The Energy Savings Potential of Smart Manufacturing

Ethan A. Rogers

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529 14th Street NW, Suite 600, Washington, DC 20045

Phone: (202) 507-4000 • Twitter: @ACEEEDC

Facebook.com/myACEEE • www.aceee.org

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About the Author

Ethan Rogers joined ACEEE in February 2012 and directs the day-to-day activities of the industry program. The program team analyzes energy use by industrial facilities and how it is reduced through investments in new, more efficient technologies. The program also analyzes and reports on energy efficiency programs targeting the industrial sector and on opportunities to increase the use of combined heat and power (CHP) to meet the nation's energy needs. The team's research reports and white papers help policymakers and other stakeholders understand sector trends, motivations, and best practices.

In addition to research, the team works collaboratively with businesses, government agencies, public interest groups, and other stakeholders in the industrial sector to advance the efficient use of energy in products, systems, and facilities.

Prior to joining ACEEE, Ethan worked at the Purdue University Technical Assistance Program (TAP), where he managed an industry-focused energy efficiency and sustainability training and implementation assistance program. He earned a BS in chemistry from Eastern Illinois University, and he holds an MBA from Butler University. He is a certified energy manager (CEM).

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Executive Summary

This is the fourth research report by the American Council for an Energy-Efficient Economy (ACEEE) analyzing the features and benefits of intelligent efficiency, that is, the additional energy efficiency made possible through the use of information and communication technologies (ICT). The current report focuses on the use of intelligent efficiency in the industrial sector. This use is often referred to as smart manufacturing.

Smart manufacturing is a broad, complex, and often confusing subject. It has many parts and many connections with other technologies. Simply put, it is the integration of all facets of manufacturing through the use of ICT. It seeks to integrate all aspects of manufacturing, regardless of level of automation, and all the individual units of an organization in order to achieve superior control and productivity. It can give everyone in the organization the actionable information they need, when they need it, so that each person can contribute to the optimal operation of the enterprise through informed, data-driven decision making.

Smart manufacturing has been enabled by the ability to connect just about any device to any other object or person. It is set to transform the industrial sector and its use of energy, raw materials, and labor over the next couple of decades. Savings opportunities encompass electricity, natural gas, transportation fuels, and other fuels as well as chemical feedstocks. This report explains how smart manufacturing can address all of these opportunities in a holistic way and help stakeholders meet their respective goals more effectively.

Given its potential to impact the nation's energy use, smart manufacturing is worth the attention of many diverse stakeholders. Understanding smart manufacturing and how it can transform energy management is obviously important to end users, but it is also relevant to energy efficiency and economic development professionals and to environmental advocates. The information in this report is intended to enable more informed energy efficiency decision making in the manufacturing sector, program development in the efficiency program sector, and policy discussions in the utility and public sectors.

Even though the terms *smart manufacturing*, the *Internet of Things* (IoT), *machine-to-machine* (M2M), and *industrial Internet* have been around for a few years, many public- and private-sector decision makers and stakeholders are only recently learning of them. We define these terms and relate them to new, cost-effective ways of managing and saving energy.

Smart manufacturing is enabled by conventional automation and by ICT. The building blocks of automation are devices, sensors, systems, processes, and controls. The building blocks of ICT are hardware, firmware, software, communication protocols, networks, and interfaces. Many of today's devices are sold embedded with software (called firmware) that enables connection with other devices. Combining devices with other equipment and sensors forms systems; combining multiple systems forms processes.

Energy can be saved at each level. Starting at the device level, replacing an inefficient device such as a motor with a more efficient one will save energy. Additional energy can be saved as a system is made more efficient, and then again as a process is operated more efficiently. Ultimately the entire manufacturing facility operates more efficiently, and the entire manufacturing supply chain produces only the particular items requested by customers.

System optimization becomes more challenging at each level. However it is now possible to identify the optimal operating conditions of complex systems by inexpensively collecting and analyzing large quantities of performance data, often remotely in the cloud. System optimization maximizes productivity and minimizes costs. Energy is one of the key manufacturing costs that is minimized.

With the ability to measure and track energy usage comes the capability to report the performance of energy efficiency investments in real time. This data flow is valuable to energy efficiency program administrators and financial institutions that create investment instruments backed by investments in energy efficiency. For the former, it yields higher quality and more timely performance data. For the latter, it provides an inexpensive way of analyzing risk and reporting asset performance.

Several communication and device-interconnectivity issues need to be resolved before these benefits and market developments can be realized. The market is currently awash in proprietary and incompatible communication protocols and network systems. Fortunately, many industry leaders are collaborating on new common protocols and interconnection standards, often with help from federal agencies. One group, the Smart Manufacturing Leadership Coalition, is working to demonstrate a new open-access software platform for managing manufacturing processes. If successful, it could reduce the cost of market entry and become the foundation for an entirely new business sector of manufacturing solution providers.

As investments in smart manufacturing increase, government agencies can facilitate growth through funding and participation in research, development, demonstration, and education projects. Policymakers should recognize that smart manufacturing is a significant opportunity for the economy that can be accelerated by modest government involvement. Utilities and trade organizations have an equally important role to play. The issues are too complex and interconnected for a single sector to resolve on its own.

Manufacturers of smart devices and networks, information technology (IT) and telecom companies, and providers of operational solutions should all participate in developing common standards and protocols. Since there is a certain inevitability to their creation, all organizations that are likely to be affected by them will be well served to embrace and participate in their development.

As we look to the future, it is obvious that the ubiquity of energy performance data and the ability to analyze it will transform the manufacturing sector. Companies will be able to compete on energy efficiency, environmental, safety, and sustainability performance metrics. Customers, efficiency programs, and investors will have access to the information and will incorporate it into their own decision making.

Smart manufacturing will reduce the energy needed for any given level of production, both in individual facilities and throughout the national industrial sector. No overwhelming market conditions will prevent or complicate this evolution. It is part of the normal progress of manufacturing technology. It will happen because it helps manufacturers save money. Some of that money will be in the form of energy not purchased.

Introduction

This is the fourth in a series of research reports the American Council for an Energy-Efficient Economy (ACEEE) has undertaken to examine and explain intelligent efficiency, which is the additional energy efficiency that becomes possible when networked systems can optimize performance through adaptive and anticipatory decision making. This new ability to save energy has arisen through a recent decrease in the cost of sensors and data storage, an increase in analytical and computational capabilities, ubiquitous human connectivity through mobile devices, and the ability to connect just about any device to a network of other connected devices. The first ACEEE report explores intelligent efficiency qualitatively in all of its forms in all sectors across the economy. The second report focuses more narrowly on intelligent efficiency's potential to produce electricity cost savings in the commercial and manufacturing sectors. The third, a white paper, describes applications of information and communications technologies (ICT) to freight transportation.

In this report we narrow the focus even further to examine energy-saving opportunities in the industrial sector made possible by smart manufacturing technologies and practices. Smart manufacturing leads to intelligent efficiency by integrating all aspects of the manufacturing process through ICT. If predictions are correct, smart manufacturing will bring about a revolution in the way things are made and a step change in the efficient use of energy.

The scope of smart manufacturing is broad and complex. This report will focus on the potential for energy savings at the facility level and the possibility of leveraging improved data collection and reporting capabilities in new energy efficiency programs. Future research will extend this work to explore large integrated enterprises and entire supply chains. We will also examine the ability of intelligent efficiency measures to provide real-time measurement and validation (M&V) information to utility-sector demand-response and efficiency programs.

PURPOSE AND AUDIENCE

The purpose of this report is to inform energy efficiency decision making in the manufacturing sector, program development in the efficiency program sector, and policy discussion in the utility and public sectors. Since smart manufacturing will transform the industrial sector over the coming decades, all these stakeholders need a better understanding of the features and benefits of intelligent efficiency and its energy-savings potential. It is estimated that investments in smart manufacturing could generate cost savings and new revenues that could add $10–15 trillion to global gross domestic product (GDP) over the next 20 years (Evans and Annunziata 2012).

Even though there has been much press about smart manufacturing, many decision makers at manufacturing facilities are not yet aware of how these technologies can help them manage costs and save energy. Understanding this potential may alter their internal business case analysis and their position on whether or not to participate in energy efficiency programs.

This report aims to describe established process-automation and emerging smart manufacturing technologies for energy efficiency practitioners, economic development professionals, and environmental advocates who may not be familiar with how energy is used and saved in the industrial sector but who are now looking to the sector to meet energy resource acquisition, economic development, and environmental mitigation goals. Opportunities within the sector encompass electricity, natural gas, transportation fuels, and other fuels, as well as chemical feedstocks. Addressing all of these opportunities in a holistic way, smart manufacturing can help each stakeholder group meet its respective goals.

It is important to recognize, though, that integration and automation projects cannot usually be justified on energy savings alone (Forrester 2012). More often, energy savings is an underappreciated co-benefit. This makes efforts by energy efficiency programs to encourage investments in intelligent efficiency challenging. To fulfill their mission, programs are obligated to ensure that their incentives are properly targeted and cost effective. Looking ahead, however, as the ability to capture system-level energy consumption data improves, the very features of smart manufacturing that currently pose a challenge to program administrators could become the basis for new incentive models that make those concerns moot and also overcome other more daunting challenges.

Combined with current data analysis capabilities, smart manufacturing will enable companies to inexpensively quantify efficiency gains compared to past performance. Investments in smart manufacturing could provide energy savings data to manufacturers and their utilities in real time and with a high degree of confidence. Such capability meshes well with utility demand-response and energy efficiency program objectives, and it is therefore likely to be of interest to efficiency program developers and administrators who are in search of new program ideas to meet future resource obligation requirements.

ORGANIZATION OF THE REPORT

Smart manufacturing has many parts, and it is easiest to understand when broken down into the fundamental pieces that make the greater whole possible. To that end, this report starts with the features and energy-savings benefits of the simplest components and then builds toward the networked and integrated whole. Case studies and figures provide reference points for the many devices, systems, processes, and network components we describe, as well as their ability to produce new and incremental energy savings.

Many technology challenges and market barriers must be overcome before smart manufacturing's potential can be realized. The market is currently segmented with numerous incompatible devices and proprietary systems. Since integration can be difficult and expensive, the solutions are often complex (if they are even possible), and the benefits hard to guarantee. Many private and public organizations are working together to address these market barriers, lower costs, and drive down risk. These efforts range from agreeing on common definitions and communication protocols to developing new nonproprietary software platforms that can support cloud-based data analytics. This report highlights these collaborative efforts and explains the challenges that remain to be addressed.

We also review and expand on the idea, first introduced in the second ACEEE report, that investments in intelligent efficiency might become eligible for financial assistance through energy efficiency resource acquisition programs. We describe how smart manufacturing could facilitate greater energy efficiency investments through improved calculation of energy savings and improved risk analysis for financial markets. We present possible scenarios and evaluate the benefits and challenges.

The concluding sections of the report discuss of the need for greater private-sector participation, recommend more proactive public-sector support, and argue that the integration of smart manufacturing technologies and practices into the industrial sector will improve productivity, competitiveness, and the use of energy resources.

What Is Smart Manufacturing?

> Smart manufacturing marries information, technology and human ingenuity to bring about a rapid revolution in the development and application of manufacturing intelligence to every aspect of business. It will fundamentally change how products are invented, manufactured, shipped and sold. It will improve worker safety and protect the environment by making zero-emissions, zero-incident manufacturing possible. —Jim Davis, SMLC (Warren 2011)

Smart manufacturing has many parts and many connections. It is a broad, complex, and often confusing subject. Simply put, it is the integration of all aspects of manufacturing, regardless of level of automation, and all the individual units of an organization, for the purpose of achieving superior control and productivity.

Smart manufacturing is many things. It is the sensors and devices that are embedded with software and that can communicate with one another and with other systems through networks. It is automated control, integrated manufacturing, and networked companies improving productivity through information sharing and informed decision making. It is improved measurement, evaluation, and validation via cloud-based data analytics. It is the harvesting of big data to analyze operations, identify faults in systems, understand customer interests, and inform operators. It is the combining of enterprise resource planning (ERP) and production management systems, and the connection of both with product design systems that take into consideration environmental issues throughout a product's life cycle. It is the networking of an entire supply chain, from mine to manufacturing to merchandise on a retail shelf, from farm to factory to table. It is the capability, it is the stuff, it is the phenomenon that is transforming manufacturing.

Smart manufacturing is the ability for everyone in the organization to have the actionable information they need, at the time they need it, so that they can contribute to the optimal operation of the enterprise through informed, data-based decision making. It is more than technology. It also encompasses worker training, management systems, and corporate culture.

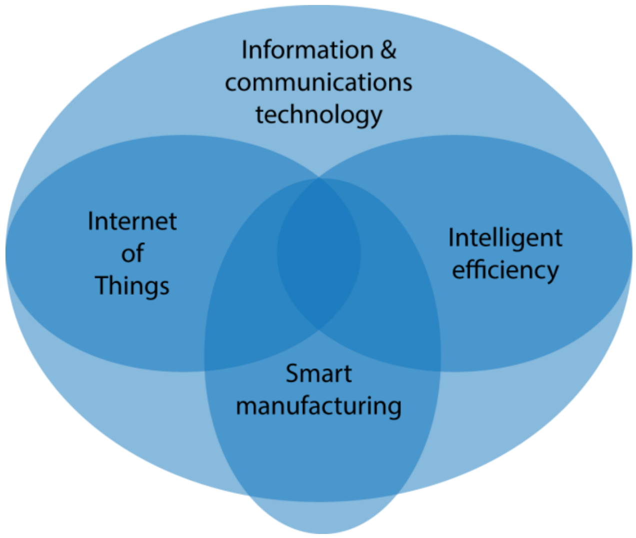
Smart manufacturing has been made possible by the ability of just about any device or object to communicate with any other device, object, or person. This "Internet of Things" is enabled by embedded software and common protocols that allow information sharing through and across networks. There are now more devices connected to the Internet than people (Ericsson 2011). Machine-to-machine (M2M) communication is further empowered by the ubiquity of mobile broadband-enabled Internet access. Sometimes referred to as the "pervasive Internet" (Harbor Research 2011), it is making connectivity and networking available independent of location. Within the industrial sector, the integration of devices through the Internet is also called the "Industrial Internet" or the "Industrial Internet of Things." It allows manufacturing to move from simple device integration and connectivity to the higher-level challenges of connecting people and devices on a network and having them effectively communicate with each other.

The elimination of barriers to interconnectivity and the falling prices of networks and data analytical capabilities are creating a new market that will support entirely new business models for the solution providers. This will enable them to offer new products and services that will improve the productivity of workers and facilities, provide managers with greater visibility and control, and result in energy savings.

Smart manufacturing is different than automation, a manufacturing practice that has been around since the dawn of the Industrial Age. And though it builds on automation, smart manufacturing is also more than just the next iteration of process automation and resource management. If automation simplifies an operator's task of turning a piece of equipment on or off, then smart manufacturing simplifies the decision as to when to turn a piece of equipment on or off by closing the gaps in connectivity that currently exist between devices, systems, facilities, and people. It provides the ability to run a process, production line, facility, and even an entire company more efficiently through more informed decision making.

The practice of automating production is a form of continuous improvement in which companies automate processes or parts of processes on a continual basis. At any given time, different systems within a plant will be at various stages of automation. In a similar fashion, the conversion of a plant to smart manufacturing is seldom a discrete or singular event. "It's a business and technology journey, not a technology" (Davis et al. 2012).

Smart manufacturing is also related to intelligent efficiency, as they both use ICT to achieve efficiency goals. Intelligent efficiency is energy efficiency made possible by the deployment of affordable next-generation sensor, control, and communication technologies that gather, manage, interpret, communicate, and act upon disparate and often large volumes of data to improve device, process, facility, or organization performance. Smart manufacturing contains many elements of intelligent efficiency but in its entirety is not a subset of it. While intelligent efficiency is focused on energy efficiency, smart manufacturing has a larger enterprise efficiency purpose. Energy efficiency is most often not the motivation for such investments. It is, however, an important co-benefit to the improvements in process control and productivity that are most frequently the primary investment motivations. Figure 1 shows the relationship between smart manufacturing, intelligent efficiency, ICT, and the Internet of Things.



Subsets of ICT

Intelligent efficiency. Energy savings resulting from ICT-enabled connection of sensors, devices, systems, facilities, and users.

Smart manufacturing. Superior productivity resulting from the integration of all aspects of manufacturing.

Internet of Things. M2M interaction through the Internet.

Figure 1. Relationship of ICT, IoT, intelligent efficiency, and smart manufacturing

HIERARCHY OF TECHNOLOGIES

To differentiate between conventional energy measures and intelligent energy measures, it may be helpful to revisit a methodology discussed in *Intelligent Efficiency: Opportunities, Barriers and Solutions* (Rogers et al. 2013). The same concepts apply to automated manufacturing and smart manufacturing.

We will illustrate the difference using the example of a pumping system that pulls water from the city water supply and moves it to a water tank several hundred feet away.[1] The water tank supplies various processes through the factory, so water is drawn out at varying rates throughout the day. The goal is to use as little electricity to supply water to the plant as is needed to keep up with the pace of customer demand for product.[2]

The methodology establishes a hierarchy of technologies ranging from the most basic to intelligent efficiency measures with adaptive, anticipatory, and network capabilities. Table 1 shows the hierarchy. The levels connote complexity rather than additional energy savings, although energy savings generally increase as we move toward Level 4.[3]

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[1] This example is a friction-dominated system so that we can demonstrate how affinity laws can result in energy savings.

[2] In a conventional push system, a company estimates its sales volume, orders the appropriate materials, and “pushes” them through the production line toward the customer. In a pull system, the customer “pulls” a product from the end of the production line, which triggers the manufacture of a replacement product. That in turn pulls intermediate and raw materials from suppliers.

[3] This hierarchy is not be confused with the International Society of Automation’s ISA95 (https://www.isa.org/isa95/) international standard for developing an automated interface between enterprise and control systems.

Table 1. Hierarchy of control technologies

Level	Technology
Level 0	Manual on/off
Level 1	Reactive on/off
Level 2	Programmable on/off
Level 3	Variable response
Level 4	Intelligent controls

The pump in the water system is driven by an electric motor. The most basic way of controlling the speed of the motor is by using a simple manual on/off switch. Since there is no automation at this baseline level, we are calling it Level 0. Whether the pump is on or off has an obvious impact on the energy use of the system, but other components—the pump, valves, and piping—also contribute to the pumping system's energy use over time. The amount of energy consumed by the motor is related to the features of the pump and friction within the piping and valves.

The next level (1) is a reactive control, such as a level sensor that turns the pump motor on and off automatically. A common system would be a pump that fills the tank until it is full, at which time a float trips the off switch and the pump is turned off. When the tank gets too low, another mechanical device turns the pump on. This process continues without human intervention day in and out. This is a rudimentary example of a closed-loop system.

The next level (2) is programmability. Instructions in the water pump's programming determine the conditions (e.g., time, tank level, production scheduling) under which the pump is turned on or off.

This system seems efficient enough; however, in this and the preceding scenarios, the pump operates at full speed each time it runs. Running the pump at a lower speed can save energy. Cutting the speed in half reduces energy consumption for a given amount of time by seven-eighths, so even though it will take twice as long to fill the tank, it will take a fourth as much energy.[4] However if it is run too slowly, it may not be able to keep up with demand for water by production.

Level 3 incorporates variable response. The pump motor is connected to a variable-speed drive (VSD) that speeds up or slows down the pump in response to an instruction. That instruction could be in response to data from a sensor or from a predetermined program. For example, the pump speeds up the lower the tank gets and slows down the closer to full it gets. The VSD adjusts the speed of the pump, and with each second that the pump

[4] Flow is proportional to shaft speed, while the amount of power use by a pump is proportional to the cube of the shaft speed ($P_1/P_2 = (N_1/N_2)^3$).

operates at less than full speed, energy is saved.[5] We can call this system-level savings due to automation.

There is still some waste left to be eliminated: the difference between what this automated system uses to fill the water tank and the least amount needed to satisfy production. Prior to new smart technologies, it would have been very difficult and expensive to capture this comparatively small amount of additional savings. What smart technologies give is the ability for the production line to tell a central control how much water it needs now, five, fifteen, and sixty minutes from now. The pump can use this information to fill the water tank to the exact level needed to ensure it maintains pressure and volume for the production line.

Level 4 is the full integration of all of these enabling technologies with an additional software component that analyzes past performance and adjusts system outputs in anticipation of future performance. At this level, additional savings are possible because the process control is proactive and not just reactive. It has the ability to take past performance into consideration in determining future operating set points. This may be called system-level savings due to smart manufacturing.

Conventional production automation allows the pumping system to be integrated into the production process, which is essentially just a larger and more complex system. Processes have the same levels of control as a system, including on/off (level 0), reactive (level 1), automated (level 2), and automated and adjustable (level 3), all these to be integrated with the rest of the plant and programmed with adaptive and predictive decision making (level 4). These same levels of control are possible for facilities, for entire companies, and even throughout the manufacturing supply chain (figure 2).

[5] This is not an absolute. There are many common situations in which a VSD does not guarantee energy savings.

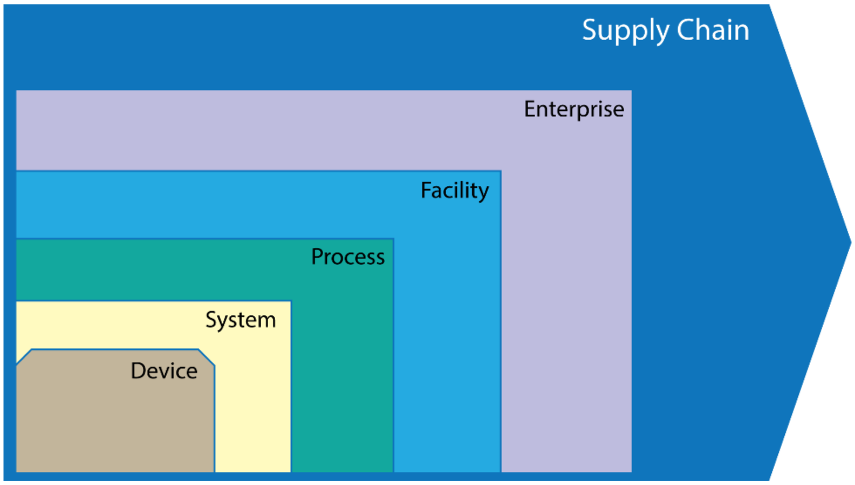

Figure 2. Order of energy savings in manufacturing

SAVINGS BY THE LEVEL

A more efficient motor is a more efficient device. Device efficiency is tied to the innate ability of the device to convert one form of energy into another. For the motor, it is electricity into mechanical motion. For the pump, it is mechanical motion into hydraulic energy. The motor, its electrical drive, the pump and associated pipes and valves, and the control mechanism and its sensors (if any) all comprise a system. Using more efficient devices or, as was just described, operating in an optimal way, can improve system efficiency.

> CASE STUDY: ENERGY SAVINGS THROUGH SYSTEM EFFICIENCY AT STEELCASE
>
> Steelcase, an office furniture supplier headquartered in Grand Rapids, Michigan, had an outdated boiler control system at one of its facilities. Steelcase has an ISO 14001-compliant environmental management system in place that required the collection of water, air, gas, electricity, and steam (WAGES) data; however, they were being collected manually. Steelcase installed a process-automation system automate control of the boiler. The system provides real-time tracking and monitoring of WAGES data. By feeding that information back to operations, the Steelcase facility was able to reduce its energy consumption by 15% and its carbon footprint by 25% (Rockwell 2012).

Process-Level Energy Savings.

The water-pumping system described above is part of a larger manufacturing process. The same network that enables the pump to schedule its load for the day also allows each system in the production line to optimize its use of energy. The system may do this automatically or it may present options to the production manager. The manager can accept its recommendations or adjust them when there are variables of which the production automation system is unaware. As each of these systems communicates with other systems, an improved optimal operating scenario can be discovered. This process-level efficiency adds to the savings that are possible at the systems level. The analysis that optimizes the process may be centralized or it may be dispersed throughout the network.

Facility-Level Energy Savings

At the facility level, smart manufacturing integrates both vertically (within a production process) and horizontally (across systems). For example, many companies now have separate business and production management systems. The first system takes care of accounting and perhaps payroll, and the second manages the machinery in the plant.

The next level of integration is for the production process to communicate with the business management systems, such as accounting, payroll, and enterprise resource planning (ERP). This will simplify the transfer and analysis of information, such as raw-material delivery times and labor hours per product shipped. When connected with suppliers, these systems can communicate to production the quality of the raw materials so that any changes to the amount of processing required can be anticipated. For example, a high-quality, albeit more expensive, raw material might require less milling than a lower-quality, less expensive raw material (Koc and Lee 2002). The business automation system can take all of these variables into consideration and recommend options that reduce energy use and overall costs.

Enterprise-Level Energy Savings

Integration of multiple production facilities makes asset and resource utilization visible to corporate management. Determining the optimal production levels for a mix of product across a fleet of manufacturing facilities is no longer a forecasting process but a dynamic one that integrates customer demand, supplier realities, and facility capabilities. Factories are most efficient when operating at capacity, so integration that improves decision making about how to best allocate resources will result in less waste.

Energy Savings Throughout the Supply Chain

After achieving success through integrating business asset management and production automation systems, the next step is to integrate management systems that organize a company's customer relationship management (CRM) and procurement and supplier relations, known as supply-chain management (SCM). Customer order processing and client-management software programs can be integrated to inform the production system of existing and pending orders. Once they are integrated, customer demand, production, and supplier data are more accessible, better contextualized, and available more quickly. The ability to make better decisions leads to the possibility of operating more efficiently. When the supply chain operates more efficiently, less waste is generated and, by extension, energy is saved. Figure 3 shows this integration of company functions.

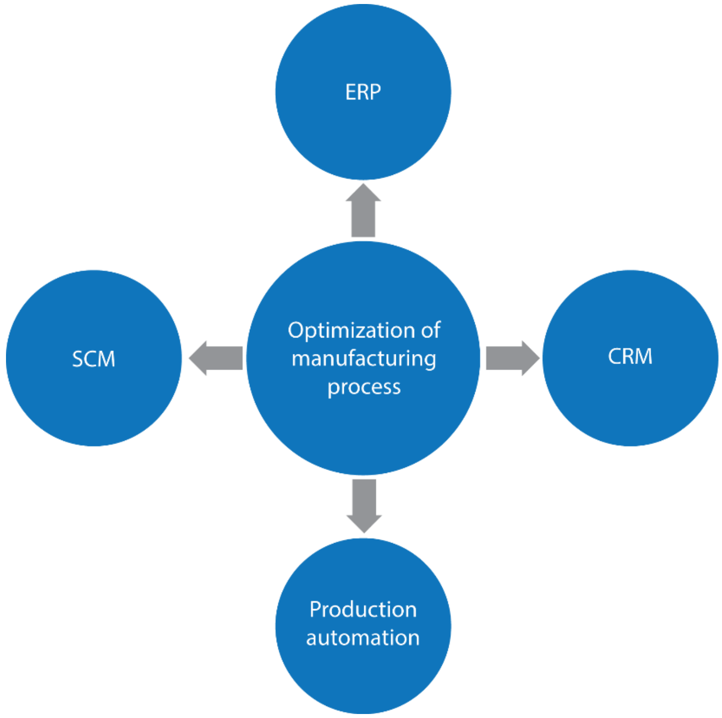

Figure 3. Smart manufacturing integrates management of all company functions: production, purchasing, planning, and sales

Energy Savings Through Product and Process Design

Full integration of the manufacturing process will include smart design or design for the environment (DfE). DfE is a design process that takes into consideration all the raw materials to be used in production (including intermediate materials and production equipment consumables), production wastes, wastes generated by product use, and the issues related to recycling the product at the end of its useful life (EPA 2014a). More and more companies are integrating DfE into their production management systems (EPA 2014b). Fully realized DfE reduces energy use at each step of the process.

The ultimate step is to integrate the supply chain from mine or farm to retail store (figure 4). Suppliers that previously estimated customer demand will now have real-time information that pulls raw material through their production processes in just the quantities and at just the times needed. The original equipment manufacturer (OEM) will have the same relationship with its distribution and retail outlets.

Figure 4. Components of a supply chain. T: transportation. This report focuses on the light blue components.

Automation and integration of these systems will lead to lower costs, increased efficiency, and faster response times (Selko 2013). It will also increase the visibility of assets, inventories, workflow, workers, and energy. In modern lean manufacturing processes, production runs at the speed of customer demand (versus projections) so that no energy is wasted making products that will not sell. By manufacturing only what will be purchased, companies can largely eliminate the waste of unsold inventory. By eliminating inefficiencies in the flow of materials, inventories of raw materials, work-in-progress (WiP), and final products can be reduced. As inventories are reduced, less energy is consumed; as the flow of materials is better managed, transportation is reduced; and as movement of materials is reduced, energy is saved. ACEEE intends to cover this topic in more detail in future research reports.

Over the next decade, the technologies and practices of smart manufacturing will complete the evolution of manufacturing from a supply-side-focused mass production to demand-driven mass customization.[6] An entire enterprise will be coordinated around the ability to respond dynamically to customer requests and supply-chain realities. Systems will harvest large volumes of data and use data analytics to model and simulate production scenarios for the purpose of identifying the best operating conditions needed to satisfy customer demands. These new factories will be flexible in what they make, where they source inputs, and how they distribute outputs.

Smart manufacturing will ultimately bring all business and production management systems together so that resource use can be maximized through instructive feedback loops, early identification of errors, and better decision making. As smart manufacturing realizes its ultimate manifestation, corporations will have end-to-end connectivity enabling the minimization of energy use and environmental impacts.

This report concentrates on the industrial sections (mining, component manufacturing, and final assembly of components by the OEM) of the supply chain. As the scope of smart manufacturing is broad and complex, we focus on the potential for energy savings at the facility level and the possibility of leveraging improved data collection and reporting capabilities in new energy efficiency programs. Future research on intelligent efficiency will expand upon this work by exploring the implications for large integrated enterprises and entire supply chains. It will also explore the ability of intelligent efficiency measures to provide real-time measurement and validation information to utility sector demand-response and efficiency programs. Given that an examination of the energy savings possible through DfE is a complicated and evolving subject worthy of its own research, this report contains only a cursory examination of its potential to impact energy savings.

Components of Smart Manufacturing

Each manufacturing facility will employ different combinations of hardware and software as it invests in smart manufacturing. Many facilities will build on top of existing

[6] Mass customization means customized products are produced in volume and at a relatively high rate of speed. It is the merging of custom work with mass production.

automation, while new facilities and old ones going through modernization will construct their systems from the ground up. Since many of the components of conventional automation—sensors, enabled devices, controllers, and analytical software—are also enabling components of smart manufacturing, they will be described first.

We will start with hardware, explain different control technologies, and then progress to software. The description of software will move from the simple to the complex. At times it will be necessary to toggle between the two because software is often embedded in hardware so that it can communicate with other devices and participate in a network. The distinction between hardware and software is not as important as it might seem, because for end users it is less important whether something is hardware, software, or some combination, than whether it provides the desired functionality. Once we have laid the foundation for conventional automation, we will go on to describe the components of smart manufacturing. We will complement the description of the smart manufacturing components with case studies of smart technologies and their operational and financial benefits.

DEVICES

The term "smart devices" has come to encompass many new technologies that leverage ICT to improve production efficiencies and enable network integration. Smart devices enable users to improve and expand the performance over that of a contemporary device by exchanging information across one or more networks. Improvements could be in convenience, value, or energy efficiency (Schlautmann et al. 2011).

Devices, systems, and facilities are deemed "smart" not because they are sentient—they are not—but because they have the ability to make logical choices about future actions. It is useful to think of a dumb device as having no embedded logic, a smart device as having embedded logic, and an intelligent device as one that is networked and has adaptive and anticipatory capabilities. This hierarchy also inheres in the range of possible outputs stretching from data through information and knowledge to wisdom.

Sensors

Sensors are the first step in getting data. They can tell how fast a motor is spinning, the pressure and rate of water flowing, or the temperature and distribution of heat inside of a furnace. Embedding sensors with connectivity allows devices or objects to sense and react to their environments. Including software logic enables remote control and monitoring and makes it possible to monitor and analyze constant data feeds; the latter has implications for real-time data acquisition and performance monitoring (Valhouli 2010).

Though the ability to measure aspects of a process or raw material has been around for decades, in recent years the large volume of sensors in automobiles and smart phones has driven down the cost of sensors precipitously. Sensors that used to cost $100 now sell for $10; those that used to cost $10 now cost less than a dollar (Jeffrey Perkins, senior director of project development, Energy & Resource Solutions, pers. comm., July 13, 2014). These new sensors may have the ability to transmit and receive information on their own using WiFi and following standard Internet protocols (EON News 2010) or be embedded in manufacturing equipment that is networked to a facility production control system.

Many new sensors are self-configuring and can perform self-diagnosis, be wireless, and interact with the smart grid (Joshua Brugemann, director, energy efficiency, NextEnergy Center, pers. comm., August 16, 2013). As smart sensors collect information at the micro level, smart meters collect information at the subsystem and facility level. In the past, a facility might have a single mechanical meter for each of its utilities (electricity, natural gas, and water). New advanced meters communicate on one-second intervals with control systems and can also send that information to a utility if it is prepared to accept it. When this capability is combined with the proper energy-management software, companies can react to demand-response requests from a utility, monitor and adjust power quality, and take advantage of new energy storage and microgrid control technologies (Stem 2014).

Input/Output Devices

The embedded computing and networking technology built into smart systems and devices enables remote monitoring and communication with other devices. This embedded software logic, or intelligence, allows devices to support process automation and control (Harbor Research 2011). The devices' bidirectional communications capabilities, often referred to as input/output (I/O), enable them to communicate with and respond to the status of other devices within a system (Koelsch 2013).

An example of I/O is the communication between an information processing system, such as a computer, and something or someone outside that system. Inputs are the signals or data received by the system, and outputs are the signals or data sent by it (UEI 2006). The term "I/O" is often used to describe a type of activity (e.g., to perform I/O) that includes an input or output operation. A person can use an I/O device such as a keyboard to communicate with a computer; a computer can also communicate with a person via a device such as a printer or monitor (Wikipedia 2014). In such transactions, the device that is the input device for one is the output device for the other. An example of an I/O for a pumping system is the control interface of the VSD. It can accept commands from an operator, or from another device. Either will instruct the motor to start, speed up, slow down, or stop. The output is the energy use and motor speed information displayed on a screen or communicated to another device. Figure 5 diagrams a simple I/O device.

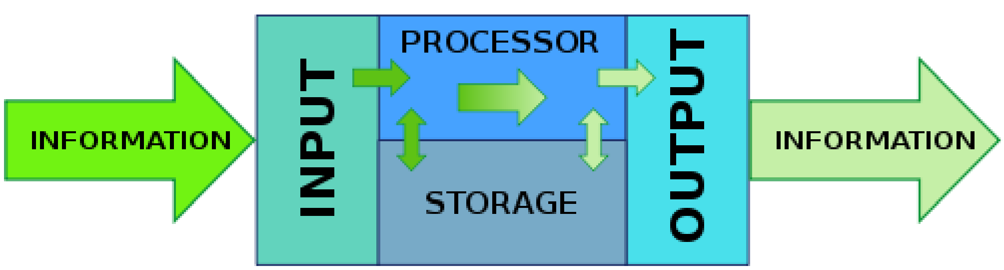

Figure 5. I/O device. *Source:* Wikipedia 2014.

Latest-generation I/O devices contain microprocessors embedded with software that enables them to convert sensed data to digital format and allows them to communicate with higher-level systems (Capehart and Capehart 2007). An I/O device could be a sensor, a controller, or an interface with an operator. These devices are the building blocks of smart manufacturing.

Smart Parts

Manufacturing is trending from mass production, in which one product is made in large volumes, to mass customization, in which each product is tailored by the customer to meet his or her needs. A famous example of mass production is the Ford Model T, America's first mass-produced car. (Fittingly, Henry Ford said of the Model T, "You can have the car in any color you want so long as it is black.") Today, in the era of mass customization, companies such as Dell allow customers to build their computer virtually, order it, and then receive it in a matter of days.

In order for the mass-customization manufacturing facility to be able to successfully make products at the pull of its customers, it must be able to track all parts and assemblies entering and leaving its facilities in real time. Each of these parts has a unique identifier that shows what it is and who it is for. The more common identifier is a radio-frequency identification (RFID) tag that can be scanned and read throughout the facility. These "smart parts" carry operating instructions for the workers and machines as the parts are carried through the manufacturing process (Zhekun, Gadh, and Prabhu 2004).

Tagging of individual parts allows each part to be treated as a unique, tailor-made item. The vital statistics of the individual part design can be stored as information on the RFID tags. This information distinguishes the part from other similar parts in the same production line. At the quality-control step, the compliance of the part is captured and fed back through the system so that any needed adjustments can be made on the fly. Better tracking and adjustments to quality reduce costs and, by extension, energy consumption (Zhekun, Gadh, and Prabhu 2004).

> CASE STUDY: USE OF RFID AT FORD MOTOR COMPANY, BMW, AND VAUXHALL
>
> Ford uses RFID technology in its engine production lines. As the engine starts down the line, the entire work sequence is loaded onto the RFID tag. Each station interrogates the tag to determine what task it should complete. Test results are written directly onto the tag. Both BMW and Vauxhall use RFID tags to accurately customize orders. A read/write smart tag is programmed with a customer's order, and the tag is attached to and travels with the car during the production process. This ensures that the car is manufactured with the correct color, model, interior, and any other options the customer specifies (Zhekun, Gadh, and Prabhu 2004; Sharp 1999; Brewer et al. 1997). The car companies save energy and materials by producing only cars customers want, and they realize greater revenues by providing custom product for which customers are willing to pay a premium.

CONTROL SYSTEMS

The purpose of a control system is to improve productivity in terms of volume, quality, and costs. Through better control of a process, fewer wastes of all types are generated. An example of a simple control system might be a speed or flow regulator. Whether mechanically or electronically, lower and upper set points are established, and when one is reached, a new instruction is initiated to turn something off, turn something on, slow something down, or speed something up. In our example of the water pumping system, to slow down a motor, less power might be delivered. To stop flow to a part of the process, a valve might be closed. To speed things up or start flow, the opposite happens.

If the control is at the device, a mechanical control is sufficient. However efficiencies of worker time and in productivity can be gained through remote and concentrated control of multiple devices. Automation, at its most basic manifestation, is remote control of a device. Simple electrical devices can accomplish this. However, to make multiple adjustments to multiple devices simply, software is required. Such investments bring with them production flexibility, throughput improvements, and greater worker productivity. This is why the industrial sector has embraced facility automation since the dawn of the Computer Age. Figure 6 shows the hierarchy of control technologies.

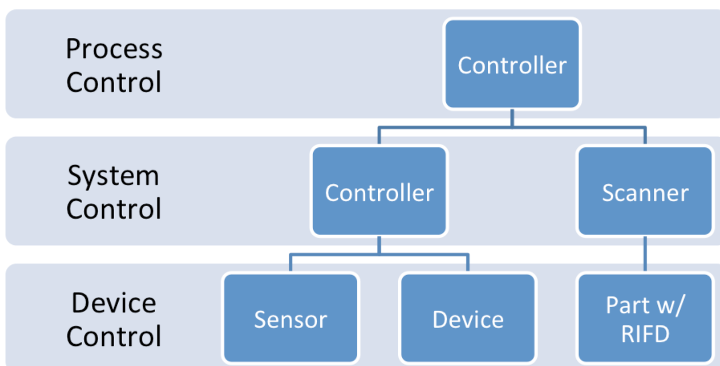

Figure 6: Hierarchy of control technologies

Manufacturing Process Control Systems

Continuous process manufacturing, such as is found in steel mills and chemical plants, commonly involves distributed control systems (DCS), which, as the name implies, have control elements distributed throughout the manufacturing process. Each component subsystem is controlled by one or more controllers. An example is a control loop consisting of a pressure sensor, controller, and control valve. Pressure or flow measurements are sent from the sensor to the controller, likely through an I/O device, and when the measurement reaches a certain point, the controller opens or closes the valve. Establishing set points for each controller allows continuous processes such as steel or chemical manufacturing to be controlled automatically.

Equipment for discrete manufacturing processes, such as automotive component manufacture and assembly, comes with programmable-logic controllers (PLCs) installed. PLCs are essentially simple digital control devices with programs to control machine operation typically stored in battery-backed-up memory. PLCs function in real time, which is to say that the system output result must be produced in response to input conditions within a limited time to prevent unintended results (Wikipedia 2014). Though PLCs have memory, they are not embedded with intelligence and can only communicate current status.

PLCs connect devices and systems in a manufacturing process to supervisory control and data acquisition (SCADA) systems. SCADA systems enable production managers to monitor and control manufacturing processes. A SCADA system's primary function is to transfer and present information to and from various devices throughout a plant while also ensuring the integrity and timeliness of the data (King 2005). Many older systems are being replaced because they are usually standalone, do not support modern, open-communication standards, and may not be able to accommodate today's human–machine interfaces and cloud-based analytical capabilities (Vernak 2014).

More recently, control systems have evolved to include security functionality to prevent and predict faults (King 2005). They also store set points, system outputs, and production history in a data historian module (PAControl 2014). These newer systems can collect data from more nodes, store greater volumes of data, and perform more complex analyses. Controllers with embedded logic can respond in a predictive manner much as a person might if they were constantly at the controls. As a result, they can maintain control closer to set points and realize additional savings in material, time, and energy.

Under normal conditions, the performance of a system controlled by a simple controller will follow a wave pattern between the upper and lower control limits. In the case of an air-conditioning system that supplies cold or hot air to your office, it might blow too much air one minute and then not enough the next—a frustrating situation. To resolve this, proportional, integral, and derivative (PID) controllers were developed. They use mathematical equations to smooth out the waveform. By reducing the wave pattern and compensating for the latency in the control loop, energy can be saved and consistency of the process improved.

COMMUNICATIONS NETWORKS

To realize all of the benefits just described, smart manufacturing will require a new level of communication between devices and operators. This is now possible because of the ability of machines to talk to other machines (M2M) without human intervention. This "Internet of Things" is changing factory automation around the world. With embedded sensors and transmitters in most new pieces of equipment, it is predicted that there will be 50 billion connected devices by 2020 (Ericsson 2011). With the availability of wireless connectivity throughout a plant, location no longer determines access to information and the ability to control processes. Davis and Edgar have this to say about communications networks in manufacturing:

> Smart manufacturing enables all information about the manufacturing process to be available when it is needed, where it is needed, and in the form that is needed across entire manufacturing supply chains, complete product lifecycles, multiple industries, and small, medium, and large enterprises. (Davis and Edgar 2013)

This is the "C" in ICT. A sensor turns a response to ambient conditions into a signal. That signal will fall within a defined range, and that is ultimately what makes it useful: data have become information. If other measurements have been saved, either in the form of a set of data or specific set points, the signal is now comparative; that turns the information into knowledge that enables decision making. In terms of controlling a process, a device or environmental condition or feature of a product is either in range or out of range. It may also be important to understand if a measurement is higher or lower than prior measurements. The trend can also be used as a signal to inform future set points or control decisions—as wisdom—but only if it can be communicated to an operator or system controller.

Bidirectional communications is not a trivial accomplishment. To achieve a bidirectional data transfer capability, both devices must have the ability to accept, store, and transmit data at the same time. Imagine working on a production line and telling the person next to you what you are doing at the same time they are telling you what they are doing. A person needs a buffer of time to receive and understand the message before he or she can act upon it. Computers are similar. They must be able to direct a message to the proper destination and confirm that it has been received and that it has been received in its entirety. These and many more issues have been resolved over the years through the development of common protocols for communication between devices within networks.

Networking Protocols

Bidirectional communication is possible when common software is embedded in the various pieces of hardware in a facility. Devices and systems at a facility may all be connected to each other in a local network, and that network may be connected a corporate network residing in the cloud accessible through the Internet. The first will require Ethernet protocols and the latter, Internet protocols. The networking model and communication protocol used by the Internet and similar computer networks is the Transmission Control Protocol (TCP) and the Internet Protocol (IP), together known as TCP/IP. However this alone will not enable every device to talk to one another. They enable devices (nodes) connected to a network to find but not necessarily understand each one another.

There are many layers of communication within networks, and at each level, multiple languages that might be used. As a result, it is common for devices to package information in different formats. Commonality of software protocols at a basic level does not always translate to the ability to share information at higher levels. A universal translator that can enable communication between all devices is an intuitive but elusive solution. More often, the solutions are customized and incomplete.

Many facilities have chosen to develop software architectures that enable communication between devices across their networks. Often called platforms, they enable control of devices and processes and support other software programs that provide additional functionality.

CASE STUDY: COMAU ADAPTIVE SOLUTIONS

Comau is a manufacturer of assembly lines for heavy manufacturing industries like the automotive sector. Their automated products must not only coordinate the motion of multiple subsystems but also synchronize tasks with other equipment and operators. They have found that Ethernet/IP-networked I/O gives them the robustness they need to have all of the components communicate with one another and the flexibility and simplicity to enable system optimization. For example, automatic tool changing of production robots enables multiple operations in the same workspace, which maximizes both available cycle time and use of floor space (Koelsch 2013).

It is these software infrastructures that contain user interfaces and that determine how easy or hard it will be to wring efficiency gains from the devices connected to the network.

Wireless

Wireless technologies such as ZigBee® or Bluetooth® that allow remote sensors to join a network have transformed the data-gathering ability of ICT and have been fundamental to enabling smart manufacturing. Previously, each device had to be wired and connected to a network. This was a time-consuming process and, in most cases, cost more than the sensor. By contrast, sensing devices with built-in network compatibility can be dropped in place and provide information to the network relatively quickly. The sensors can be powered through connection to the device or have vibration energy or light-harvesting power supplies.

With the drop in microchip prices, the adoption of common protocols, and new low-energy WiFi technologies, just about any device can be connected directly to a facility's network or through direct connection to the Internet (Harvey Michaels, director and lecturer, MIT, pers. comm., February 14, 2014). Texas Instruments recently introduced a product it refers to as "Internet on a Stick" that enables connectivity to the Internet for only $20 per chip (Richardson 2014; Mary Burgoon, market development manager, Rockwell Automation, pers. comm., July 13, 2014).

It will even be possible for every device or computer chip in a facility to be connected. Research is ongoing at MIT in which each light-emitting diode (LED) of a lighting system has its own network address and the ability to adjust to ambient light so it can constantly illuminate a work area (Harvey Michaels, pers. comm., February 14, 2014). This laboratory experiment shows the potential for networked devices to work collectively toward such larger goals as energy efficiency.

SOFTWARE

As previously mentioned, many devices have software embedded in them so that they can communicate with other devices and participate in a network. This firmware is not accessible by the end user but instead exists to enable basic functionality. A familiar example is the software in a TV that allows it to recognize and interpret a cable signal. There are additional levels of software, each residing at one or more levels of hardware and providing additional functionality for a device, system, or process. Network software can reside in a company's on-site computers, in off-site computers, or in the Internet cloud. The most elaborate software systems enable management of facilities, organizations, and collaboration between organizations.

Before the Computer Age, most manufacturing processes operated in isolation, both in terms of connection to other processes and from past performance. A water tank pump is not able to react to past performance. It cannot predict when it will fill the tank to full. And it really does not need to know. It is a dumb device that is turned on when needed and off when not.

But what if the tank did not need to be full? What if it only needed to function as a buffer for the next process? In such a situation, the tank would be sized for the maximum amount of water that the next process might possibly require. But most of the time, it does not need that much water. In fact, it needs much less. So let's say that under normal circumstance the process will function fine if the tank is only half full. We can set up a control logic using simple sensors and actuators that responds to the rule "If process normal, fill tank to half; if process not normal, fill tank to full." This simple change will save the energy required to fill the tank to full versus half full when the system is operating in normal conditions.

Of course most processes have multiple operating conditions. A control system that uses 1950s-era sensors and actuators might be sufficient for two or even a dozen operating conditions but would be inadequate for the requirements of modern mass customization manufacturing with potentially infinite operating conditions.

The intermediate step is to have a more robust logic program that includes a series of if–then statements directing the operation of the system to stable operating patterns. But ideally, we want to be able to predict what the water pumping process is likely to do five, ten, sixty minutes from now. We may even want to know what the overall production process is likely to do one, two, twenty-four hours from now.

To do that, we need the ability to look back in time and review the operating conditions for multiple production profiles and then determine what might be the optimal set points for the current situation. This is now possible with the ability to store large quantities of data in context in "data historians" for later use by powerful data analysis (King 2005). Once available only to large corporations with extensive IT departments, data and analytics can now be hosted remotely and purchased as a service. It is the robustness of the data collection, storage, and comparative analytics and their ability to generate additional energy savings that make advanced control systems superior to conventional automated control systems.

CASE STUDY: HUNTSMAN PETROCHEMICAL'S USE OF PROCESS CONTROL AND DATA HISTORIAN

Huntsman Petrochemical replaced an older process control system at one of its ethylene manufacturing facilities in Europe. The plant is one of the largest of its type in Europe, with 17 cracking furnaces. It exports intermediate products to other locations and feeds a number of downstream users. A high-fidelity process historian was added to the existing process control system, which allowed Huntsman to compare current and past conditions. This capability yielded increased production and plant reliability, and it reduced out-of-specification production and energy consumption, allowing Huntsman to make additional capital investment in a new DCS. With the addition of the new control system, the plant was able to produce the maximum amount of ethylene and propylene, reduce production disruptions and upsets, decrease furnace energy consumption, and reduce flaring by 75% (Singh et al 2007).

CASE STUDY: GOOGLE'S USE OF NEURAL NETWORKS TO OPTIMIZE ENERGY USE IN DATA CENTERS

Neural networks are essentially computer algorithms that detect patterns and make decisions based on those patterns. By crunching the data over and over again, the computer can develop a predictive model of future behavior under various conditions. The Google system gathers information on electricity usage, water consumption, and outside air temperature so that it can model the operation of its data centers. The model was refined until its predictions were almost completely accurate (99.6%). Knowing the model was reliable, the company could then use it to identify problems and recommend ways of improving efficiency inside its data centers. (Metz 2014).

PLATFORMS

For a network to function, it needs a software platform to manage the exchange and processing of information and interface with operators. Software's first step is to turn data from a sensor or meter into information. The next step is to turn that information into knowledge. The last step is to turn the knowledge into wisdom that enables the cost-efficient management of the organization.

A simple example of a platform is the software that enables a cell phone to send and receive phone calls. A smart platform, like a smart phone, enables other software programs (applications) to make phone calls, texts, video, and many other types of transactions. Most smart phones come with built-in applications and the ability to add more to meet a user's needs. Smart manufacturing platforms will come with built-in applications, such as data translators and workflow modeling tools, and have the ability to support other applications to meet facility and enterprise needs. A platform may be vendor-specific, requiring all applications to come from a single vendor, or it may use open standard, in which case multiple vendors can provide applications so long as they are compatible with established standards. Some platform products are commercial off-the-shelf (COTS), while others are purpose-built to fulfill a customer's specific process-control needs.

Smart manufacturing platforms must be robust enough to support multiple data flows. M2M presents a new "big data" challenge: integrating data flows from millions of new nodes into existing enterprise IT systems (Watson 2012). Powerful data analytics are addressing this issue and making it possible to add even more sensors and devices to existing networks.

CASE STUDY: VALERO ENERGY CORPORATION

Valero used computer modeling to determine the most efficient loading of individual pieces of equipment and to optimize energy usage at one of its refineries.

> The model took into consideration the purchase price and the supply and use of fuel, steam, and power at the facility. It ran simulations based on process unit energy demands and system constraints caused by equipment or environmental regulations. With this information it determined the optimal operating conditions. (OEERE 2005)

A smart manufacturing platform will provide a foundation for unified communications, network enablement tools, system virtualization (modeling and simulation) technologies, and the software infrastructure for interactive applications. The benefit will be improved production control and simpler worker experience and interaction (Harbor Research 2011). Figure 7 illustrates the role of software in a smart manufacturing platform.

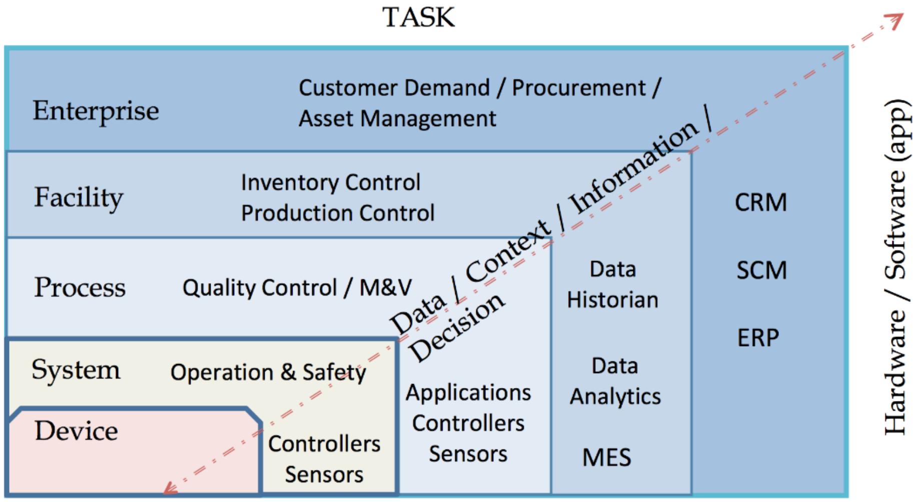

Figure 7: Software purposes and locations within an organization

SYSTEMS APPS

An application is a software program or collection of programs that provides functionality to a device, system, or operator. Applications, or "apps," have become very common features of smartphones. The same structure applies to smart manufacturing platforms.

A systems application is a software program or embedded coding that enables some functionality in a device or larger system. Many applications function in the background and are not seen by the end user. For example, a networked device will have an embedded application that can be monitored via a display app to determine its status, energy usage, performance, and need for replenishment of consumables. The end user sees the results on a display app but not the machinations of the network-enabling communications app.

Applications are often referred to as either horizontal or vertical. Horizontal applications provide functionality across a system and fall into the following categories:

- Status, monitoring, and diagnostics
- Upgrades and configuration management
- Control and automation

- Location and tracking
- Data management and analysis (Harbor Research 2011)

An example of a horizontal application that has the potential to save energy is a "no-touch" audit app for a building automation system. Such an app would collect weather, location, production, and 15-minute interval utility data as well as look for abnormalities in real time and against historical data (Davis 2014). Energy is saved through the identification of opportunities not normally uncovered during a conventional audit and by catching errors earlier than possible with routine physical inspection.

Vertical applications are solutions that integrate people with business processes and assets and are delivered as managed services. Vertical applications services include the following:

- Asset management and optimization
- Supply-chain integration and business-process management
- Customer support
- Energy management
- Security management (Harbor Research 2011)

An example of a vertical app that saves energy is one that provides closed-loop control of a production process and thereby optimizes energy use.

Figure 8 shows the relationships and interconnection of vertical and horizontal applications.

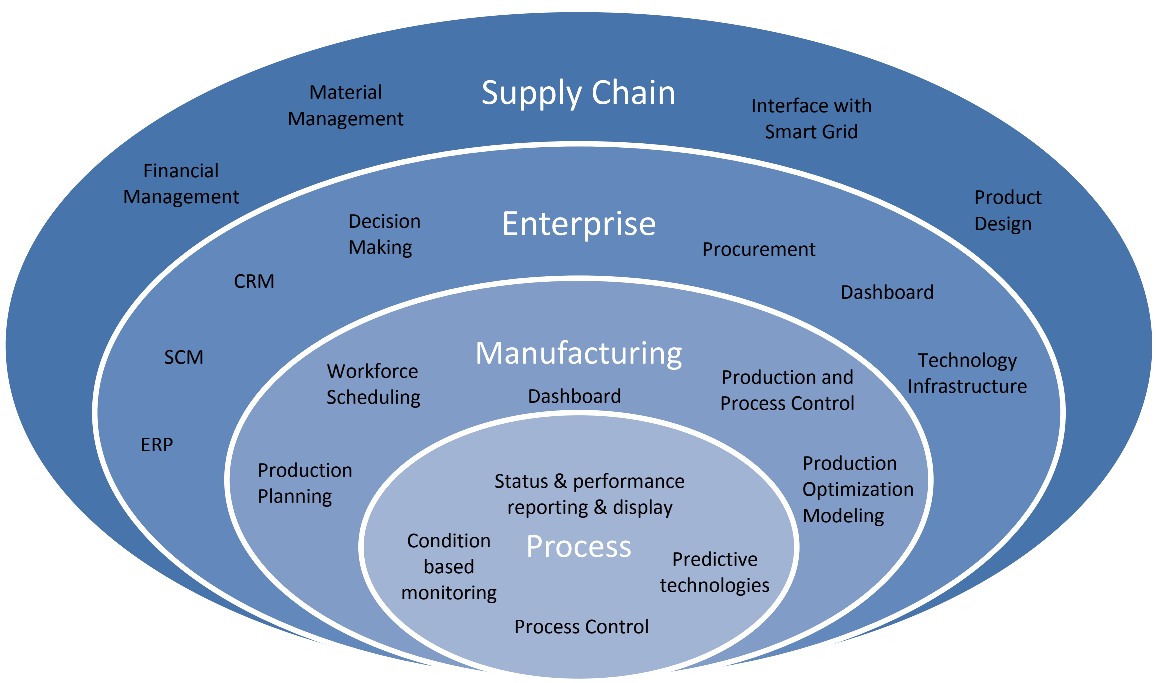

Figure 8. Relationships and interconnection of horizontal and vertical software programs and applications. *Source:* **Derived from Koc and Lee 2002.**

The existence of an open-access platform will take many costs out of application development and deployment. Access to all of a customer's data, which previously has been unavailable without customization, allows developers to create applications that can be used by multiple clients. Open-access development has proven itself as a powerful mode of innovation and development (Harbor Research 2011). Companies develop virtual storefronts that are similar to the Apple App Store or Google Gadgets (Harbor Research 2011). Unlike the system applications, these user applications will be visible to the end user and in fact may be icons on a smartphone or tablet through which they have remote contact regardless of location.

With routine tasks satisfied by the availability of multiple off-the-shelf apps, solution providers will be able to combine applications to develop custom solutions. This has the potential to change the sales dynamic from one of order taking for one-size-fits-all products to one of solving specific customer problems. Taking this one step further, the software app is no longer seen as a defined product but as the basis of a service that helps customers reduce costs. Such software as a service (SaaS) is an emerging business opportunity for telecom and IT companies. With that purpose in mind, many telecom firms are experimenting with new business models, moving away from selling airtime, for example, and instead providing managed services, from transaction platforms to back-end data analytics (Watson 2012).

MANAGEMENT SYSTEMS

ERP systems have become the business-operating backbone of many corporations. However resource planning and manufacturing execution systems (MES) are often hindered by a lack of integration with control systems on the factory floor (Koc and Lee 2002). Without the information coming from and flowing to the plant floor, important details, such as maintenance schedules, unpredicted downtime, and variability and reliability of raw materials, are not factored into the information these systems provide high-level decision makers.

Currently, for most facilities, production information flows between production and management, and ERP systems share information between business operations and supply chain. What they cannot do is have production information influence interactions with the supply chain and have supply-chain information influence production decision making (Koc and Lee 2002). The ultimate goal of smart manufacturing is to handle information only once, enabling the optimization of assets, synchronization of enterprise assets with supply-chain resources, and automation of business processes in response to customer demands (Koc et al. 2005).

As the name implies, an ERP is an enterprise-level resource and asset-management system. The more it can reach down into the day-to-day operations and collect data, the more informed decisions management can make. This extends beyond collecting production and energy information. Though beyond the scope of this report, the ultimate goal is the integration of all methods of monitoring, reporting, and managing organizational tasks: environmental monitoring and compliance systems, customer relationship software systems, purchasing, financial, payroll, and even worker training. Where energy use is influenced by these control practices, time-value information from energy suppliers via the smart grid can be used to minimize costs and improve profitability. Figure 9 shows the interrelated functions of a smart manufacturing ERP.

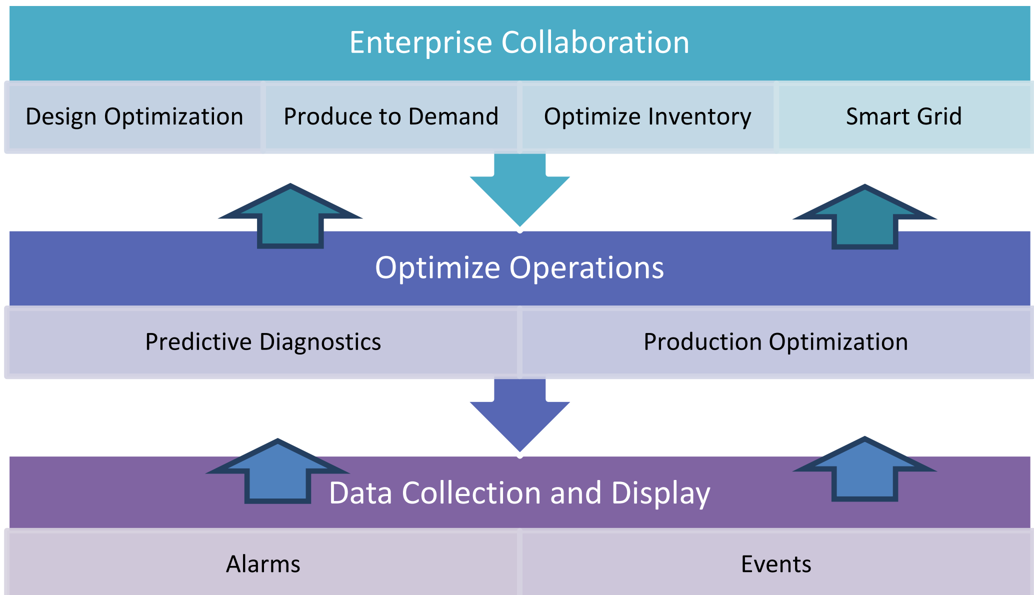

Figure 9. Software roles and relationships. *Source:* Sujeet Chand, Rockwell Automation (Chand 2011).

There are management systems for functions at all levels of an organization. Some of them involve software, such as an ERP, while others may not, such as an ISO 50001 system for energy management. A smart manufacturing platform can collect and integrate the information from both and simplify organizational management. This is often done through interfaces that provide information as knowledge and that enable wisdom.

User Interfaces

Most manufacturers have collected data from machines on their factory floor for many years and have linked the equipment together for greater efficiency with a process control system. This is the current baseline for manufacturing (Warren 2011).

More advanced companies are investing in new data analytical capabilities that can be stored remotely and have user interfaces that convert the data into actionable information that enables real-time problem solving (Selko 2013). They provide the right information at the right time to users in a context that is clear and simple to understand. They translate information into knowledge that facilitates wise decision making.

This is significantly different than automation that operates without human intervention. There are points in all complex manufacturing processes at which decisions must be made by people because the data needed or the logic required are not available within the existing automation system, or because it would not be appropriate for a machine to make the decision. It is at these intersections that the inorganic communicates to the organic, i.e., machine to human.

In response to the need for these interactions, a whole industry has developed around creating dashboards, i.e., interfaces that present system performance in a meaningful and actionable way to operators. Since many people are visual learners, comparative charts and graphs and simple color scales are the modes of choice to communicate system performance. Many of these products leverage smartphones, tablets, and social media applications (Herbert 2014). They commonly are used at three levels: machine control, operation, and enterprise. For example, a service technician could have the ability to securely and remotely chat with a device to check status and run diagnostic routines. The technician could post notes for other technicians, customers, or managers on the device's Facebook-style wall (Harbor Research 2011). At a higher level, these interfaces can put customer demand, production, and supplier data in context at a rate that is faster and more accessible, enabling companies to make quicker decisions and improve efficiency (Selko 2013).

Some dashboards are created specifically to manage energy, or there may be a page or graphic on a page that reports energy use and trends (Tyler Reitmeir, Sotecia, pers. comm., November 21, 2013). At an advanced level, a dashboard is an energy visualization system that correlates energy and process data to provide operators with energy measurements in the context of production outputs or inputs that resemble other production metrics such as kWh per widget or Btu per million gallons. This contextual energy is then tracked, trended, and analyzed to support continuous improvement initiatives (Dussault 2013).

CASE STUDY: FARIBAULT FOODS

Faribault, a Minnesota-based food processing company, installed a new heat and energy recovery system along with new automation controls and monitors. The new system collects and presents water, air, gas, electric, and steam (WAGES) consumption information through dashboards. The production process also has integrated intelligent motor controls that provide access to motor performance and health information. The investment resulted in a reduction of natural gas consumption by more than 38%, CO_2 emissions by over 3,000 metric tons annually, and more than 100 million gallons of water each year. At the same time, throughput increased 90%, and production waste was reduced because of the improved process control (Rockwell 2011).

INTELLIGENT MAINTENANCE

Predictive maintenance of production equipment can significantly reduce variable and non-variable costs of production through smart manufacturing. Condition-based monitoring and data analytics can eliminate potential downtime. They use a networked monitoring system to compare a product's performance against historical data of the device in question and against others within the company or the vendor's purview. The system identifies degradation and prognosticates the need for maintenance instead of waiting for fault detection (Koc and Lee 2002).

CASE STUDY: TOYOTA

Toyota's Kentucky and Alabama facilities use Rockwell Automation software to improve their maintenance troubleshooting capabilities. As a result of information

> provided by the software applications, real-time error corrections are possible resulting in reduced rework and scrap. Use at the Alabama facility has resulted in annual cost savings of $550,000. (Selko 2013)

By knowing the condition of machines in the manufacturing process, the production manager or engineer can estimate impacts on material flows and production volumes and synchronize with the ERP system. The revised inventory needs and materials delivery can also be synchronized with other business tools such as customer relationship management (CRM), allowing the company to advise customers of any changes to delivery schedules.

Making only the inventory that is demanded by customers saves energy. Energy is also saved by ordering only as much raw material or components as needed, running equipment only as much as needed, and maintaining equipment so that it operates in optimal condition.

SMART DESIGN

Compared to the energy used in production processes, the energy used in designing a product is not as significant. However, as the saying goes, "time is money." Time is also energy use. The longer the design process, the more energy consumed by the design staff and their facilities. Products designed digitally through computer-aided design need not be physically modeled through expensive and energy-intensive custom manufacturing; instead, they can be virtually rendered, tested, and used. This accelerates time to market and reduces the likelihood of making a product that will not perform well.

> #### CASE STUDY: NISSAN'S USE OF SMART DESIGN
>
> Nissan uses product life cycle management software in its three U.S. production plants as part of its Value Up for Product Process and Program Innovation initiative to improve product development performance. By embracing this design practice, it has been able to reduce its development cycle from 20 months to 10.5 months, decreasing design changes by 60–90%, and it is now experiencing 80% fewer problems after vehicle release. (IndustryWeek 2013).

Designing a product also includes developing the process by which the product will be manufactured. Much like a building, there is a greater opportunity to reduce future energy consumption when a production line is still only a concept on a piece of paper than there ever will be again. A common rule of thumb is that 75% of the costs of manufacturing are determined during product design (Warren 2011).

Smart design involves the concept of design for the environment mentioned earlier. It is the process of thinking through future energy use and production byproducts and developing product designs and production processes that minimize both. It may also take into consideration wastes that customers will generate using the product and the ability of the product to be recycled at end-of-life. Design informed by production process realities and sustainability performance metrics such as embedded energy have the potential to reduce overall costs and improve profitability.

The challenge is integrating all the variables and associated information. New IT capabilities now make computer simulation of production processes possible. Design processes can integrate feedback from actual production operations so that material flow can be optimized during ramp-up of production (Siemens 2014). By using these technologies, companies are achieving shorter time-to-market, faster production cycles, and greater production-floor flexibility (IndustryWeek 2013).

Energy Savings

It is clear that improved use of energy as a result of intelligent efficiency will have significant economic benefits. Our own research indicates that the manufacturing sector could realize savings of $15 billion (figure 10) in annual electricity costs savings by 2035 with aggressive investments in smart manufacturing technologies (Rogers et al. 2013). Collectively, experts in the field of manufacturing automation anticipate that, on average, companies will realize a 20% reduction in energy intensity (Rogers et al. 2013).

Prior ACEEE analysis estimated that increased investments in smart manufacturing could reduce energy cost expenditures by the U.S. manufacturing sector by $7-25 billion per year by 2035. Figure 10 shows the potential range in the form of three scenarios. The middle scenario assumes an increase in investments of 1% per year over current trends and increasing over 20 years to 3%. It also assumes that these investments pay for themselves within two years. The high scenario assumes twice as much investment and the low scenario half as much investment.

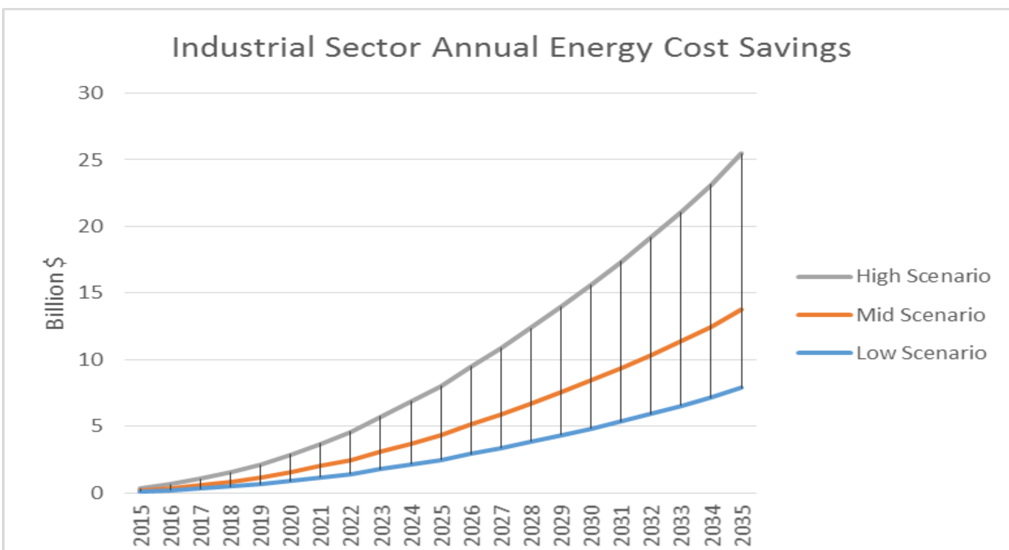

Figure 10: Estimated industrial-sector energy cost savings. *Source:* Rogers et al. 2013.

These savings will have a direct impact on the bottom line of participating companies and the competitiveness of individual facilities. Furthermore, such investments introduce a new level of flexibility and responsiveness to manufacturing processes that will help companies make additional investments in productivity and efficiency.

Smart manufacturing brings about savings at all levels of a process and an organization. It has the potential to make each piece of something and every collection of pieces more efficiently. The leading motivation to invest in automation is to improve productivity. Most energy savings are ancillary benefits to other higher-priority performance metrics for manufacturers. If one measures productivity as the ratio of throughput to the value of capital equipment and operating costs, then improvements in productivity can come from greater output, lower value of equipment, or lower operating costs. Since energy is a variable cost of production, it is important to companies as a component of this larger metric. When an investment improves the productivity of a process, workforce, facility, or company, it also tends to save energy.

Smart manufacturing has the potential to bring about a step change in manufacturing efficiency and ability to fulfill customer demand. In the process, it will reduce the energy intensity of manufactured products. At the most basic level, energy intensity is the amount of energy used by a facility divided by production volume. It is an average amount of energy used per unit of production and an important metric to keep in mind when discussing industrial energy efficiency, because most facilities increase in size and capacity over time. Productivity improves, consolidation happens, and new product lines are added. Therefore, the amount of energy consumed by a facility may go up even as its overall efficiency improves. Energy intensity, also referred to in the inverse as energy productivity (the amount of product for a given amount of energy), is a better method of gauging the use of energy at a facility.

Many investments in smart manufacturing will directly yield significant energy savings, while others will produce only marginal and inconsistent savings. It is the collective impact that is noteworthy. In aggregate, they will have a profound effect on consumption; it is this potential that will be important to organizational management and may be of interest to local energy efficiency resource acquisition programs. Regardless of a facility's size or energy intensity, pursuit of these potential savings will be a necessity. To be competitive in the 21st century, manufacturers must manage all of their costs.

The section above called "What Is Smart Manufacturing?" introduced a hierarchy of technologies with increasing levels of complexity. It is important to note that the higher levels do not automatically translate into greater energy savings. For example, a reactive control for warehouse lighting will save as much or even more energy than a programmable system. Nevertheless, in a cost-benefit analysis, these levels are useful for determining the portion of overall energy savings attributable to the intelligent or smart aspect of a system. For example, they can help determine incremental savings due to an enabling technology such as a VSD, as well as the additional savings that are possible when that drive is networked with an intelligent plant production management system.

Here is a simple breakdown of where energy efficiency gains are possible in a smart manufacturing system:

(Efficient device) − (Inefficient device) = Savings
(Device operating only as needed to meet demands) − (Device operating in on/off mode) = Savings
(Process operating only as needed to meet production target) − (Process operating in on/off mode) = Savings
(Past performance instructing current performance) − (Best guess at optimal settings) = Savings
(Smart design) − (Conventional design process) = Savings
(Connected systems and business units) − (Conventional isolated systems and business units) = Savings

Energy is usually a variable cost of production, and as such, it should be measured, monitored, and managed. Fortunately, the technologies that comprise smart manufacturing make these tasks easier. The same data collection abilities that enable system optimization also can be used to report performance in real time to management and other stakeholders such as a utility energy efficiency program administrator.

LEVERAGING ENERGY PERFORMANCE DATA

Utility-sector efficiency programs have traditionally focused on assets that can be purchased. With the improved data-collection and -analysis capabilities of smart manufacturing, these programs could transition to performance-focused incentives. Enabled by the smart grid and customers' investments in smart manufacturing, the needs of utilities to control short-term power purchase expenses and long-term resource acquisition costs could be assisted by customer energy savings. Utilities could encourage short-term demand response through time-of-use energy prices and encourage long-term investments that reduce future demand with project cost share and rebates.

In such scenarios, efficiency programs might finance in-part investments in intelligent efficiency as part of an energy supply agreement that gives them in exchange the ability to better manage and confirm the acquisition of efficiency resources. It is also likely to enable them to do so more cost effectively and with higher confidence in the savings.

For the manufacturer, the supply of energy becomes integrated into the supply chain just as any raw material. There will be multiple purchase options that can be selected based on short-term and long-term priorities. Through these market mechanisms, additional efficiencies will be gained in the local utility grid likely yielding even more energy savings. Though beyond the scope of this report, those savings will bring down costs and amplify the benefits already realized by companies investing in smart manufacturing.

CASE STUDY: EFFICIENCY VERMONT ENSAVE COMPRESSED-AIR LEAK ABATEMENT PROGRAM

Efficiency Vermont, the statewide efficiency utility, is piloting a program that ties financial incentives to measured energy savings, a true pay-for-performance demonstration. Working with a compressed-air vendor, program administrator VEIC establishes an energy-use baseline for a facility's air compressors and then uses real-time meter data to capture post-upgrade energy savings (Ethan Goldman, energy infomatics architect, Vermont Energy Investment Corporation, pers. comm., June 11, 2014). The information, currently handled in batch fashion by the vendor, may eventually be transmitted by WiFi or cellular service for remote analysis (VEIC 2013). This concept of paying for net energy savings could be applied to more complex investments such as building and process automation.

Challenges and Responses

The benefits of smart manufacturing are not guaranteed. While the marketplace is certainly motivated to see these technologies grow, there are barriers to market penetration and customer acceptance. The greatest barrier is the lack of interoperability at all levels of manufacturing. There is also the need to balance the management of intellectual property, business performance, and network security. The size and price of sensors are coming down, but they need to operate at lower power, ideally with independent power sources. Finally, smart manufacturing requires a workforce with the proper skills and knowledge and a new culture of worker empowerment and sustainability.

COMMON STANDARDS AND PROTOCOLS

The most significant of these barriers in the near term is the lack of common standards: standards for storing information, communicating information, and even the display of information. Much of the existing market has evolved around proprietary solutions. In order for these technologies to gain widespread use, hardware and software developers will have to agree on technology standards, develop open protocols, and establish network technologies that end users can be confident will last into the foreseeable future.

The incompatibility of network communication protocols, software programs, and management systems imposes a significant cost on the manufacturing sector. It is a basic inefficiency that wastes a great deal of time and effort by manufacturers and the vendors who serve them.

A likely solution for local networks is Ethernet Industrial Protocol (EtherNet/IP). This is a communications protocol managed by the Open DeviceNet Vendors Association (ODVA) and designed for use in process control and other industrial automation applications. It is an industrial application-layer protocol through which control systems communicate with their components such as PLCs or I/O systems.

Another relevant development enabling the Internet of Things is the ICT sector's growing adoption of Internet Protocol version 6 (IPv6), which is an update to the Internet protocol that allows the use of a 128-bit address in the message header. (IPv4 only allocates space for a 32-bit address.) IPv6 addresses the challenge of address exhaustion and also enables somewhat better security. In addition to providing a virtually infinite number of unique addresses, IPv6 will make it easier to manage networks because of its auto-configuration capabilities and improved security features (Evans 2011). However it will only address lower-level M2M communications. It will not address higher-level M2M communications nor wireless incompatibility issues (Ethan Goldman, VEIC, pers. comm., July 14, 2014).

In order for the pervasive Internet to take hold, we need a universal alternative to the many current techniques for connecting ordinary devices to the Internet. Many types of wireless networks are closed or semi-closed proprietary systems. This results in non-interoperable products and a less-than-ideal situation for users (Harbor Research 2011).

Since device connectivity rarely requires optimal performance, compatibility is a much more important objective. The European Telecommunications Standards Institute (ETSI) has partnered with several other standards agencies to create a global M2M standard (ETSI 2010). Assuming this becomes the international standard, domestic organizations and agencies should align their work to support it.

In a related effort, several IT and communications companies came together earlier this year to form the Industrial Internet Consortium (IIC). This group aims to influence the development of standards for Internet and industrial systems and to develop test beds for real-world applications of emerging technologies (Industrial Internet Consortium 2014).

Even machine–human interfaces will benefit from standardization. The same benefits that accrue to the use of a common keyboard, or icons on electronic devices, or even street signs, will accrue to the manufacturing sector through the standardization of icons and task definitions. The Lawrence Berkeley National Laboratory (LBNL) is working on the former, and the Smart Manufacturing Leadership Coalition (SMLC) is working on the latter (Bruce Nordman, research scientist, LBNL, pers. comm., February 4, 2014; Davis and Edgar 2013).

The Institute of Electrical and Electronics Engineers (IEEE) is also working on standards for the security and privacy of data as they are communicated through various architectures (Evans 2011), and the National Institute of Standards and Technology (NIST) is working with other agencies and the private sector to develop cybersecurity metrics and protocols (NIST 2014).

LOW-POWER SENSORS

In order for the Internet of Things to reach its full potential, sensors will need to become self-sustaining (Evans 2011). The wiring of sensors can be difficult and expensive, and this limits where they can be placed. As the price of sensors falls and they can manage more and more data, the remaining issue is how to give them the ability to generate their own power so that they do not have to be hard wired. Technologies currently available and under development include powering sensors through photovoltaics or through the motion or vibration of nearby equipment.

TRAINED WORKERS

Neither companies nor society will be able to fully realize the benefits of smart manufacturing without an adequately trained workforce. A manufacturing workforce with advanced training and skills is the key to the nation's competitive advantage (Davis et al. 2009). A survey of 388 manufacturing executives found that 41% of respondents identified attracting and retaining skilled workers as a top concern, 28% are concerned about knowledge transfer as employees leave, and almost 30% have expanded recruitment and training programs for skilled workers in the past 24 months (Industry Week 2013). In an effort to address these concerns, Rockwell Automation facilitates worker training through its FIRST program (For Inspiration and Recognition of Science and Technology), a nonprofit that aims to inspire interest and participation in scientific and technological pursuits. CEO Keith Nosbush says, "How we create this skilled manufacturing workforce is one of the most pressing questions this country faces" (Caminiti 2011).

SHARED INFRASTRUCTURE

It is clear that without a modern, shared industrial software infrastructure, industry's adoption of smart manufacturing will be limited. Process control and automation systems implemented in piecemeal fashion will continue to limit innovation and capability. Entrenched software platform providers in the process automation and control sector use proprietary data formats and communication protocols that essentially lock customers into their servers and controls software. These proprietary formats limit the ability of manufacturers to purchase from other vendors. They also limit the ability of companies to network facilities with different systems for better control. A new set of business models and interoperable technology infrastructures is needed if smart manufacturing is to reach its full potential (SMLC 2014).

The challenge is that no single entity has the capacity or the influence to develop a comprehensive smart manufacturing software platform. Fortunately, as described later in this report, several organizations have come together to address this issue and have formed the SMLC. They are working to develop approaches, standards, and shared infrastructure that will facilitate the broad adoption of manufacturing intelligence (SMLC 2014).

In a parallel and complementary effort, the Digital Manufacturing Design Innovation Institute (DMDI) is engaging manufacturers and technology companies in precompetitive collaboration focused on what it refers to as the "digital thread" that ties together all aspects of product design, development, manufacture, and distribution (DMDI 2014). This initiative focuses on developing a common method of using ICT to incorporate smart design and DfE throughout a product's lifecycle.

SECURITY

Manufacturing companies often have separate business and production systems. The first system takes care of accounting and perhaps payroll, and the second manages the machinery in the plant. Traditionally there is a firewall between hardware and software systems with access to the Internet and those that control production. Safety and proprietary considerations have driven this separation. Access to production equipment through the Internet has serious security and safety ramifications, as illicit access to production systems could damage property and compromise worker safety. A recent survey of 1,300 German businesses and universities found that IT security could delay the adoption of smart manufacturing. Of those surveyed, 66% indicated that security concerns were a sufficient reason to put off investing in next-generation production facilities (Roberts 2013).

The vulnerabilities of sensors, wireless communications, networks, and control systems are also making manufacturers hesitant to adopt common security technologies. In response to this market barrier, the U.S. Department of Commerce, NIST has launched a smart manufacturing cybersecurity research initiative. It aims to develop a risk management framework with supporting guidelines, methods, metrics, and tools to enable manufacturers, technology providers, and solution providers to assess and assure cybersecurity for smart manufacturing systems (NIST 2014). Successful development of this framework and methodology will stimulate the adoption and use of (a) new security technologies and (b) smart manufacturing systems that offer the security, reliability, resiliency, and protection against disruption that manufacturers want (NIST 2014).

COSTS AND PROFITABILITY

Realizing the benefits of smart manufacturing can be a challenge because many of its components are still prohibitively expensive. Moreover, to get that last fraction of savings, you often have to purchase all of the equipment and software. For example, although local area networks (LANs) are required for most automation and smart manufacturing capabilities, the majority of companies do not have them because they are so expensive.

Prices also need to come down for process management systems to become more common, especially if they require integrating multiple vendors' proprietary systems. The sector can reduce costs by developing services and tools to facilitate application development and by integrating across networks and access technologies to support seamless device connectivity (Ericsson 2011). New business models that avoid cross-subsidization can help align benefits with the costs identified on an invoice.

FUTURE-PROOFING

Some ICT and manufacturing professionals are concerned that there are not enough standards in place to future-proof investments and that the development of and investment in new smart manufacturing products should wait until such standards are set. Other organizations such as SMLC anticipate that current industry best practices will become the basis of future standards and that it is prudent to move forward now. The more hardware manufacturers and software developers that contribute to this and other collaborative efforts, the better for the sector and the clients it serves. In any case, adaptation will be required eventually as standards are almost always updated over time.

Many end users are concerned with future-proofing their existing investments as well. If a device is going to be in use for 10 to 15 years, then its technology should not become obsolete and unusable in this timeframe. A manufacturer might invest in a second-generation (2G) network-compatible device with the expectation that will last for up to 20 years only to realize 10 years in that the sector is moving to 3G or 4G (Watson 2012). In fact, the ICT market is anticipating that 3G will play a larger role in M2M and the Internet of Things, and as a result, some network operators are shifting a majority of their data applications to 3G so they can transmit more data from a given device (Harbor Research 2011). At the same time, 4G has become the basis of most cellular telephone services because it offers greater bandwidth and, with that, greater communication capabilities. Without forward and backward compatibility, 2G and 3G products may soon become obsolete.

Future-proofing starts with the ability of devices to communicate with each other and increases with the ability of management systems to operate across business units. When building a new baby food plant in Biessenhofen, Germany, Nestlé, an international food conglomerate, decided to fully integrate its automation system based on EtherNet/IP with the anticipation that it would future-proof the company's network designs (Bassett 2013).

At the device level, embedded firmware can be updated remotely and automatically as part of the technical-support component of the equipment purchase contract. At some point, though, the hardware will no longer be able to support the evolving software upgrades. Much like a personal computer, its limited ability to receive and send information will render it functionally, if not technically, incompatible with the rest of the network. One possible solution is development of a common interconnection or a standard plug for swapping out ICT hardware. Another is to move as much of the computation capability as possible to the cloud where it can more easily be updated and then to simplify the devices so they will have a longer useful life.

At the plant production control level, the development and adoption of connectivity standards are not enough to future-proof a SCADA system. As a system grows larger and more complex, its management and administration become very important to the company. To satisfy future needs, vendors will have to collaborate on protocols that enable their customers to manage the expansion and maintenance of their systems (King 2005).

Bringing It All Together: A Smart Manufacturing Platform

Over ten years ago, manufacturers identified a key barrier to the growth of smart manufacturing, namely, the lack of an open-access platform that provides core tools and capability for applying advanced data analysis, modeling, and simulation in core manufacturing processes (Denise Swink, chairman of the board, SMLC, pers. comm., November 19, 2013). Many large international corporations with multiple plants across multiple divisions had become frustrated at the cost of implementing one-off solutions to connect existing systems that did not integrate with each other. They also wanted to drive down the risk and cost of IT infrastructure. They saw that the growing technology gap was affecting the entire manufacturing sector, including the critical base of small and medium companies who were key suppliers and markets.

To address these issues, several organizations came together to form the Smart Manufacturing Leadership Coalition (SMLC). Their aim was to build a precompetitive infrastructure including network and information technology, interoperability, and shared business data methodologies. The discussion of SMLC that follows in this section is based on Davis and Edgar (2013) and Denise Swink, pers. comm., November 19, 2013.

The goal of the coalition is an open architecture, network infrastructure, and platform that will enable existing systems, which are often constrained in the scope of what they can do, to do more, and to do it better. It depends on the Internet but focuses on providing access to core tools, managing the infrastructure to make data actionable, and extending existing capabilities at a given plant by addressing manufacturing business objectives directly. The Smart Manufacturing (SM) Platform is a cloud-services specification that will be operated as a shared resource and be available for private or hybrid use on a company's intranet. The SM Platform is not intended to replace legacy systems but to give them a way to interoperate so they extend or gain new capabilities. A key component of the platform is a "marketplace" in which commercial and community-source data collection, analytic, modeling, and interface applications can be selected, assembled, and deployed as operational systems. SMLC is laying the groundwork for an entirely new business sector by establishing an industry-shared, community-sourced platform that also provides a clearinghouse for associated apps.

More particular SMLC goals include:

- Industrial community modeling and simulation platforms for smart manufacturing
- Affordable industrial data collection and management systems
- Enterprise-wide integration of business systems, manufacturing plants, and suppliers
- Education and training in smart manufacturing

SMLC aims to demonstrate the means to dramatically change the cost of production and time to market for new products. Table 2 shows these and other benefits.

Table 2. Anticipated benefits of a smart manufacturing platform

Expectation	Extent
Reduction in cost of implementing the IT infrastructure	80%
Reduction in safety incidents	25%
Improvement in overall operating efficiency	10%
Reduction in cycle times	40%
Reduction in water usage	40%
Improvement in time to market in target industries	10x
Reduction in consumer packaging	25%
Increased revenue in adjacent industries	25%
Increased revenue in new products and services	25%

Source: Davis and Edgar 2013

Figure 11 is a rendering of the interaction and outputs of dozens of software programs in the SMLC smart manufacturing platform.

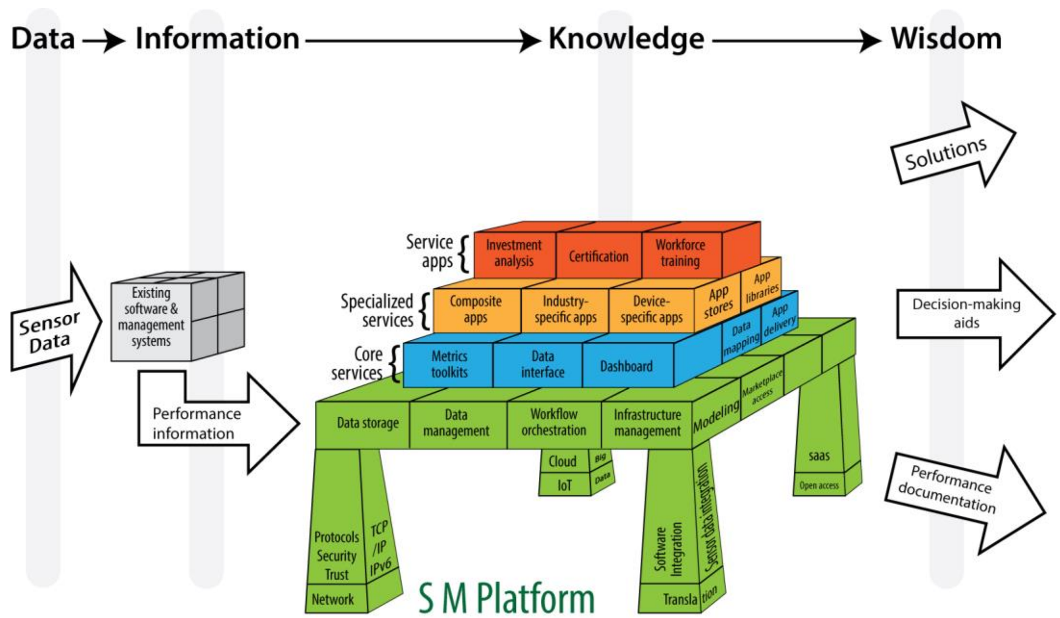

Figure 11. SMLC smart manufacturing platform

A significant piece of the SMLC program is the piloting of the multiple layers of software that make up the SM Platform. SMLC pilot projects involve company test beds in which the features of the platform are built and which demonstrate the platform's effectiveness. SMLC makes the smart manufacturing concepts embodied in the platform available to companies of all sizes.

The SMLC test beds enable members of the coalition to test at a pilot scale the ability to control multiple components of a smart manufacturing process. Current test-bed problem areas include a mix of the following:

- *Smart line operation.* Dynamically manage production machinery and processes across an entire operating line with respect to production efficiency, energy consumption, and machine maintenance. Establish benchmarks for machine performance under various conditions and configurations. Integrate respective energy consumption profiles into decision making.
- *Use of high-fidelity modeling and simulation in production.* Use rapid in-production qualification of components, products, and processes to manage a production process. May also incorporate parallel modeling of alternative operating scenarios.
- *Use of global integrated metrics in production decision making.* Create dynamic business and operation tradeoff decision-making models that can integrate global metrics data from across the factory, the enterprise, and the supply chain.
- *Supply-chain management.* Use cloud-based integration of data to establish bidirectional capabilities through the supply chain to reduce variability of production and management risks. This will also improve raw-material and work-in-progress tracking and traceability.

In January of 2012, SMLC was awarded a Department of Energy (DOE) grant to develop a platform test bed demonstrating the potential of smart manufacturing to reduce energy use. One of the first test-bed demonstrations is currently ongoing at a Praxair facility that manufactures hydrogen. Methane is steam-reformed at high temperature into hydrogen. The yield is driven by temperature and flow (Denise Swink, pers. comm., November 19, 2013). These variables also affect the degradation of the reformer, so production managers must make tradeoffs as they prioritize production versus wear-and-tear on equipment.

The demonstration project features cloud-based data analytics that involve high-fidelity modeling translated into a reduced-order model that is communicated to the plant system via the SM Platform.[7] Praxair has used such performance modeling before; however, for the first time, the instrumentation inside the reformer provides information to the model that gives a significantly richer, real-time description of the internal furnace operation. Instead of collecting data once a month, managers can now collect data continuously in real time. The data make it possible to see and model substantial variation in the furnaces so that the operation can be controlled with much more granular internal manipulations to optimize heat distribution, substantially improving the furnaces' energy productivity. In the future the model will include demand information from customers and suppliers (electric companies), enabling full economic modeling and a determination of the lowest-cost scenario.

Finally, an important issue for plant operators is the relationship they have with their management system: does it work for them, or do they work to serve it? For example, without a production management system, a plant engineer might develop a simple spreadsheet to keep track of half a dozen production variables in order to identify a trend line that could be used to inform decision making. A larger integrated system may want the same information plus a dozen other data points. At this point the operator is sending information up to the system and then asking for analysis back. The large integrated system may have powerful analytical capabilities but, because of a one-size-fits-all software package, be unable to provide the operator the trend line they need to inform their decision making. An open-access platform for which anyone can create applications reverses this relationship and makes it possible for the applications to work for the operator. Solutions tailored to individual operators enhance their productivity—and ultimately save energy.

The same situation exists at an enterprise level, except to a much larger degree. It is not just getting the right data from one system or even one plant, but from multiple processes, plants, and business units. Large multinational corporations are involved in SMLC because they currently have a choice between very expensive and incomplete integration of essentially incompatible proprietary systems, or the costs and wastes of not integrating the enterprise. An open-access platform gives them a better choice. It will enable them to integrate all of their processes, facilities, and business units.

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[7] A reduced-order model replaces a given mathematical model of a system or process with a model that is not as complex but that still describes—approximately—certain aspects of the system or process.

Through their participation in the SMLC effort, manufacturers and solution providers have come together to provide the choice. The scope of the SM Platform is greater than any single company, even a large one, could handle on its own. It is only by working together now in a precompetitive collaboration to develop common protocols and methodologies that manufacturers will gain more control of their own resources later. More control of their resources will translate to improved control of their costs and of their ability to meet customer demands.

Including Smart Manufacturing in Energy Efficiency Programs

Leading efficiency programs in the electric utility sector are looking for new ways to help each customer save more energy. What is promising about including smart automation and controls in these programs is that, if done right, it will not only deliver additional savings but also provide an improved measurement capability.

DYNAMIC BASELINE

Efficiency programs have been challenged to develop M&V protocols that warrant a high degree of confidence without being expensive to implement or burdensome on customers (Friedman et al. 2013). The computational power of data analytics enables companies to establish a baseline much more easily and inexpensively than before.

In the past, it would have been extremely difficult, if not impossible, to determine energy savings from individual projects implemented simultaneously. The calculation would be even further complicated if the production mix changed. The various parts of the process require different quantities of raw materials and energy. However, when modern data analytical capabilities are brought to bear on the collection of performance data from each device and at each level of a production process, facility operators can look through the massive amount of data and establish correlations between devices, products, and energy consumption. This capability can solve the challenge of establishing a baseline for a facility that changes production volumes and product mixes. A company can now establish a baseline energy use for virtually any operating scenario.

With this new ability to establish a dynamic baseline, facility operators and efficiency-program administrators will be better able to determine how much energy is saved by specific investments in equipment and changes in operating practices. They will also find it easier to forecast energy use over both the short and the long term. Production forecasts could now predict energy use a day or week ahead, and the volume of energy savings could be projected several years into the future to help make new investment decisions. And since these calculations can be automated, the exchange of information can happen in or near real time and less expensively than conventional data collection and reporting.

PROGRAMS FOCUSED ON PERFORMANCE RATHER THAN ASSETS

Intelligent efficiency provides an opportunity to move from energy efficiency programs that are device-based to programs that are systems- and performance-based. Older programs may be reaching the limits of what can be achieved with fixed rebates for purchasing specific items. They may be interested in the idea of paying for performance, especially if they are looking for new program ideas that will appeal to their larger industrial and commercial customers.

The fact is that the opportunities to save energy from more efficient devices are small in comparison to the potential for energy savings from system optimization. In our water pumping system, for example, only so much energy can be saved by installing an efficient motor or pump. Operating the system optimally can save significantly more energy.

With the ability to determine a dynamic baseline, industrial facilities can participate in programs that incentivize them to invest in energy-efficient systems. They can also participate more actively in the demand-response programs that have long been offered by their electric utilities. These programs give facilities a discounted rate in exchange for the utility's right to curtail a portion of their power supply during periods of high electricity demand. The utility determines when it needs a customer to curtail load and issues a call for demand reduction. The customer must reduce consumption or pay very high "buy-through" rates.

As an alternative to this program, a manufacturing facility could be connected to the smart grid that provides time-of-use pricing.[8] The business would react to the pricing by reducing load during peak times when the cost of electricity exceeded the value the business could gain from using it. Several solution-provider companies have started offering services to manage a business's energy costs by optimizing its facilities' response to time-of-use pricing (Viridity 2014; Stem 2014; FirstFuel 2014).

To facilitate the growth of demand response, several utilities and grid operators have come together to form the Open Automated Demand Response (OpenADR) Alliance and to create a new protocol for communicating demand-response information (OpenADR Alliance 2013). Bidirectional communication with a utility in real time goes beyond simple demand response, which tends to benefit a facility only in the short term. The OpenADR platform could become the basis not just for demand response but also for utility facilitation of distributed generation and energy efficiency. Coupled with the analytical capabilities of smart manufacturing, OpenADR gives businesses a new ability to manage their future energy consumption needs and supplies. Utilities could use the protocol to dispatch on-site distributed generation resources, just as they currently dispatch their own generation resources. They could communicate demand-response requests that customers could respond to with any combination of energy efficiency and on-site generation resources.

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[8] The ratio of the demand for electricity to its supply varies throughout the day and throughout the year. Time-of-use pricing reflects this dynamic, with increased prices during periods of high demand and lower prices during periods of weak demand. It is intended to encourage customers to conserve energy or shift their usage to different times of the day.

CASE STUDY: PACIFIC NORTHWEST NATIONAL LABORATORY GRIDWISE DEMONSTRATION OF TRANSACTIVE CONTROL

Pacific Northwest National Laboratory (PNNL) is working with Bonneville Power Administration (BPA) and technology companies IBM, Invensys, Johnson Controls, and Spirae to test a reactive and predictive grid demand model. Though none of the district utilities in the BPA territory currently uses time-of-day pricing, the pilot leverages this pricing model to communicate the value of supplied energy and system constraints to them. Each utility functions as a node that receives and transmits information about supply and demand. Power system modeling and simulation software analyzes current information from the many nodes, compares it with historical information to predict future supply and demand, and communicates the same back to the utilities (Nathan Howard, Spirae, pers. comm., February 21, 2014). Each utility can then share this information with its larger customers in a way that encourages and enables demand response such as curtailment of load (Virden 2012; Spirae 2012).

Armed with the ability to determine current and future savings, the factory manager and the efficiency program administrator can begin a conversation on paying for performance. Once in place, a smart manufacturing system can compare current operating conditions with a previous baseline under similar operating conditions. From that it can determine the net energy savings from a past investment that will result from a new investment. Performance information is reported to the program administrator and the incentive paid is based on energy saved. Programs may provide most of the incentive up front based on forecasted energy savings and release the balance later as actual performance is reported. That balance may increase or decrease depending on whether more or less energy has been saved than what was forecasted, and it may be released over a period of one or more years.

CASE STUDY: HYPOTHETICAL EXAMPLE OF AN INTEGRATED LIGHTING SYSTEM

Energy for lighting can be a significant cost in distribution centers and other large buildings in the manufacturing supply chain. To reduce this expense, a company may choose to install more windows to take advantage of daylight. During the summer, however, the solar gain could drive up energy use by requiring more cooling. To compensate, the company could tint its windows or, with current technology, install windows that adjust their tint in response to the intensity of outdoor light (View 2014). This technology can be linked with lighting control technology to optimize indoor lighting levels (Enlighted 2014). Both can be connected to a building management system (BMS) that also controls the heating and cooling system (JCI 2014). The BMS has Internet and smart-grid connectivity so it can receive and respond to time-of-use pricing signals (Kwantera 2014). It combines and analyzes the inputs from the daylight sensors, room occupancy sensors, weather forecasts, and energy pricing to optimize lighting, heating, and cooling to achieve the lowest cost of operation while still meeting occupant requirements for visibility and comfort.

Assuming the utility and manufacturing sectors can agree on protocols for determining energy savings, there is a good deal of promise in the concept of including smart manufacturing projects as eligible investments in industrial energy efficiency programs.

FINANCING OF ENERGY EFFICIENCY

Access to timely, low-cost performance data is also of interest to the financial community. The financing of energy efficiency projects has been hampered by the cumbersome and expensive tasks of predicting the potential energy cost savings and of verifying savings once the project is complete. With the ability to predict future and document past performance with greater accuracy and confidence, the financial community will be able to treat investment in efficiency in much the same way as it treats other investments.

While the financial incentives provided by government and the utility sector for industrial energy efficiency currently total around $1 billion per year (Chittum and Nowak 2012), a single large corporation might make an equivalent amount of capital expenditures every year or two. Manufacturers routinely borrow from private lending institutions to finance these capital improvement projects. They must justify the ability of the project or projects to produce income and/or reduce costs. The more cost data a project can provide up front, the easier the lending risk analysis.

Lending firms turn their loans into financial instruments that are sold to the private equity market. The market for energy efficiency retrofits is estimated to be $900 billion and projected to be capable of 6-10% returns (Joule Assets 2014). Given the new predictive capabilities of smart manufacturing, it could transform risk analysis in the manufacturing sector and the financing of energy efficiency. The private financing of energy efficiency does not require approval of state legislatures or public utility commissions, nor is it constrained by utility, state, or federal agency budgets. Its scope is limited only by the desire of businesses to borrow.

Recommendations

Smart manufacturing's potential to improve the competitiveness of domestic manufacturers argues for continued support by DOE and other agencies with economic development missions. Support might include funding and participation in research, development, and deployment. Agencies can also use their early convening powers to help develop voluntary standards and protocols. For example, they could advance the development of international standards for M2M communication protocols and help resolve issues related to growing spectrum congestion.

The creation of open-access platforms is a significant opportunity for the economy, but one that is too expensive and complicated for industry to tackle on its own. Government can function both as a convener and an investor for precompetitive industry collaboration. It can also facilitate innovation by making resources such as the National Laboratories' high-performance computing facilities available to technology and solution providers. Department of Defense (DoD) manufacturing facilities might also be used to demonstrate smart manufacturing platforms.

IT cybersecurity also requires government leadership, and the scope of international threats calls for the resources of multiple federal agencies. The ongoing NIST Cybersecurity for Smart Manufacturing Systems project is an example of what is needed. The Department of Homeland Security, DOE, and DoD all have a role to play in helping domestic manufacturers protect their communications and networks. Assistance should include education and training on cybersecurity threats and responses, demonstrations of new frameworks and methodologies, and help in developing protocols and standards that support IT security.

Regulatory agencies can aid innovation by realizing that its nature has changed. In the past, most innovation occurred before any data were collected. The purpose of data collection was defined at the outset, and the data were only used for the purpose for which they were collected. Given current data analytical capabilities, this is a limiting requirement. As we are seeing in the technology sector, and as we can expect in most sectors in the future, data collection will be just the beginning of the innovation process (Castro and Misra 2013). The data become the clay from which new things will be created.

An open-data approach allows more open-ended data collection and leads to innovation in the field of energy efficiency, as demonstrated by the DoD Green Proving Ground and the White House Green Button initiative (Seidel and Ye 2013). However the data must be anonymized, and the use of the information must be monitored and restricted to avoid harm to consumers (Castro and Misra 2013).

Industry can benefit by forming voluntary collaborative efforts such as the SMLC, the Industrial Internet Consortium (IIC), and the Digital Manufacturing Design Innovation Institute (DMDI). These groups engage in precompetitive research and development on the use of intelligent efficiency in manufacturing, including work on sensors, controls, standards, protocols, worker skills, and best practices. Their efforts should support seamless device connectivity, universal mobile service access, and open-access models.

Manufacturers and software developers should support the development of open-access platforms through their participation and financial support. Vendors of existing proprietary products should recognize that even though open-access platforms will require them to migrate to a different business model, doing so will ultimately lead to a larger market than currently exists. By engaging early, they will have opportunities that late adopters will not. This transition will not be unlike the one communication technology companies had to make with the advent of the Internet and the move from landlines to mobile phones and computers. There is a certain inevitability to it, so all the organizations that are likely to be affected will be well served to embrace and participate in the change.

The private and public sectors also need to come together to prepare today's workforce for tomorrow's smart manufacturing career opportunities. The evolution of this technology is progressing too rapidly for people to keep up with on their own. The private sector has the best sense of future employment needs and should communicate them to local, state, and national education and training agencies. Without a proactive approach by both sectors, investments in smart manufacturing will not realize their full value, and existing workers will not be as effective as they could be.

In the energy efficiency sector, programs targeting the manufacturers should progress from a focus on device efficiency to energy savings from systems. Intelligent efficiency enables superior data collection and reporting of energy savings. Efficiency programs should explore ways of using these new capabilities to create programs that are more responsive to the business community and less expensive and more effective than single-device rebates.

The financial sector should explore using these same data collection and performance prediction capabilities to improve the risk assessment of financial instruments backed by investments in energy efficiency. With the ability to set dynamic baselines, the reporting systems will also be able to verify asset performance and, by extension, confirm the efficacy of the financial instrument.

The energy efficiency and financial sectors should publish and share the results of their early demonstration projects. Others can learn through these examples and develop their own initiatives to leverage intelligent efficiency.

Finally, because intelligent efficiency will inevitably transform the industrial sector, it is important for all stakeholders to gain a better understanding of its features and the benefits and energy savings it can bring.

Summary

Smart manufacturing will transform the manufacturing environment. It will enable mass customization, reduce waste, and document energy, water, and material savings with accuracy and speed. That information will be shared throughout the organization and its supply chain in an actionable format that facilitates decision making and the management of the entire manufacturing process.

Smart manufacturing will become an economic engine of growth in the industrial sector. Innovation will respond to customer demand to develop better and more-targeted products. Design, development, and delivery to market will be quicker and at a lower cost.

Aided by government involvement and technical resources, precompetitive collaboration within the vendor and manufacturing communities will bring about common protocols and standards. The interoperability of systems will grow the market to the benefit of customers and vendors alike. Government agencies can facilitate this growth through funding and participation in research, development, demonstration, and education.

Development of an open-access smart manufacturing platform will create an entirely new business sector. While existing proprietary systems will be displaced in the short term, the much larger market for an open-access product and ancillary services will more than compensate. With the development of standard communication, security, and data-integrity protocols, the creation of open-access platforms, and the education of companies about their value, vendors will spend less of their sales cycle talking about technology and more about solutions. This approach will speed up innovation, increase customer adoption, and reduce costs.

The ubiquity of performance data and the ability to analyze them will enable companies to compete on energy efficiency, environmental, safety, and sustainability performance metrics. Customers will have access to the information and will incorporate it into their decision making.

Energy intensity, that is, the amount of energy embedded in a unit of production, will continue to decrease in individual facilities and all across the industrial sector. No overwhelming market conditions will prevent or complicate this evolution. It is part of the normal progress of manufacturing technology. It will happen because it helps manufacturers save money. Some of that money will be in the form of energy not purchased.

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