100 hp press brake applied 3000 tons of pressure). The individual energy consumption characteristics of the press brakes were not understood and general motor system characteristics, such as those of a compressed air system, were applied to the press brakes when developing its sequence of operations. Further, the Chief Executive Officer sought a method for monitoring which equipment was running in real-time and following a product through its production steps.

In order to manufacture metal tubes, a large piece of sheet metal is positioned in the press brake jaw and once positioned, a heavy dye, or metal stamper, impinges on the metal bending it to a desired curvature. The dye is controlled manually by an operator. Tubes are not made in a single bend, but require several iterations until finally complete. The stamps to make the first curvature require the most iteration as this is the most difficult section of flat metal to bend. The depth of the jaw only allows for half the tube to be bent before the metal sheet has to be removed from the jaw and re-positioned so that the back half of the metal can be formed. Much of the tube bending process relies on the skill and experience of the operators. The operator has to determine the locations to stamp the metal, the number of stamping iterations, assess if the curvature is sufficient, and determine the amount of force to apply. Once formed, the tube is further processed (e.g., pickling, sizing and heat treating) before being shipped out to the customer. The press brakes had only two motors – a motor to move the jaw and a large fly wheel motor to move the dye.

The facility would leave their press brakes on idle when not in use rather than shutting them down to avoid large in-rush currents at start-up which were thought to be contributing significantly to the facility's electric demand charges. Due to concerns regarding electric demand charges, management had focused primarily on reducing electrical demand and had not considered electrical usage in its operational planning. With little information available on the behavior of the press brake motors, initial decisions used generic motor behaviors to create energy saving protocols such as implementing soft starts. Moreover, it was thought that spinning the flywheels on the press brakes when in idle required very little energy.

Devoldere et al (2007) have characterized the electricity consumption characteristics of press brakes operated through computer control. However, the press brakes operated by the facility in the example for this paper are manually operated. Therefore, key characteristics of the facility's operations, such as processing time, cannot be determined from Devoldere et al.

In order to better understand the contribution of the press brakes to the electric demand charges and develop production monitoring options, a metering assessment was conducted at the facility. The following were the objectives of the metering assessment:

1. Determine the contribution to electric demand from the press brakes
2. With the objective of minimizing electric consumption and costs, determine if the press brakes should be left idle or shut down while not in operation
3. Identify a methodology for real-time production monitoring

To begin the metering assessment, the current data collection assets were assessed. The facility did not have any existing metering or data collection assets beyond its monthly electric bill. Further, daily production numbers were not readily available. The electric bill data revealed that the facility was assessed an average of 400 kW in demand and consumed 130,000 kWh per month in electricity.

Due to the limited existing data collection assets, the energy consumption of the press brakes would have to be temporarily submetered. High resolution electricity consumption data collected through temporary submeters was used to analyze the electricity consumption of several pieces of process machinery. Four mechanical press brakes and a sizing machine were studied continuously over 3 months. 3 months was a sufficiently long period to cover several operational cycles. Current data was collected on each of the machines at a frequency of 2 Hz. Electrical meters were installed on the electrical panel for each press brake and sizing machine. The data was stored in a spreadsheet and mathematical software packages were used for data analysis.

The five pieces of equipment logged were a 100 HP press brake (referred to as 'logger 1'), 2 x 50 HP press brakes ('logger 2 and 'logger 3'), a 25 HP press brake ('logger 4') and a 25 HP sizing machine ('logger 5'). Loggers collected current data, and voltage was inferred from equipment nameplate information. The loggers could store up to 2 GB of data and were powered by a single D-cell Li-ion battery. Current was measured using a clamp current transducer. Each pair of logger and current transducer cost 400 USD.

The application of the temporary metering assessment protocol (Figure 1) to the facility is summarized in Table 1.

Step in metering assessment protocol	Application at facility
Determine what needs to be understood	Electrical demand characteristics of press brakes, establish start-up/shutdown protocol, and develop real-time production monitoring
Collect existing data assets and identify data gaps	Facility-level electricity information available. Production data unavailable
Develop temporary metering guidelines	Meter press brake and sizing machine current at 2 hz for 3 months. Install meters at electrical panel
Install meters and gather data	Data stored locally and gathered at conclusion of 3 months
Analyze data	Mathematical software packages used to analyze data. Results provided in Sections 3.1 – 3.3, 4.
Evaluate need for permanent metering	Permanent metering for productivity monitoring identified

	(see section 4). Original goal of understanding electrical demand characteristics and start-up/shutdown protocol met with temporary metering
Develop metering guidelines	Permanent metering locations, frequency, and analysis algorithms developed

Table 1: Metering assessment protocol as applied to facility described here

3.1. Contribution of demand from press brakes:

At the time of investigation the facility had implemented a staggered startup sequence for its press brakes in order to lower demand charges. The facility assumed that the synchronized startups of press brakes were driving the peaks in demand. Generic motor and compressor behaviors including inrush currents and power required to accelerate the fly wheel from rest led to this assumption. The first focus of data analysis was to use electrical consumption data to test this assumption and improve the associated operational protocol.

A 15 minute rolling average of the accumulated data was used to conservatively estimate the peak electrical demand. In Figure 2, the day of the highest recorded 15 minute average of all five loggers is displayed. The demand for each piece of equipment logged along with a dotted line representing the net demand from the five machines is displayed.

Figure 2: Power and 15 min average power of 5 logged machines over a 24-hr period with the highest observed demand

Figure 2 shows that the large fluctuations in the rolling average of the total electrical demand correspond primarily to equipment being on, be it loaded or unloaded. While equipment start-up and loading behavior affect the overall demand, the contribution to the demand is less significant than the contribution from idle loads.

As an example of the contribution to demand of different activities, Figure 3 takes a snapshot around a 5 hour window of operation corresponding to peak demand hours from the same day as Figure 2. From Figure 3, several key correlations become apparent. All four press brakes are on during this time window. At its peak, the highest recorded total demand is 131 kW occurring shortly before 10:30 AM and corresponding to the 100 hp ('logger 1') and the two 50 hp press brakes ('logger 2' and 'logger 3') being loaded. However just after 11 AM, all of the equipment is idle. Despite the dramatic difference in activity, the electrical power drops approximately 7 kW, or 5% of the peak. By comparison, shutting off even the smallest equipment when idle would contribute significantly more demand savings. If, for example, operations on the press brakes associated with logger 2 and logger 3 were sequenced such that operations associated with logger 2 were rescheduled to after 1:30 pm once the press brake associated with logger 3 was shut down, the facility would offset nearly 25 kW in demand.

Figure 3: 5-hr snapshot to determine contribution of idle load to overall demand

Table 2 compares the power consumption of the four press brakes in idle and at peak load in the 5 hour snap shot from Figure 3. In some cases, the idle load is higher than 50% of the peak load power. Consequently, the press brakes consume a large amount of energy while in idle. It is apparent that minimizing the time equipment is on and idle could yield much more significant demand savings than the initial concern of overlapping activity.

<i>Logger/press brake</i>	<i>Idle Load (kW)</i>	<i>Peak Load (kW)</i>	<i>Idle load as a percentage of peak load</i>
1	55	102	54%
2	17	55	31%
3	25	48	52%
4	25	36	69%

Table 2: Idle load as a percentage of peak load for logged machines for 5 hour snap shot in Figure 3

The suggested policy in response to the findings from the data analysis would be to shift the criteria dictating scheduling from preventing overlapping processes to shutting down machines altogether when not in use. The implementation of a control parameter for when to shut off a press brake requires analysis of process flow requirements, equipment cycling concerns and the energy cost of restarting equipment versus idling it. The first two parameters were beyond the scope of this investigation but the last was available through further data analysis.

3.2. Idling vs shutting down press brakes when not in loaded

Figure 4 shows the start-up current profile for the 100 hp press brake (logger 1). The peak in rush current lasts for less than ten seconds and the power consumption reaches a maximum of slightly greater than 800 kW. Considering the electric demand for the facility was measured in intervals of 900 seconds (15 minutes), the contribution of the in rush current to the demand is minimal.

Figure 4: Start-up electricity usage for logger 1 (press brake 1). The independent axis has been scaled such that 0 min and 0 seconds corresponds to the flywheel spinning at full speed and the press brake ready for use

However, the in-rush power does create a non-negligible contribution to the total electricity usage (kWh). The initial electrical consumption of the press brake motors is due to the fly wheel acceleration. The typical start-up time to get the fly wheel to full speed is found to be approximately 55 seconds. After 55 seconds, the press brake is ready to operate and the energy consumption is a steady 55 kW (if idling). The total consumption integrated over the start-up period is found to be equivalent to the energy consumption after 2 minutes and 34 seconds of idle activity. If operated to minimize demand charges, the press brakes should be shut down if not in use for more than 2 minutes and 34 seconds. Conversely, if the press brakes will be idle for less than 2 minutes and 34 seconds, it should be left on to reduce electricity usage charges.

An example of the savings can be seen in Figure 5 which shows the electric consumption of the 100 hp press brake (logger 1) for one particular 8-hr shift. In this shift, the machine was only used for total of 1 hour and idled for the remaining 7 hours. Between the three usages, there were long periods of idle activity far exceeding the 2 minute and 34 second threshold. By scheduling operations in immediate succession, the facility could have saved over 250 kWh in electric usage for this shift.

Figure 5: Press brake 1 operation in an 8 hour shift

It should be noted that following the generic best practice to always shut down idle machinery would have not optimized the energy savings in the current example. Rather analysis of the metering data was required to determine an operational protocol dictating when to shut off machines in order to maximize energy savings.

3.3. Real-time productivity monitoring:

Through processing the electrical data, a pattern to the activity shown in Figure 5 is evident. Activity occurs in pairs – the machines are loaded, followed by a brief period of unloading and a subsequent period of loading again. A snap shot of one pair of activity is shown in Figure 6.

Figure 6: One pair of activity period on press brake 1 ('logger 1')

Each period of activity corresponds to half a tube being stamped. The initial stamp requires the greatest pressure force from the press brake because it occurs at an edge. From speaking with the press brake operators, edges require more force and precision to curve than any other point along the sheet metal. Subsequent points are much simpler and quicker to stamp. The first few oscillations in each period correspond to stamping the tube at the edge. Towards the end of each period is a short sequence of high activity corresponding to stamping the remaining metal. The period of inactivity corresponds to the metal being pulled out of the jaw and re-positioned. After the metal is repositioned, an electric signature similar to the first period of activity is seen corresponding to the forming of the back half of the tube. With the electric signature of the tube bending determined, current data can be used to monitor the number of tubes manufactured in a day/shift. Two periods of activity correspond to one tube being formed in the press brake. By converting the electric consumption data into a binary signal where each period of activity that lasts for at least a certain duration (>1 minute) is converted to a single value and all other periods are converted to a zero value, a simple method for remotely monitoring the activity on a press brake is developed. This method was applied to the 8 hour snap shot shown in Figure 6. The results are shown in Figure 7 and it is evident that eight tubes were manufactured in the 8 hour snap shot.

Figure 7: Productivity on press brake 1 in an 8 hour shift

With this simple productivity monitoring technique, current data can be used to determine the time it takes to form a tube, bottlenecks in the manufacturing process, operator productivity, and status updates of a tube in process of being manufactured.

4. Results of metering assessment

The metering assessment resolved some of the facility's outstanding questions about its press brakes through temporary metering and identified a method for monitoring production through the use of permanent submeters.

Temporary metering identified an operating protocol to minimize electric demand:

- Turn off press brakes when not in use for 2 minutes and 34 seconds. Using this guidance, the largest press brake could have been turned off 140 hours per month during the 3 months observed
- Whenever possible, stagger operations of press brakes

Before implementing the strategy it was recommended that the facility review any specifications regarding equipment cycling and its process flow requirements.

Temporary metering also identified an electric signature for forming a tube in a press brake. By identifying the electric signature, permanent electric submeters could be installed on the press brakes with the data analyzed to isolate instances of the identified electric signature. In order to identify the

electric signature of the press brakes, the facility should collect current data from the control panel at a frequency of around 0.2 hz (one data point every twelve seconds). This approach can provide the facility with a real-time method for productivity monitoring using permanent submetering.

The metering assessment and subsequent data analysis provided the necessary information for the facility to potentially implement smart control technologies. If integrated with automated remediation as necessary, the productivity monitoring technique identified would represent a central characteristic of a smart manufacturing facility –the effective use of data to monitor productivity and take corrective action when necessary with minimal human interaction. Additionally, the press brakes could be retrofitted with automatic shutoffs if idled for too long presenting another application of smart controls. Through action such as these, the conventional facility could be transitioned into a smart facility through retrofit. This dispels any notions that a smart facility must be new construction.

The example advances the SMM appropriate methodology for integration of data analytics and a continual improvement-based EnMS proposed by Thiede et al (2013) by:

- 1) Collecting energy consumption and productivity information from a single meter. This reduces the need for multiple meters and enables the development of energy performance metrics that are tied to productivity, a best practice when establishing a continual improvement-based EnMS, and
- 2) Offering temporary metering as an option to address the challenge of determining the appropriate metering methodology when neither permanent metering nor single measurements emerge as the obvious metering plan. This is particularly applicable to complex machines where energy consumption varies from part to part and cannot be modeled using existing information

The example illustrates some of the challenges SMM facilities may encounter when seeking to use submeters to improve productivity, reduce energy costs, or join the smart manufacturing revolution. SMM facilities will often not have the staff or resources dedicated to energy management and are even less likely to have the staff or resources to evaluate optimal submetering strategies and conduct the subsequent data analysis. Technical assistance in the form of a metering assessment as outlined in this paper may be required to develop submetering strategies. An immediate concern, such as high electric demand charges, can provide an initial objective of the metering assessment. The subsequent data analysis may yield further benefits of energy submetering.

5. Conclusion:

Submeters have great potential as a tool to enable facility managers to reduce energy consumption and improve productivity through continuous monitoring of the processes and systems within their facility. Their effective use is also essential to the smart manufacturing revolution. However, much of their potential may go unrealized due to implementation barriers, such as unclear use of data, unknown return on investment, and difficulty evaluating the numerous metering options. Even if implemented, without an understanding of how to turn the data into actionable information, the potential benefits of submetering may not be realized.

This paper presents a metering assessment as a method to help realize the potential benefits of submeters, particularly at an SMM facility, and transition a facility into a “smart” facility through retrofit. The metering assessment consists of temporarily submetering energy uses of interest and conducting analysis on the data to identify optimal permanent submetering strategies.

To demonstrate the effective use of a metering assessment, an example from a metal tube SMM facility was provided. Through a metering assessment, the facility was able to resolve outstanding scheduling issues and identify permanent submetering needs. After examining the data collected through the metering assessment, recommendations were made to reduce idle time on the facility’s press brakes, which could in turn reduce demand. The data also revealed a unique electric consumption signature to their tube fabrication process. Using this signature, high resolution submetering is a viable option for monitoring production and assessing facility productivity. Such use of submetering data is a characteristic of a smart manufacturing facility. The example illustrates the type of technical assistance required to bring the smart manufacturing revolution to SMM facilities.

As a future research step, methods for automating the data analysis to reduce the effort and time required to identify the uses of the submeter data can provide facility managers with greater self-reliance. Vijayaraghavan and Dornfeld use event stream processing as the foundation of a software framework to determine the energy consumption and performance of process machinery. The authors assert that such data processing can leverage complex data streams to inform actions to improve the environmental performance of process machinery. In their case, the authors were studying machine tools (Vijayaraghavan and Dornfeld 2010). In the present study, mechanical press brakes were studied. Continued research into the energy consuming characteristics and signatures of common manufacturing processes may inform the development of libraries of energy signatures and algorithms for automating the type of analysis conducting in the present paper. Further, the development of data processing software that can identify commonly occurring/observed energy consumption patterns as a basis for identifying abnormal operations may forego the need to correlate energy consumption data to facility-specific typical work cycles and production characteristics. Additionally, the development of common data storage structures for use across multiple manufacturing processes may facilitate the development and uptake of universally applicable analysis software packages. If software packages for automating the type of data analysis described in this paper are coupled with submeters as part of an off-the-shelf energy monitoring system, facility managers will be provided with actionable data to reduce energy consumption, improve productivity, and join the smart manufacturing revolution through retrofit.

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