Advanced Sensors, Control, Platforms, and Modeling for Manufacturing (Smart Manufacturing): Technology Assessment

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1. Introduction to the Technology/System

1.1 Overview

Advanced manufacturing technology is rapidly transforming the global competitive landscape. Incremental technology upgrades alone may no longer be sufficient for companies to be competitive in the 21st century. Advanced Sensors, Control, Platforms, and Modeling for Manufacturing (ASCPMM) will help address this need by enabling cross connection of diverse data, process control applications, and decision workflows using advanced sensors and a network-based, open architecture, plug-and-play platform. The ASCPMM topic, also known as Smart Manufacturing, represents an emerging opportunity faced broadly by the U.S. manufacturing sector. ASCPMM encompasses machine-to-plant-to-enterprise-to-supply-chain aspects of sensing, instrumentation, monitoring, control, and optimization as well as hardware and software platforms for industrial automation. Advanced sensors, processors, and communication networks are used to improve manufacturing efficiency through the real-time management of energy, productivity and costs at the level of the factory and enterprise. A holistic systems approach, from raw materials to end-user services, is used to identify manufacturing pathways that optimize production rates that meet consumer demands while minimizing excess production at each manufacturing step[1]. Smart manufacturing is related to intelligent efficiency, as they both use Information Communication Technology (ICT) to achieve efficiency goals. Intelligent efficiency is energy efficiency achieved through sensor, control, and communication technologies, while smart manufacturing has a larger enterprise efficiency purpose with energy efficiency being a co-benefit to the improvements. Figure 1 shows the relationship between smart manufacturing, intelligent efficiency, ICT, and the Internet of Things. 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[2]. Over that period, the manufacturing sector could realize savings of \$15 billion in annual electricity costs savings with average company energy demand reducing by 20%[3].

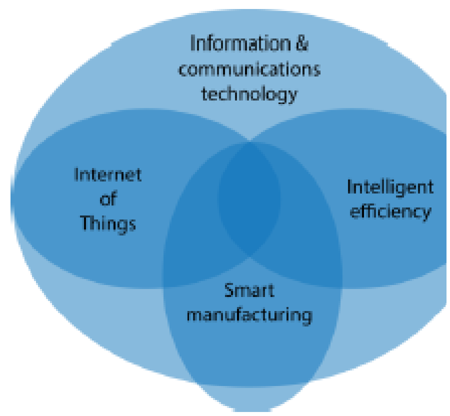

Figure 1. Relationship of ICT, Internet of Things, intelligent efficiency, and smart manufacturing from Rogers, 2014.[1] Subsets of ICT include; intelligent efficiency: energy savings resulting from ICT-enabled connection of sensors, devices, systems, facilities, and users; smart manufacturing: superior productivity resulting from the integration of all aspects of manufacturing; Internet of Things: machine-to-machines interaction through the Internet.

1.2 Challenges and opportunities

While aspects of ASCPMM have been successfully implemented in several key discrete industries, challenges remain in implementing ASCPMM more broadly throughout manufacturing. Key challenges to implementation include traditional capital investment, the type of manufacturing process, and the process environment, such as:

- The turnover rate of capital assets can be very slow. In many manufacturing facilities, process equipment, such as the blast furnace and distributed control systems, is used for many decades before they are retired or replaced; as a result, technology advancements are often evolutionary rather than revolutionary.
- Incremental investments in process control and IT are viewed as optional and non-critical with high cost factors. The value is low when implemented incrementally and in a compartmentalized manner, resulting in perceived low value. This imposes a cost barrier for ASCPMM.
- Energy-intensive industries, while relatively advanced, often rely on continuous production where materials being processed, either dry bulk or fluids, are continuously in motion, undergoing chemical reactions or subject to mechanical or heat treatment. These plants typically operate 24 hours per day, seven days a week with infrequent maintenance shutdowns, such as semi-annual or annual. Some chemical plants operate for more than two years without a shutdown. Blast furnaces can run four to ten years without stopping for a major revamp.[4]
- Technological advances in sensing and control may have to endure high temperature, high-pressure, and/or harsh environments. For example, a sensor used to monitor ultra-supercritical boilers must withstand a temperature of over 700ºC and pressure of 5000 PSI. A gasifier environment not only has similar high temperature and pressure, but also corrosion and erosion. Instrumentation and sensors used in ASCPMM today may not be suitable for certain process conditions. These sensors must also be affordable, able to extract more sophisticated data, and ideally be able to transmit wirelessly in real-time.

1.3 Public and private roles and activities

ASCPMM was specifically called out in the White House Advanced Manufacturing Partnership (AMP) 2.0 Steering Committee as one of three highest priority advanced manufacturing technology areas in need of federal investment.[5] Individual industry players are not likely to individually address the key foundational challenges that need to be overcome for widespread adoption such as technology integration and open, interoperable platforms. Government intervention will facilitate technology development and commercialization of ASCPMM to U.S. manufacturing industries. Public-private partnerships, such as the Smart Manufacturing Leadership Coalition (SMLC), are needed to build the infrastructure that no single company can tackle independently.[6,7,8] Some nations are also heavily investing in new manufacturing technologies. Japan's National Institute of Advanced Industrial Science and Technology (AIST) received 63% of their funding (~¥58,000, or $580M) in FY 2012 from the Japanese Government to advance the state of Japanese manufacturing.[9] EU nations are investing significantly in ASCPM technologies, in what they refer to as Industrie 4.0 and with a powerful combination of public and private funding to advance the development and deployment of these technologies.[10] The German's Fraunhofer-Gesellschaft also receives significant funding from the government (€382M, or ~$500M) to advance the state of German manufacturing.[11] With government playing a role in mission-oriented, pre-competitive research, energy-intensive industries can accelerate the adoption of smart manufacturing strategies– with national benefits in the form of energy reduction, greater industry competitiveness, productivity and safety, and boost the U.S. sensor and automation industry.

2. Technology Assessment and Potential

2.1 Performance advances

ASCPMM technologies help optimize efficient turnarounds, reduce maintenance times, and improved operational and quality control for energy-intensive industries due to improved diagnostic and predictive monitoring. ASCPMM technologies can also provide better business logistics, enabling increased daily output, more rapid innovation, and faster product launches and transitions. Modeling and simulation led to a $200M savings due to reduced metal use and automated process control resulted in at least $2.5M/year in benefits per major refining unit.[12,13] Advanced low-cost and fused sensors have a technology gap in their development and qualification to support greater data development from across a factory. Advanced sensors coupled with high fidelity time-dependent physics-based computational models enables greater deployment of real-time model predictive control in advanced and energy-intensive manufacturing processes, for the optimization and management of energy at the level of the factory, rather than individual process control points.

ASCPM technologies apply various components to yield performance advances across different industrial sectors. Ultra low power/cost sensors allow for data collection on different devices across the manufacturing supply chain.[14]. Embedded input/output devices can provide bi-directional information transfer in computing and networking processing.[15] Cloud computing architecture[16] allows for data collection and communication that application of advanced optimization algorithms.[17] Advance parts tracking provides identifiers, such as radio-frequency identification (RFID) tags, that allow for tracking of manufacturing components across the supply chain. [18] All of these components provide the opportunity for performance advances, such as:

System optimization

When implemented in each stage of energy intensive manufacturing processes, digital control systems with embedded, automated process controls, operator tools, and service information systems can optimize plant operations, energy consumption, and safety. These components can be used for collecting and analyzing large quantities of performance data to identify relationships between operational performance and energy use and to provide predictive control modeling.[19] Real-time communication between each step in given manufacturing process and a cloud infrastructure then allow system-wide algorithms to simultaneously operate each manufacturing component to anticipate and meet productivity demand with the minimum energy use.

Customization

Expanding the communication network to consumer demand can promote customization of product manufacturing. Advanced inventory tags can be used to track items from production to final customized fabricated products. Real-time communication can adjust production rates based on changes in consumer orders. Digital manufacturing can also enable customization, such as 3-D printing allowing products to be manufactured on-demand from electronically communicated digital designs

Predictive maintenance

Asset management using predictive maintenance tools, statistical evaluation, and measurements will maximize plant reliability – again contributing to greater productivity and energy efficiency. Data collection can be used for fault detection and diagnostics to predict when manufacturing parts will need repair or replacement, thus minimizing down time.

Distributed control systems

Increased network communication among different components throughout the manufacturing process improves the opportunity to have distributed control systems where each component subsystem is controlled by one or more controllers. For distributed control systems (e.g., for a complex oil refining process that consists of various unit processes), distributed control has mainly two advantages over centralized control. First, the reduction in computational burden of the controller due to the system decoupling. Under the distributed control scheme, the local operations decisions can be evaluated locally by only taking local process into account. Only the proposed decisions are broadcast to other subsystems for system-level coordination. Second, system robustness. A fault that occurs to any of the subsystems can be much more easily isolated and corrected under the distributed control.

Smart energy management system (EMS)

Smart energy management systems provide a cost-effective solution for managing energy consumption. Smart systems integrated within the industrial energy management system and externally with the smart grid could further enable real-time energy optimization and create entirely new ways of energy load management, even allowing for better excess for energy production and return to the grid. These systems are based on the integration of existing wired/wireless communication technologies combined with smart context-aware software which offer a complete solution for automation of energy measurement and device control[20].

Flexible manufacturing system

Smart manufacturing provides a level of flexibility to react in case of changes, whether predicted or unpredicted. Data collection and analytics can be used to develop production scenarios that will help anticipate the best operating conditions to meet changes in product demand.

Cloud-based manufacturing

Cloud computing has been in some of key areas of manufacturing such as IT, pay-as-you-go business models, production scaling up and down per demand, and flexibility in deploying and customizing solutions. Cloud computing can support manufacturing as distributed resources are encapsulated into cloud services and managed in a centralized way. Clients can use cloud services according to their requirements. Cloud users can request services ranging from product design, manufacturing, testing, management, and all other stages of a product life cycle[21].

Broader application of ASCPM technologies has great potential specifically in the energy intensive manufacturing sectors, as outlined in the AMP 2.0 Letter Report with the following examples.[22]

- With advanced sensing and model-based optimization techniques, an aerospace metal-parts manufacturer expects to save on the order of $3 million per year, in its plant that includes both continuous and discrete processes, on furnace operations alone.
- A chemicals company projects 10-20% energy savings for a hydrogen production plant with improved sensors and modeling, translating to a reduced natural gas cost of $7.5M per year.
- A plant provides ancillary power services for the Independent System Operator (ISO), using demand-response and direct load control for frequency regulation of the grid. Reported revenue to the plant is over $1M annually.
- A three-mill cement grinding plant reduced specific energy consumption by as much as 5% with a customized model-predictive control approach.

- A robotic assembly plant for a large OEM anticipates reducing energy consumption by 10-30% using optimization tools for robot motion planning.

2.2 Technology and System Integration Needs for Improvement

Important technical system integration challenges to realize the energy benefits of ASCPMM have been outlined by the AMP working team[8] and are presented below in approximate order of their ability to be implemented. The research to address the more challenging gaps is also important and can bring substantial rewards to the nations that succeed in the effort.

2.2.1 Open standards and interoperability for manufacturing devices, systems, and services

Vendor lock-in is a widely acknowledged barrier to innovation in sensing, control, and platforms for manufacturing. Standardization of information and communication has been attempted but with limited success and slow outcomes. It should be noted that standards, even open standards, are not sufficient by themselves. Interoperability must also be assured.

2.2.2 Real-time measurement, monitoring and optimization solutions of machine energy consumption and waste streams

In several manufacturing sectors, product quality, throughput, and plant efficiency suffer because of the lack of fast, noninvasive measurement methods. In many cases, samples must be analyzed or tested in a lab, or production must be affected for accurate measurement. Depending on the factory and process, noninvasive measurement could take different forms: stand-off imaging, disposable embedded sensors, inferential sensing, and others. In all cases reliable and cost-effective techniques are needed. These same technologies can be implemented for optimizing the energy consumption in a plant environment, for both continuous and discrete manufacturing processes.

2.2.3 Energy optimization of processes and integration with smart grids, cogeneration, and microgrids

Dynamic energy optimization in industrial plants can improve manufacturing efficiency while simultaneously facilitating the integration of renewable generation in the grid. Affordable and accessible energy-holistic manufacturing simulation models will benefit design and operation. Choices of fuel/power use, generate or purchase decisions, integration of storage of different types, model-based optimization, can all be done vastly better than they are today, across a broader swath of the nation's manufacturing base.

2.2.4 Health management for manufacturing equipment and systems

Specific techniques for fault diagnosis, detection of incipient problems, and condition-based and predictive maintenance. Techniques developed generally lack rigor and broad applicability. Here too sector-specific techniques will often be needed, but broad classes of equipment are deployed across many manufacturing sectors and can be targeted—e.g., pumps, motors, burners, and furnaces. In addition to plant performance and efficiency, the safety of people and the environment are at stake.

2.2.5 Low-power, resilient wireless sensors and sensor networks

A now long-standing promise of the wireless revolution has been pervasive sensing. Yet despite advances the promise remains well short of fulfillment. Encapsulating a radio with the transducer is not sufficient. Power management, possibly with energy harvesting, and reliable and fault-tolerant communication tied with the physical measurement is required—and solutions must be robust to the manufacturing environment and work practices. Addressing these gaps is crucial.

2.2.6 Integration with Big Data Analytics and Digital Thread

The technology areas referred to in this report are all data- and model-intensive. Advanced sensing, control, and platforms--and their integration--will produce vast amounts of data that can be mined for further models and simulations development; monitoring, control, and optimization techniques; and intelligent decision support systems. Sources of data are multifarious--weather forecasts, markets, plant historians, real-time process state and part quality data, equipment specifications, supply-chain databases, and others. Just as one example, the integration of storage technologies and the nascent efforts for using weather-based demand prediction for participating in energy markets present an opportunity to integrate Big Data analytics and digital thread technologies to the next level and embed decision support systems to make trade-off decisions on operations and asset utilization.

2.2.7 Platform infrastructure for integration and orchestration of public and private data and software across heterogeneous and human systems

Cyberphysical platforms integrate computing and communication capabilities in the sensing and actuation functions of components. Public and private applications and data resources need to interconnect to achieve horizontal enterprise views and actions. Many data and information "seams" are not well bridged with existing systems and platform technologies. As the complexity of platform integration grows there is further need for methods to design and build platform infrastructures while addressing issues of privacy and cybersecurity associated with the data shared.

2.2.8 Software-service oriented platforms for manufacturing automation

Manufacturing automation relies predominantly on single-vendor monolithic software architectures. Service architecture approaches can enable the extensive and systematic application of data analytics, models, and software innovations in physical manufacturing (cyber involvement). Such approaches will enable multiple development environments, infrastructures that support composability, and cloud-based orchestration. Appropriate cybersecurity considerations must be incorporated from the outset.

2.2.9 Theory and algorithms for model-based control and optimization in the manufacturing domain

The model-based control and optimization paradigm is widely and successfully used in some manufacturing sectors but has had limited application in many others. Industry-specific aspects must be considered if useful tools and technologies are to be derived. Topics of interest include nonlinear, stochastic, and adaptive control; large-scale and enterprise-wide optimization; integration of planning, scheduling, and control; and co-design of manufacturing processes with sensing and control strategies.

2.2.10 Modeling and simulation at temporal and spatial scales relevant across manufacturing

Models are at the core of many ASCPM technology gaps. Not only is an increasingly rich diversity of real-time and life-cycle modeling resources important, but also important are the tools and methods to more easily and cost-effectively build, deploy, and maintain models across large heterogeneous systems. Model alignment is also an outstanding need, especially since advanced manufacturing is dependent on models for various functions—e.g., planning, optimization, diagnostics, control.

2.3 Potential Impacts:

ASCPMM technologies can result in significant near-term benefits to the US to positively impact quality, yield, productivity and energy efficiency both within and through interoperability. Within the next five years the footprint of ASCPMM technologies in discrete manufacturing will begin to attain that of the continuous process industries.

The potential impacts in existing facilities can be seen in larger companies, such as ExxonMobil and Proctor & Gamble (P&G), that have already began addressing the technical implementation of ASCPMM.[23,24] ExxonMobil's first step towards ASCPMM was focused on an integrated information sharing network. They deployed standards and cyber security, life cycle cost and life expectancy management, remote access and data visualization. The result is a global enterprise network that enables information sharing, management, and data visualization across 100 cogeneration plants in more than 30 facilities. P&G has relied upon super-computing for their initial product design and evaluation. High performance computing arrays host complex, rigorous calculations such as computational fluid dynamics algorithms to model and solve problems such as the scale-up of the mixing of fluids in commercial scale equipment. This "Atoms to the Enterprise" approach has allowed P&G to answer critical manufacturing questions, e.g. what if, why not and how much, faster and at a lower cost.

The potential impact of ASCPMM is more readily realized in new manufacturing facilities where available technologies can be easily incorporated. For example, a smart automobile factory could utilize ASCPMM technologies to enable the acceptance of custom orders from dealers and adapt on the spot to customers' preferences, while allowing the company to track parts to their source. In the longer term, new manufacturing processes would be optimally designed simultaneously with their sensor and actuator suites and control strategies. End-to-end supply/demand chains would be integrated and optimized in real-time. New sectors such as bio-manufacturing and nano-materials will be operationally mature in their application of sensing and control and in their automation platforms. The resurgence of US manufacturing will be driven in great part by ASCPMM advances.

An analysis of the potential efficiency benefits of implementing promising smart manufacturing measures was conducted by Rogers, 2013.[3] Assuming a 50% penetration of intelligent controls and an increase in investments of 1% per year over current trends and increasing over 20 years to 3%., Rogers determined that the industrial sector could save between $7 and $25 billion in energy cost per year by 2035.

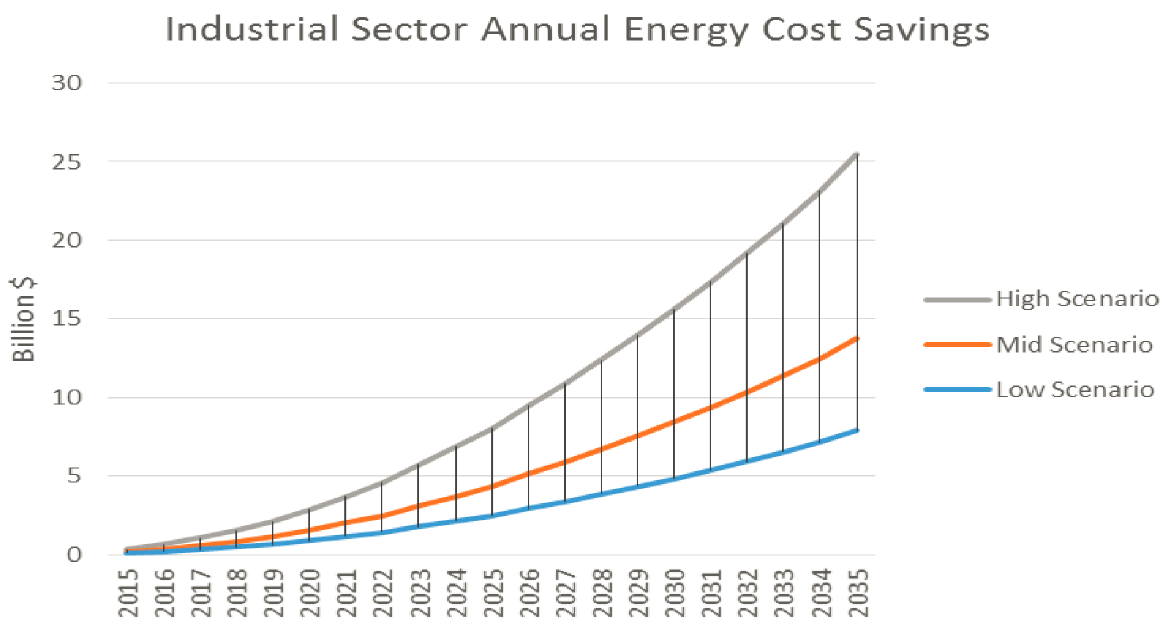

Figure 2. Estimated industrial-sector energy cost savings from Rogers 2013.[3]

The AMP Working Team outlined the following specific goal statements related to the integration of ASCPMM technologies[8]:

- Manufacturing automation equipment from different vendors seamlessly interoperates and allows plug-and-play configurations within three to five years.
- Energy use and waste streams per unit output from manufacturing plants are reduced by twenty percent in three years and fifty percent in ten years, after implementation.
- The deployment cost of sensors fall by an order of magnitude, enabling pervasive real-time measurement solutions within five to ten years.
- Process optimization and control systems, automatically and in real-time, adapt to changes in feedstock, market demands, and plant performance within five to ten years.
- Potential faults and failures are detected and corrected when still incipient, reducing plant downtimes by fifty percent in five years and ninety percent in ten years.
- Data and information platforms provide extensive access, scalability, reusability and actionable orchestration of analytic, modeling, simulation and performance metric software resources.

3. Program Considerations to Support R&D

While industrial automation is a >$60 B industry and several U.S. manufacturing sectors have benefited from advances in sensing and control over the last few decades, penetration of these technologies has not been widespread. In particular, US small and medium enterprises have lagged behind larger organizations on productivity growth due in large part to the lack of adoption of such technologies. Beyond technology expertise, the implementation is impeded by lack of cost-effective IT platforms and infrastructure and other implementation gaps identified earlier. The following R&D efforts and public-private partnerships can accelerate the integration of ASCPMM into the manufacturing sector.

Universal network protocols are needed to connect devices across various manufacturing sectors. The protocol needs to establish translation across types of sensors and provide “future proofing” that allows for adaptability as new sensor technologies are developed. Universal protocols for software and communication platforms (e.g., open-architecture and open-source) can enable plug-and-play connectivity to ease integration and customization across different ASCPMM components, different manufacturing requirements, and the latest IT hardware and standards.

The potential for systems optimization through sensor distribution vastly increases once sensors can operate and communicate without requiring physical connections. Research is needed to accelerate the development of self-sustaining sensors that require no dedicated power source (i.e., powered though waste heat or physical movement) or specific WiFi connection (i.e., communication through cellular or satellite networks). Additionally, sensors suitable for withstanding high temperature, high-pressure environments or sensors with embedded knowledge that makes them smarter and easier to integrate into sensor networks employed in manufacturing. Robust sensors have potential application in harsh, energy-related manufacturing processes.

The AMP 2.0 Working Team recommended a national ASCPMM Coordinating Committee with experts from industry, academia and relevant government agencies could be established to focus on the following deliverables

- Interoperability: Develop and implement interoperability standards and protocols for key systems with vendor support
- Standards and Nomenclature: Develop and propose new methods for addressing relevant industry standards on an as needed, highly fast tracked basis working with key Standards Developing Organizations
- Technology road-mapping and development of a research agenda: Develop technology roadmaps and prioritize research investments with government agencies on next generation sensors, process control and platform technologies in collaboration with relevant funding agencies (e.g. NSF, DoE, NASA, DoD, DARPA, NIST etc.) and private sector participants to accelerate development
- Coordinating Digital and Smart Manufacturing requirements: Digital design and Smart Manufacturing have distinct requirements that need to be integrated without losing appropriate emphasis on either.

The AMP 2.0 Working Team also recommended sector-focused demonstration and implementation activities that address the following needs:

- Physical and virtual test beds for technology demonstration and evaluation
- ASCPMM technology evaluation, development, demonstration, and customization services to small, medium, and large enterprises, in collaboration with vendors (for later stage TRL/MRL technologies)
- Training and facilitation for technical and managerial staff by linking with industry and technical/community colleges
- Coordination with digital design and advanced materials centers, institutes and/or initiatives on common infrastructure and technologies so that the full life cycle of technology solutions are integrated at the point of demonstration and delivery.

4. Risk and Uncertainty, and Other Considerations

The consumer and discrete manufacturing industry has in recent years employed information technology (IT)-based platforms and sensors to individual stages of decision making and production. This approach has enabled greater plant-wide efficiencies leading to lower costs and higher productivity and quality, particularly in the discrete value-added manufacturing sectors, such as automobile manufacturers. However, similar advancements have been slow to migrate to energy-intensive industries due to differences in manufacturing methods (continuous and batch processing versus discrete production), low turnover rate of capital assets, an evolutionary (instead of revolutionary) approach to technology updates and harsh production environments. The following system-level factors currently inhibit implementation of ASCPMM technologies, especially in the small- to medium-enterprise segments of US manufacturing. These challenges are well researched and documented in various publications by the NIST, the Smart Manufacturing Leadership Consortium, and serve as the key reasons for the recent Manufacturing Technology Acceleration Centers (MTAC) pilots and the Manufacturing Extension Partnership (MEP) program administered by NIST[1].

- Complexity and Initial Cost: Since technical solutions are complex and interdependent, taking action on comprehensive 'horizontal' methodologies comes with a full gamut of investment, market, technology, legacy, security and organizational changes for manufacturers that will be felt across small, medium and large companies in different ways. Small and medium enterprises in particular face greater challenges in successfully navigating the risks associated with these changes.
- Rapid changes in technology: While emerging technologies and models can drive cost down, complexity increases as new cloud technologies necessitate changes in data, information and modeling products, services and business models. Additionally, due to the interdependence of solutions, value chain access is hard for new entrants, inhibiting innovation and the ability to limit risks.
- Industry knowhow: While many of the technologies encompassed by the ASCPMM space are broad-based, the application is often industry or even entity-specific. This limits large investment by both technology vendors and potential manufacturers unless value can be demonstrated for the proposed new approaches.
- Workforce availability: Due to complex and interdisciplinary nature of the technologies, workforce talent is limited. An investment in this area can lead to a shift in workforce needs causing a dearth of workings in some areas and an oversupply of workers in other areas.
- Security: The expansion of information transmission with smart manufacturing creates vulnerability in privacy for both companies and consumers. Information security protocols will be necessary to address privacy concerns that could hamper the adoption of this information sharing.

5. Sidebars and Case Studies

5.1 Case Studies

[1] Connecting Small Manufacturers with the Capital Needed to Grow, Compete and Succeed: Small Manufacturers Inventory and Needs Assessment Report, November 2011, MEP, NIST.

Examples of current improved process control benefits are highlighted in the following table. However, these achievements are still below the ASCPMM objective that is set by the SMLC, among them 20% increase in operating efficiency and 25% improvement in energy efficiency.[25] Thus, in order for the energy-intensive industry to achieve widespread energy benefits and operational efficiencies from ASCPMM, innovations and advances will be needed in a number of areas.

Case studies using Smart Manufacturing concepts[26]			
Industry	**Company**	**Smart Manufacturing Concept**	**Benefits**
Petroleum Refining	Chevron[13]	Advanced Process Control with Advanced Software for Adaptive Modeling	• System is optimized for efficient turn-around of refining units • $2.5-$6.0M/year in benefits per major refining unit • Increased capacity and more energy efficient
Cement	Holcim, Capitol Cement, Others[27]	Framework & Architecture to customize control systems including predictive control	• 70% reduction in programming & trouble shooting time • Resolved 6-10 potentially critical situations per year that would otherwise have caused a shut down • Increased production stability ~36% • Reduced energy use 3% (in new facility!) • Added $5M/yr to bottom line by improving plant availability 15%
Chemical	Eastman Chemical[28]	Model Predictive Control (MPC)	• Currently 55-60 MPC applications of varying complexity • $30-$50M/year increased profit from increased throughput

5.2 Sidebar: Superior Energy Performance and Smart Manufacturing

Smart manufacturing promises great improvements in manufacturing performance and efficiency by capturing and leveraging data from factory networks through tailored, insightful analyses and automating control. Installed sub-metering in manufacturing processes provides real-time, equipment-specific energy consumption data and automated process alerts. In addition to saving energy, sub-metering also helps to identify equipment that is nearing failure, proactively reducing equipment downtime through preventive maintenance and extending the service life of equipment throughout the facility.

Launched in 2014, the Superior Energy Performance ® (SEP™) Program is an industrial energy management certification program developed and implemented by the U.S. Department of Energy (DOE) and the U.S. Council for Energy-Efficient Manufacturing. The SEP program is accelerating the realization of smart manufacturing benefits by emphasizing improved measuring and control of operations to reduce energy costs. SEP utilizes the ISO 50001-energy management system standard as its foundation, augmented with additional requirements such as third-party measurement and verification (M&V) of energy savings. SEP is driven by quantitative energy performance improvement targets: SEP-certified facilities are required to meet the ISO 50001 standard and improve their energy performance up to 25% over three years or 40% over 10 years.

The average cost of installing the necessary energy management metering systems for nine initial SEP-participating plants averaged $29,000 or 27% of external SEP implementation costs (i.e., all costs other than internal facility labor), but showed a great deal of variance across facilities— $0 to $159,000.[2] This range is largely due to some facilities having already installed metering before engaging in the program, and four facilities taking the opportunity to install a far greater level of metering than needed to meet the certification requirements of SEP. As SEP matures, internal labor costs are expected to fall, leaving sub-metering as a larger portion of overall SEP implementation costs. As sensing, instrumentation, monitoring, control, and optimization equipment becomes more advanced and less costly, more types of equipment and plant operations will be monitored at a more granular level, enabling even greater energy savings and system optimization benefits. This metering and monitoring equipment help to verify that smart manufacturing investments are yielding a positive return-on-investment.

The systematic data-driven approach that smart manufacturing is empowering is facilitated by the structured SEP approach to energy management. For example, the program requires manufacturers to meter, monitor, and record energy consumption data for the entire facility as well as identified significant energy uses (SEUs). In addition, SEP requires defining energy performance indicators, training process operation staff, creating operational control procedures, and taking corrective action to adjust operational procedures and controls. These requirements help to institutionalize energy management within manufacturing facilities and smart manufacturing technology applications.

[2] Therkelsen et al., *Assessing the Costs and Benefits of the Superior Energy Performance Program*. http://eetd.lbl.gov/sites/all/files/aceee_sep_paper.pdf

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