



NIST GCR 16-007

Economic Analysis of Technology Infrastructure
Needs for Advanced Manufacturing
Smart Manufacturing

August 2016

Prepared for—

**Economic Analysis Office
National Institute of Standards and
Technology**

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Gaithersburg, MD 20899

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This publication is available free of charge from:
<http://dx.doi.org/10.6028/NIST.GCR.16-007>

NIST
**National Institute of
Standards and Technology**
U.S. Department of Commerce

Acknowledgements

Many contributed to the preparation of this report, and we wish to acknowledge in particular the private companies, industry associations, research institutes, universities, and government agencies whose experts contributed data and insights underlying the analysis herein.

In addition to this study's lead authors, significant contributors included Luca Alessandro Remotti of the Joint Institute for Innovation Policy (formerly of Intrasoft S.A.), Raimund Broechler of Intrasoft S.A., and Jeff Cope of RTI's Innovation Advisors.

We would also like to acknowledge the advice and subject matter expertise contributed by NIST economic and scientific staff. Specifically, we are especially grateful for the contributions of

- Gary Anderson of NIST's Economic Analysis Office,
- Timothy Burns of NIST's Applied and Computational Mathematics Division,
- Stephen Campbell of NIST's Economic Analysis Office,
- Heather Evan of NIST's Program Coordination Office,
- Simon Frechette of NIST's Systems Integration Division,
- Albert Jones of NIST's Systems Integration Division,
- James Liddle of NIST's Center for Nanoscale Science and Technology,
- Eric Lin of NIST's Materials Science and Engineering Division,
- Richard Ricker of NIST's Materials Measurement Science Division,
- Christopher Soles of NIST's Materials Science and Engineering Division,
- Albert Wavering of NIST's Intelligent Systems Division, and
- Paul Zielinski of NIST's Technology Partnerships Office.

Disclaimer

This publication was produced as part of contract GS10F0097L with the National Institute of Standards and Technology. The contents of this publication do not necessarily reflect the views or policies of the National Institute of Standards and Technology or the US Government.

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U.S. Department of Commerce
Penny Pritzker, Secretary

National Institute of Standards and Technology
Willie May, Under Secretary of Commerce for Standards and Technology and Director

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Executive Summary

Smart manufacturing involves the integration of cyber and physical systems, which can enable innovative production processes and new product systems. However, industry faces barriers to the adoption of all but the simplest of smart manufacturing technologies. Enhancements in the technology infrastructure supporting smart manufacturing are needed to develop next-generation smart manufacturing technologies.

Technology infrastructure like standards and technology platforms provides the necessary underpinning for advances in smart manufacturing. Meeting critical needs in technology infrastructure can drive product and process improvements that are only in the conceptual stages today. Such improvements will lower the cost and increase the benefits from adopting existing and future smart technologies.

Economic impacts associated with meeting technology infrastructure needs for smart manufacturing could approach \$60 billion per year. This represents, on average, a 3% reduction in the shop floor cost of production. The estimate is likely to be conservative because it does not capture several hard-to-measure benefits, such as improved product quality and accelerated market transformation.

ES.1 SCOPE OF THE ANALYSIS

This study is a collaborative effort of multiple units within the National Institute of Standards and Technology (NIST) to determine infrastructure needs to support advanced manufacturing. The purpose of the study is to provide NIST with information on industry's technology infrastructure needs and help inform NIST's strategic planning and current/future investments. The report investigates the barriers to adoption of

smart manufacturing technologies and processes, with a focus on the underlying technology infrastructure.

Smart manufacturing incorporates not only generating and capturing data, but also understanding its implications and taking action as a result of that knowledge. Specifically for this study, we defined smart manufacturing as

the creation, communication and use of electronic information, as well as the interface of these information systems with the human element, for data-driven decision making and performance optimization. This includes how data and information generated during the production process are communicated and used during design, engineering, and production phases of the product cycle.

We present findings of an economic analysis of the technology infrastructure, which includes standards, measurement, and general-purpose technology, and the role of this infrastructure in the efficient development and adoption of smart manufacturing in the United States. The objectives of this strategic planning study were to:

- identify current and emerging trends related to smart manufacturing;
- identify technology infrastructure needs to support the development and adoption of smart manufacturing technology;
- document the challenges and barriers that inhibit the development of technology infrastructure;
- estimate the economic impact of meeting these technology infrastructure needs; and
- assess potential roles for NIST in meeting technology infrastructure needs and realizing economic benefits.

ES.2 ANALYSIS APPROACH

The methodology includes both the collection and analysis of qualitative and quantitative data. We conducted more than 80 interviews with a wide variety of smart manufacturing product and service providers, smart manufacturing end-user companies, and industry observers. We also had informal conversations with individuals at conferences and industry events, which contributed to the findings in this report.

The interviews investigated current trends, barriers to adoption, benefits that could be achieved from an improved technical infrastructure, and potential new roles for NIST. Quantitative information was collected on the potential benefits in terms of increased productivity, decreased production cost, and improved product quality. These quantitative impacts were used to calculate national economic impacts associated with an improved technical infrastructure to support smart manufacturing.

Quantitative responses were summarized at the firm level and applied to all or part of the industries represented by the interview respondents. Firm-level impacts were estimated for each firm that provided quantitative impact data during the interview. We made the effort to estimate impacts only for the relevant portion of the firm as reported by the respondent. Average impacts per expenditures for a given NAICS code were then scaled by national NAICS-level expenditures to obtain national impact estimates.

We grouped smart manufacturing activities and associated technology infrastructure into six capability areas, which are used throughout the report to facilitate discussion and presentation of results:

- Managing digital data streams through models
- Sensing and monitoring
- Seamless transmission of digital data
- Advanced data and trend analysis
- Communicating information to decision makers
- Determining required action and implementing action

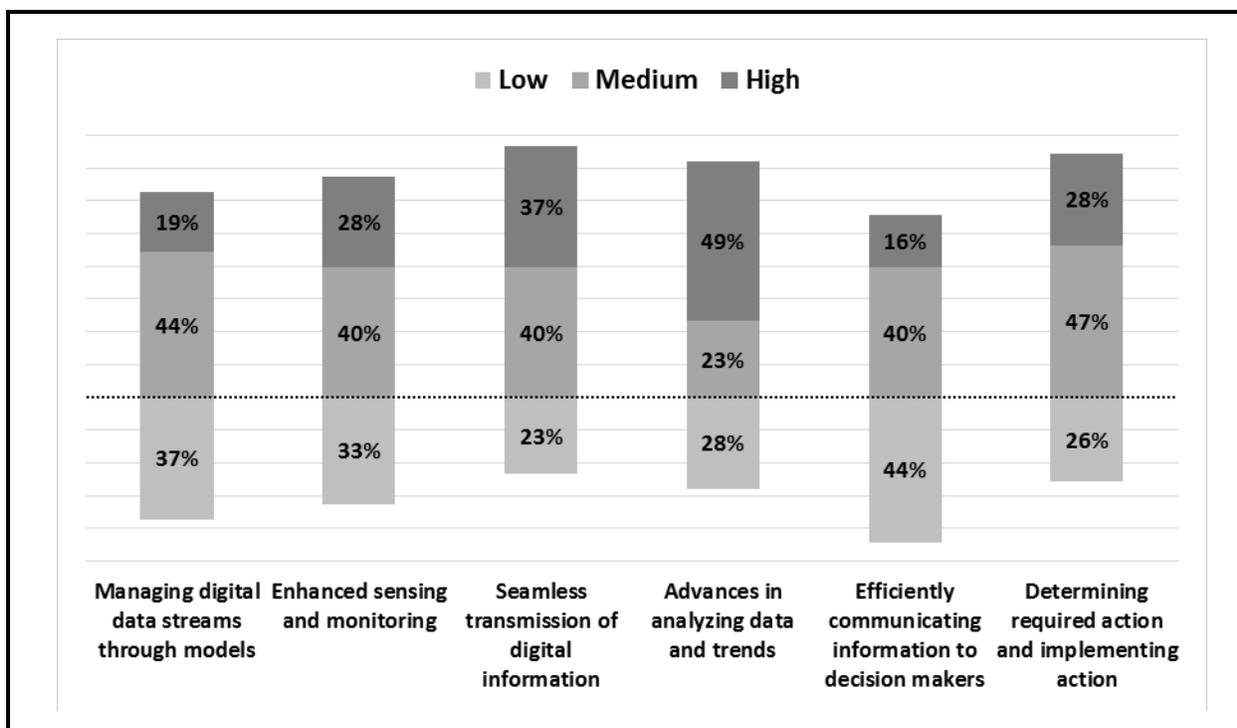
ES.3 ANALYSIS OF TECHNOLOGY INFRASTRUCTURE NEEDS

To identify potential areas where NIST could effectively collaborate with and complement industry, interviewees were asked to characterize the level of additional development needed for each of the six smart manufacturing capability areas and corresponding infrastructure technologies. Interviewees were asked to classify each capability according to a scale of “low,” “medium,” or “high” level of additional development

needed. Figure ES-1 summarizes the responses to the level of additional development needed, by capability.

As shown in the figure, advances in analyzing data and trends was characterized by 49% of interviewees as needing a *high* level of additional development. Next, 37% of interviewees rated seamless transmission of digital information as needing a *high* level of additional development. Relative to the other needs, the least important need for further development was communicating information to decision makers—only 16% of interviewees gave it a *high* rating.

Figure ES-1. Level of Additional Technology Infrastructure Development Needed for Smart Manufacturing Capabilities



Note: All columns sum to 100%.

Table ES-1 provides a summary of the technology infrastructure needed to support smart manufacturing capabilities along with the associated potential benefits and impacts resulting from an enhanced technology infrastructure. These benefits are the underpinning of the economic impacts estimated as part of the study. The following is a discussion highlighting the needs and barriers of each smart manufacturing capability area.

Table ES-1. Smart Manufacturing Capabilities and Technology Infrastructure Needs

Smart Manufacturing Capabilities	Technology Infrastructure Needed to Support Capabilities	Potential Benefits and Impacts of Enhanced Technology Infrastructure
<p>Managing digital data streams through models:</p> <ul style="list-style-type: none"> • CAD models including material characteristics, • simulation models of part creation and plant layout, and • rapid automated costing functions 	<p>High-fidelity process models, physical model representation for flexible objects, simplified modular applications of CAM software for less sophisticated uses, data standardization, standard and simpler equipment interfaces to facilitate consistent data entry for less-skilled workers, standard terminology for automated part costing</p>	<ul style="list-style-type: none"> • Ability to capture feature-based information in design models • Streamlined simulation of part creation • Enhanced ability to design for manufacturing • Reduced product-development-to-production cycle
<p>Enhanced sensing and monitoring:</p> <ul style="list-style-type: none"> • “state estimation” of critical manufacturing machines (for example: vibration, acoustics, temperature, tolerances, and pressure), and • real-time monitoring of product attributes as they move through various stages of the production process 	<p>In-process measuring and monitoring for physical processes, self-powered sensors, robust sensors to withstand harsh manufacturing processes, data standardization, methods for calibrating sensing and monitoring systems</p>	<ul style="list-style-type: none"> • More efficient measurement of equipment usage such as overall equipment effectiveness • Reduced scrap • Enhanced in-process product quality • Ability to predict machine issues and intervene with preventive maintenance • Reduced unplanned downtime • Increased sensor reliability • Greater visibility and transparency into manufacturing operations
<p>Seamless transmission of digital information:</p> <ul style="list-style-type: none"> • wireless transmission of digital information without interference from other data channels, • seamless integration of smart sensors, • interoperability between different platforms such as CAD/CAM, and • secure data transmission (wired and wireless) 	<p>Secure data transmission; secure cloud computing and data sharing; standard communication protocols; retrofitable, plug-and-play data communications systems; data interoperability of 3D model parameters and product manufacturing information</p>	<ul style="list-style-type: none"> • Reduced costs in factors of production such as capital, labor, energy, and materials through the increased ability to holistically analyze data, which leads to more efficient, optimized production. • Energy reductions, active energy management • Reduced downtime, increased uptime • Improved security, reduced risk of IP or safety issues • Reduced integration time (commissioning, debugging, etc.) • Freeing up staff time that is currently spent on connectivity and collating data

(continued)

Table ES-1. Smart Manufacturing Capabilities and Technology Infrastructure Needs (continued)

Smart Manufacturing Capabilities	Technology Infrastructure Needed to Support Capabilities	Potential Benefits and Impacts of Enhanced Technology Infrastructure
<ul style="list-style-type: none"> Advances in analyzing data and trends: interpretation and aggregation of data from sensing and monitoring networks, “Big Data” techniques for manufacturing, predictive maintenance, Reduction of false positives, and cloud computing and fee-for-service cloud based algorithms for product design, simulation, and manufacturing design 	<p>Algorithms to interpret data from disparate sensors and systems; definition of important, relevant, and meaningful data to collect for predictive maintenance</p>	<ul style="list-style-type: none"> Improved uptime Enhanced monitoring of in-process quality Reduction of false positives Increased overall equipment effectiveness Better utilization of existing data sources
<p>Efficiently communicating information to decision makers:</p> <ul style="list-style-type: none"> comprehensive information interfaces human-computer interaction-based design, and easy-to-interpret interfaces accessible from any location 	<p>Common taxonomy across platforms and disciplines</p> <p>Standards in interface design for manufacturing equipment</p>	<ul style="list-style-type: none"> Accelerated development of interfaces by the private sector More timely, evidence-based decision making
<p>Determining required action and implementing action:</p> <ul style="list-style-type: none"> real-time feedback of enhanced sensing and monitoring data into factory decision making, automated optimization-based decision making that functions independent of human interaction, machine-learning decision-making algorithms for manufacturing, and reconfigurability of manufacturing systems 	<p>Tested and validated decision models</p>	<ul style="list-style-type: none"> Optimized manufacturing processes Greater visibility and transparency in real-time manufacturing operations

ES.3.1 Managing Digital Data Streams through Models

Managing digital data streams through models is key for product development and, ideally, would facilitate interoperability across CAD/CAM systems and include material characteristics as part of the digital information stored and shared. These models could then be used to streamline simulation for parts creation. Plant layout simulation and rapid automated costing functions are two additional types of data modeling that were commonly mentioned in the interviews.

The length of time and difficulty in developing high-fidelity process models can be a barrier to the use of process

simulation. Creating realistic high-fidelity process models can take up to a year, and can be so complex that they require PhD-level employees to create them and high-performance computing systems to run them; moreover, in many instances, the end product still fails to provide accurate modeling.

Industry also needs more open-source platform development to allow large and small companies alike to rapidly innovate, express needs, and develop common platforms. Most large software companies want to sell end-to-end automation packages and pursue this approach as a competitive strategy. However, this limits flexibility. A marketplace is needed to encourage startups in this space and related Big Data applications.

ES.3.2 Enhanced Sensing and Monitoring

Sensors are being integrated into most new machines produced today. Although a broad range of sensor capabilities is available, in many instances manufacturers are not fully taking advantage of these technologies. All study respondents said that state estimation of critical machines is an area that industry is continually pursuing. Manufacturers believe that existing sensors are adequate for many applications, and that the most crucial need lies in improvement of data analysis capabilities. Nevertheless, we found that the industry still lacks many sensing and monitoring capabilities, and that the existing technologies need significant improvement. In addition, integrating sensing capabilities into older legacy systems is costly, and is often limited by technical constraints.

Manufacturers said that solutions are needed that are lower risk, economically feasible, and have fewer calibration and false-positive issues. Standards for reliability would significantly reduce the risk. Manufacturers feel that, currently, standards are loose and should be more stringent. For example, if a sensor has too much fluctuation, the time period in which the sensor is accurate needs to be extended. Tolerances of sensors needs to be improved. If standards were produced (and enforced), then developers would be forced to comply and publish the tolerance rates; users would then know what they are buying at various cost points. Companies individually conduct testing in their labs, but this is very costly and not efficient from a social perspective.

ES.3.3 Seamless Transmission of Digital Data

Interoperability between platforms is not a new issue, but one that study respondents still cited frequently as a significant source of ongoing inefficiency. Standards developments, such as the Standard for the Exchange of Product (STEP), have notably improved interoperability in several areas, but more advances are needed.

The most commonly cited technology-specific barriers included networking/communications between machines and equipment from different vendors and different eras. Significant time is spent setting up machines and equipment to talk to a network. Even equipment with an “Ethernet-enabled” label is a source of frustration because companies do not all use a standard communications protocol.

Respondents indicated that it has been a struggle to get manufacturers to adopt solutions such as MTConnect. Original equipment manufacturers (OEMs) and user communities have concerns about using this technology, and smaller companies are not familiar with the standard. More OEMs need to build the capabilities into their equipment, but small OEMs do not have the staff capabilities to develop the software to integrate the standards into their equipment’s sensing capabilities.

The technology of transmitting data via wireless technology was also cited as an issue by some, but not all, respondents. Concerns centered on interference between transmissions of several data channels from multiple pieces of equipment. Neither quality nor cost of bandwidth were mentioned as issues. However, security was often cited as a concern—both data security and physical plant security when hazardous or explosive materials were involved.

Cost and uncertainty of benefits associated with connectivity continue to be barriers, and markets have not been able to adequately address these barriers. The total investment costs of connecting assets are high, and it is often difficult to guarantee or demonstrate the benefits/return. Differences across plants and older, legacy equipment make plug-and-play solutions difficult to develop. In addition, entrenched vendors continue to promote proprietary software and solutions that inevitably increase costs and limit adoption.

ES.3.4 Advanced Data and Trend Analysis

The analysis of big data is a rapid-growth sector. However, most manufacturers in our study thought that the manufacturing sector was not receiving sufficient attention from data analysis service providers. Most of the data analysis firms are better positioned to serve the financial service sector or marketing departments. They lack the engineering or chemicals expertise to support much of the manufacturing sector.

The cost associated with computing power and analysis software can be significant, and represents a barrier to adoption of smart manufacturing, especially to small and medium enterprises (SMEs). In general, we found significant disagreement with respect to future use of cloud computing. For some, the concept did not resonate at all due to concerns about the security of proprietary data and protection from hacking. However, for others, the benefits of the cloud's low-cost computing power and storage outweigh the risks. Typical comments were that a company "does not have to put the most sensitive information on the cloud. It is good for what it's designed for."

Best practices and techniques for data analysis emerged as the top technology infrastructure need in this area. Prediction, particularly predictive maintenance, was a central theme. In addition, advances in algorithm testing and development were needed to provide guidance on interpreting data from different sensors and determining which data are most meaningful to collect for predictive maintenance. To the extent that it is possible to develop standard algorithms that can be customized by end users, this approach would be ideal.

ES.3.5 Communicating Information to Decision Makers

Respondents interviewed were most familiar with activities related to physical components, data exchange, and related standards. However, the "softer" side of smart manufacturing, which includes efficiently communicating information to decision makers, was also cited as an area needing further research. For example, the value of smart manufacturing data and activities would be increased through research to develop simpler, user-friendly communication interfaces that would be customized for smart manufacturing and integrate statistical methods for establishing thresholds to trigger decisions.

Many industries encounter issues related to efficient and concise information interfaces. “Ease of use paradigms” are needed. Plant staff members need to be able to access and understand software and information in a manageable way. Mobile access with tablets would be a key selling factor; however, the wireless aspect of tablets may introduce security concerns.

Efficiently communicating information to decision makers is about the metrics used to communicate with decision makers rather than the design of interfaces. Overall equipment effectiveness (OEE) is one example of a high-level metric that has gained some traction in industry but is not consistently defined.

ES.3.6 Determining Required Action and Implementing Action

The ability to determine and implement required action was referred to as the “... ultimate capability. Without it, the other capabilities are of no use.” Most manufacturers expressed the need for enhanced decision support tools that would help make decisions much faster, including information and analysis tools targeted at both manufacturing operators and upper management. Using artificial intelligence and learning systems to identify and direct the most appropriate actions based on data analysis would advance the goal of building an automated and more flexible factory.

Improvements in decision systems will require continued research on statistical methods for analyzing Big Data (pattern recognition, trends, and correlations) and the intelligence to make critical decisions based on risk assessment and optimization modeling. This is a multidisciplinary research area in which coordination must be improved across the different sectors pursuing these enhanced capabilities.

Respondents thought that substantial opportunities to enhance the technology infrastructure in this area were needed and are possible, but could not offer specific recommendations. Manufacturers commented that it would be helpful to have closed-loop systems, but again offered little specific guidance on what technology infrastructure was needed to develop these systems.

ES.4 SUMMARY ECONOMIC IMPACTS

Total economic impacts associated with an enhanced technology infrastructure to support smart manufacturing are estimated to be approximately \$57.4 billion per year and would accrue over multiple years. Discrete parts manufacturing accounts for \$30.8 billion and process manufacturing \$26.6 billion.

Figure ES-2 shows cost savings for each factor of production, by discrete parts and process manufacturers. The largest impact was associated with labor savings in discrete manufacturing sectors. In the process industries, the greatest savings was in materials (feedstock), followed by energy and labor.

Figure ES-2. Annual Cost Savings by Factors of Production (millions of USD) for Process and Discrete Industries

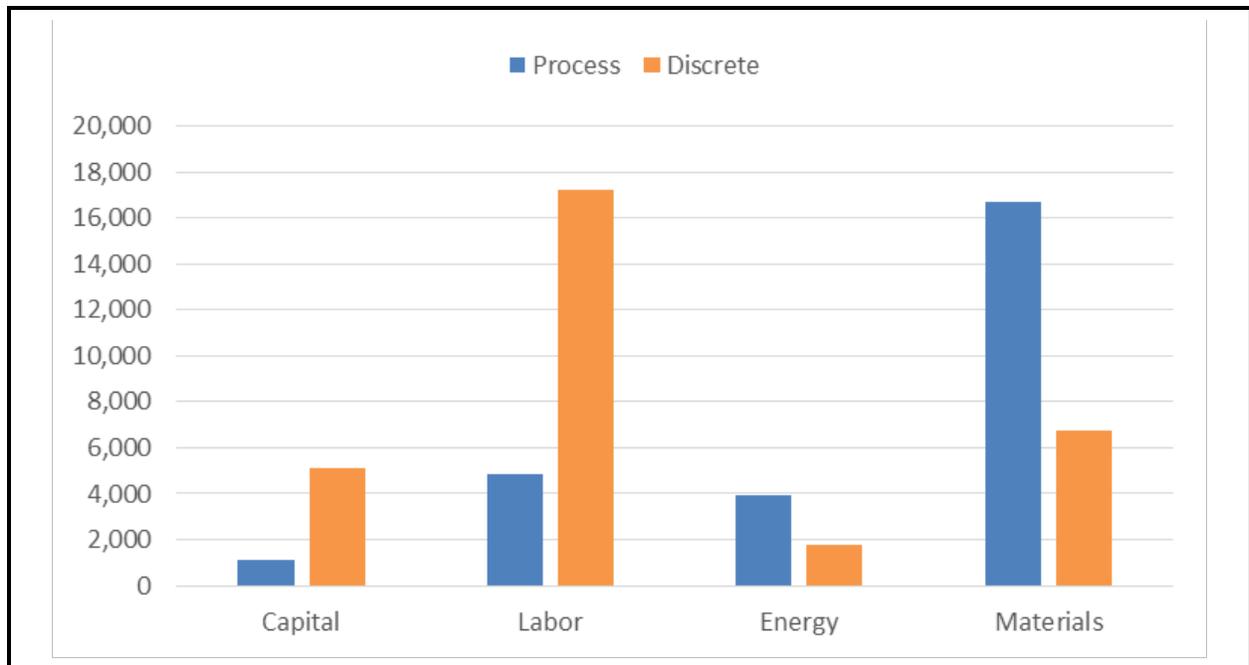
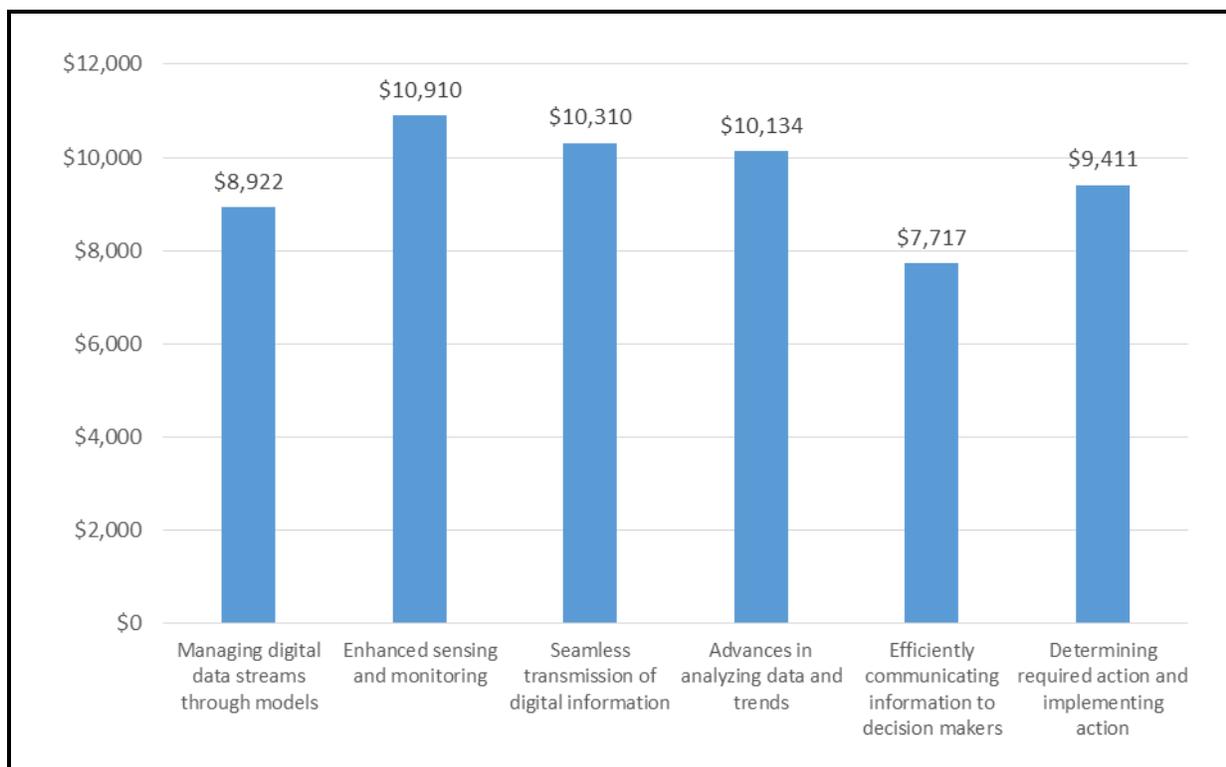


Figure ES-3 shows the distribution of total impacts apportioned to each of the six capabilities. The distribution of impacts is based on the relative importance scores provided by the manufacturers interviewed. Enhanced sensing and monitoring, seamless transmission of digital information, and advances in analyzing data and trends all have potential annual impacts

Figure ES-3. Total Cost Impact, by Capability (Millions of 2013 US\$ per year)



greater than \$10 billion. All of the identified capability areas were estimated to have annual benefits of over \$7 billion, reflecting the generally overall importance of all the categories and their interdependency.

The relative magnitude across all the categories is evidence that there are strong complementarities or “interaction effects” among the capabilities. For example, it was stated that enhanced sensing and monitoring was only as important as the ability to transmit, analyze, and communicate the information.

Note that the economic impact estimates presented are considered to be conservative in that they focus on reductions in manufacturers’ production costs that would result from meeting the identified technology infrastructure needs. Not included in the economic impact calculations is the economic value associated with reduced R&D costs, improved product attributes, increased sales, or accelerating the introduction of new products to market.

1 Introduction

The growth of smart manufacturing has been touted as a driving force for reinvigorating the manufacturing sector in the United States. U.S. industry has long accepted that it will need to focus on production efficiency and labor productivity to maintain its competitive position in global markets. With the increasing complexity inherent within the manufacturing system, smart manufacturing has the potential not only to enhance the generation and capture of data, but also to build an understanding of the data's meaning and to take action as a result. The implementation of smart manufacturing is key to advancing the U.S. manufacturing sector.

There is no shortage of studies investigating the potential impacts of smart manufacturing, claiming potential productivity and efficiency gains ranging from 5% to 30%. Two major U.S. consortia—the Smart Manufacturing Leadership Coalition (SMLC) and the Digital Manufacturing and Design Institute (DMDI)—both state that a 10% gain in overall efficiency is possible. Given that the technology focus of the SMLC and DMDI are overlapping but different, the sum total of their projected impacts is likely higher than 10%. Acatech—the German National Academy of Science and Engineering—estimated that German firms could boost productivity by 30% with Industry 4.0, European smart manufacturing initiative. A second study of German firms prepared by the Boston Consulting Group was more conservative, estimating that productivity gains of implementing the Industry 4.0 smart manufacturing initiative would range between 5% and 8%.

Whereas almost all studies agree that smart manufacturing has significant potential, there is less agreement on why it is not being adopted at a faster rate in key manufacturing sectors of the U.S. economy; and, if barriers to adoption do exist, is there a role for government in mitigating these barriers and

accelerating the penetration of smart manufacturing technologies and processes?

This report investigates the barriers to adoption of smart manufacturing technologies and processes, with a focus the underlying technology infrastructure. We present findings of an economic analysis of the technology infrastructure, which includes standards, measurement, and general-purpose technology, and the role of this infrastructure in the efficient development and adoption of smart manufacturing in the United States.

The objectives of this strategic planning study were to

- identify current and emerging trends related to smart manufacturing;
- identify technology infrastructure needs to support the development and adoption of smart manufacturing technology;
- document the challenges and barriers that inhibit the development of technology infrastructure;
- estimate the economic impact of meeting these technology infrastructure needs; and
- assess potential roles for the National Institute of Standards and Technology (NIST) in meeting technology infrastructure needs and realizing economic benefits.

As part of the analysis, the study investigated the connections between identified technology infrastructure needs and the market barriers that are impeding their adoption. We discuss how specific barriers could best be addressed with public-sector participation. NIST, for example, has unique capabilities and expertise in applied research on the development and diffusion of new technology, such as

- promulgation and adoption of standards;
- coordination, facilitation, and performance of cooperative research and development (R&D);
- facilitation of technology transfer; and
- communication and dissemination of scientific knowledge.

1.1 DEFINITION OF TECHNOLOGY INFRASTRUCTURE

Technology infrastructure is the broad base of public and quasi-public technologies¹ and technical knowledge that support the R&D and production efforts of firms, universities, and laboratories, as well the development and adoption of improved and entirely new products, processes, and services (e.g., higher quality, more effective, more efficient, more productive).

Technology infrastructure supports and accelerates advances in advanced manufacturing capabilities. Specifically for smart manufacturing, enhanced technology infrastructure has the potential to enable capabilities such as

- modeling and data creation;
- sensing and monitoring;
- transmitting information across multiple platforms; and
- analyzing data and trends.

Technology infrastructure includes infratechnologies and technology platforms, which are defined in subsequent subsections of this report. Government agencies fund the majority of technology infrastructure research due to their public-good content (Tassey, 2008). NIST is the government agency that serves this role in the United States. This quasipublic technology infrastructure, together with proprietary technologies, comprise the three major elements of industrial technology (Tassey, 2008).

1.1.1 Infratechnologies

Historically, NIST has focused resources on this aspect of technology infrastructure. Infratechnologies are a varied set of “technical tools” that include measurement and test methods, artifacts such as standard reference materials that allow these methods to be used efficiently, scientific and engineering databases, process models, and the technical basis for both physical and functional interfaces between components of systems technologies such as robotics and automation technologies. Tassey (2008) wrote that “[c]ollectively they constitute a diverse technical infrastructure, various types of which are applied at each stage of economic activity.” New

¹ Technologies with varying degrees of public-good content.

infratechnologies often replace less efficient forms of infratechnology that support current standards (Tassey, 2008).

Infratechnologies influence the development of technology platforms and proprietary technologies. They also support efficient R&D, production and market transactions such as complying with customer requirements and regulations.

Infratechnologies provide the technical basis for standards that are set using consensus standards-setting processes that are usually led by industry organizations. Their benefits include full disclosure of information, reduced uncertainty regarding product attributes, and an overall improved level of trust that helps to reduce market transaction costs.

The provision of infratechnologies requires a combination of industry and government investment, because infratechnologies have substantial public-good content (Antonelli & Link, 2014). Some industries depend on hundreds of distinct infratechnologies and associated standards. Furthermore, a particular infratechnology may have spillover benefits for many industries.

1.1.2 Technology Platforms

Technology platforms are precompetitive proofs of concept that demonstrate the potential commercial viability of a new or improved product, process, or service. These fundamental technical concepts originate from basic science research and can even be enabled by measurement infratechnologies (Link & Scott, 2010).

A characteristic of a technology platform is that it is often the case that it will be foundational to multiple products and processes, the scope of which is typically broader than the business model of any one firm. Therefore, no firm is able to fully appropriate the benefits of investing in the development of a technology platform, so that achieving the socially optimal level of investment will generally require additional public investment.

1.1.3 Proprietary Technologies

Proprietary technologies are not included in the definition of technology infrastructure for this study. Proprietary technologies are commercialized products, processes, and services that may be derivatives of technology platforms and

have been influenced by infratechnologies. Generally, firm investments in proprietary technology fall under the category of R&D spending. Ubiquitous proprietary technologies may behave like quasi-public goods despite being funded and developed by private sector firms.

1.1.4 Summary of Key Definitions

Table 1-1 contains abbreviated definitions of the key concepts outlined above for ease of reference. The table also lists examples of each term to make these concepts more understandable. Technology infrastructure is the focus of this study because of its quasi-public-good characteristics.

Table 1-1. Definitions of Key Concepts

Term	Definition	Examples
Technology infrastructure	The broad base of quasipublic technologies and technical knowledge that support the R&D and production efforts of firms, universities, and laboratories, as well the development and adoption of improved products, processes, and services.	<ul style="list-style-type: none"> • Infratechnologies • Technology platforms
Infratechnologies	A varied set of “technical tools” that include measurement and test methods, artifacts such as standard reference materials that allow these methods to be used efficiently, scientific and engineering databases, process models, and the technical basis for both physical and functional interfaces between components of systems technologies such as factory automation and communications.	<ul style="list-style-type: none"> • Standard reference materials • Reference data sets • Process models • Techniques for process and quality control • Calibration services • Traceability of measurements and test methods
Technology platforms	Precompetitive proofs of concept that demonstrate the potential commercial viability of a new or improved product, process, or service. A characteristic of a technology platform is that it is often the case that it will be foundational to multiple products and processes, generally from multiple firms.	<ul style="list-style-type: none"> • Bell Labs’ transistor proof-of-concept using solid-state physics principles^a • Prototype networks such as ARPANET and NSFNET that led to the Internet^a • Proof-of-concept for vibration-powered devices that could power remote sensors
Proprietary technologies	Commercialized products, processes, and services that may be derivatives of technology platforms and have been influenced by infratechnologies. Proprietary technologies do not have quasi-public-good characteristics	<ul style="list-style-type: none"> • Industrial robots • Collaborative robots • Machine vision systems

^a Tasse, 2008.

1.2 DEFINITION AND BOUNDS OF SMART MANUFACTURING FOR THIS STUDY

The term *smart manufacturing* spans a wide range of functions and technologies, and means different things to different stakeholder groups and industries. In general, smart manufacturing refers to production systems at the equipment, factory, and enterprise levels that integrate cyber and physical systems to enable innovative production, products, and systems of products (Kilmer, 2014).

Specifically for this study, we defined smart manufacturing as

the creation, communication and use of electronic information, as well as the interface of these information systems with the human element, for data-driven decision making and performance optimization. This includes how data and information generated during the production process are communicated and used during design, engineering, and production phases of the product cycle.

Although the specifics of smart manufacturing vary by industry, the flow and use of data almost always involve the following core components:

- *modeling and data creation* to support design, testing, and automation;
- *sensing and monitoring* to collect real-time information on processes;
- *transmitting information* across multiple platforms and levels of the supply chain;
- *analyzing data and trends* to support real-time process control and management;
- *communicating information* to decision makers to support efficient and/or automated analysis; and
- *determining and implementing* required action in a timely and/or closed-loop setting.

Currently, and for the foreseeable future, a human being will participate in these processes performing several different tasks. Human involvement will be necessary to achieve the full potential of smart manufacturing, as will optimized manufacturing processes and advanced artificial intelligence. Additionally, improvements in analysis capabilities will be required. For example, advanced statistical methods for

analyzing big data (pattern recognition, trends, and correlations) are needed, as is intelligence to make critical decisions based on risk assessment. These advancements will require a multidisciplinary research effort that will depend on coordination across the different sectors pursuing these enhanced capabilities.

1.3 SCOPE OF INDUSTRIES AND SUPPLY CHAIN INCLUDED IN THE ANALYSIS

This study focused on manufacturing and product design activities within the traditional North American Industry Classification System (NAICS) codes of 31 to 33. These industry sectors capture the majority of smart manufacturing opportunities and provide a bounds for the study scope. As shown in Table 1-2, the study included major discrete parts manufacturers and process manufacturers as well as their suppliers of parts, equipment, software, and process-related services.

Excluded from this study are the agricultural sector, extraction of natural resources, and logistical activities related to supply of input materials and delivery of final products. Although opportunities related to smart technologies and processes are applicable to these industry sectors, it was necessary to bound the study to focus on industries and processes with the greatest economic potential.

Table 1-2. Major Industries Included in the Study

Discrete Parts and Assembly	Batch and Continuous Process
Motor vehicles and parts	Food
Aerospace products and parts	Chemicals
Fabricated metals	Pharmaceuticals and medicine
Plastics and rubber products	Oil and gas
Wood products	Electricity
Furniture and related products	Paper
Electrical equipment and appliances	Primary metals

1.4 MARKET FAILURES AND BARRIERS TO DEVELOPMENT AND ADOPTION

A motivating principle for this study is that private investments in innovation and diffusion of new technologies typically generate social value in excess of their private returns. As a result, some socially productive technology investments are not undertaken because private firms do not perceive the research as profitable.²

This failure of markets to provide firms with the incentive to make socially productive investments in technology infrastructure opens up a role for public sector intervention to improve the efficiency of technology markets. The possibility that public sector investment in technology infrastructure can lower the costs or increase the benefits of adopting smart manufacturing technology suggests a role for NIST that fits well within its mission statement.

As will be discussed in this report, many of the general market failures listed in Table 1-3 have been identified as barriers to the development of the technology infrastructure needed to support and promote the adoption of smart technologies.³

The sidebar lists needs/barriers, either policy or business related, that underpin the technology issues investigated in this study of smart manufacturing. For example, ***institutionalized risk aversion*** and ***unwillingness to enable standardization*** are commonly cited barriers to development and adoption of smart manufacturing technologies and processes. Similarly, lack of a ***common ontology*** creates interoperability issues in the sharing of electronic data, and is a barrier cited by manufacturers and machine equipment producers. Participants in this study suggested that government could help coordinate with companies to characterize the critical key performance indicators to measure on machines and determine how best to access the measurements.

Barriers to Adoption

- Institutionalized risk aversion
- Unwillingness to enable standardization
- Concerns about data security/liability and intellectual property (IP) protection
- Lack of access to technology by small and medium-sized enterprises
- Lacked of workforce with needed skills
- Lack of common ontologies

² The private rate of return is less than what is required (the private hurdle rate), even though the social rate of return exceeds that required by society (the social hurdle rate).

³ The taxonomy of barriers presented here draws insight from Link and Scott (2010) and Jaffe (2005).

Table 1-3. Sources of Market Failure: Barriers to Developing and Adopting New Technology

Barriers	Impacts Platform Technologies	Impacts Infratechnologies
• Inability to appropriate all social benefits, such as positive network externalities	√	√
• Scope of commercial applications broader than the market strategy of any one firm	√	
• Risk that R&D outcomes will be technically insufficient (technical risk)	√	
• Commercial or market risk, that is, the risk that R&D outcomes, while technically sufficient, will not be well received by the market, thereby providing an unacceptable return on investment (ROI)	√	
• Long and uncertain lag between R&D investments and returns	√	
• Asymmetric information between developers and adopters of new technology		√
• Difficulties in bringing together component technologies from different industry segments	√	√
• Industry structure, such as network externalities, presenting market-entry barriers to new technology		√

As will be discussed in the following sections, it is important to distinguish between general R&D market failures and those that specifically affect technology infrastructure. Although technology platforms, which are a form of early stage, are subject to the more common R&D market failures, such as appropriability and institutional risk aversion, infratechnologies are more of a special case.

Infratechnology market failures affect both research and marketing/distribution throughout supply chains. For example, a lack of standardization, certification, and test beds are market failures that create inefficiencies and increase transaction costs. The provision of infratechnologies by government can help overcome these issues.

1.5 BENEFITS FROM AN IMPROVED TECHNOLOGY INFRASTRUCTURE

Technology infrastructure provides the underpinning for advances in smart manufacturing. It lowers the cost and increases the benefits from adopting existing smart

manufacturing technologies. Removing or lowering market barriers to adoption will increase penetration and yield economic benefits; the efficiency gained will ultimately improve the competitive position of U.S. manufacturing. Enhancements in the technology infrastructure will also lead to the development of next-generation smart manufacturing technologies that could drive product and process improvements that are just in the conceptual stages today.

1.6 REPORT OVERVIEW

The remainder of this report presents an analysis of technology infrastructure needs to support smart manufacturing. The core findings are based on in-depth interviews conducted with stakeholders throughout the manufacturing sector and the supporting supply chains. This report is organized as follows:

- **Section 2** presents the methodology used in the analysis, including data collection, survey instruments, data analysis, and estimating of economic impacts.
- **Section 3** provides an overview of key concepts related to smart manufacturing, stakeholder groups included in the study, market trends, and barriers to adoption.
- **Section 4** presents findings from the stakeholder interviews. It presents a discussion of barriers to the adoption of smart manufacturing technologies, and the potential economic benefits from meeting smart manufacturing technology infrastructure needs.
- **Sections 6 through 10** focus individual capability areas and present the specific technology infrastructure needs for smart manufacturing and potential roles for NIST in developing solutions to fill those needs.
- **Section 11** provides the study conclusions and overarching themes.

2

Analysis Methods and Primary Data Collection

We conducted more than 80 interviews with a wide variety of smart manufacturing product and service providers, smart manufacturing end-user companies, and industry observers. We also had informal conversations with individuals at conferences and industry events, which contributed to the findings in this report.

The interviews investigated current trends, barriers to adoption, benefits that could be achieved from an improved technical infrastructure, and potential new roles for NIST. Quantitative information was collected on the potential benefits in terms of increased productivity, decreased production cost, and improved product quality. These quantitative impacts were used to calculate national economic impacts associated with an improved technical infrastructure to support smart manufacturing.

This section discusses the details on the data collection process and the methodology for quantifying the potential impacts.

2.1 OVERVIEW OF ANALYSIS METHODS

The methodology includes both the collection and analysis of qualitative and quantitative data. It is important to understand where and why existing technologies have not penetrated the market, as well as what new and improved capabilities/ technologies would be most beneficial. Industry stakeholders were interviewed to investigate their current use of smart manufacturing technologies and practices, and the barriers limiting expanded or more rapid adoption. These discussions

began with a general overview of barriers, such as adoption costs, overarching technical issues, and risks and return. Each interview last about an hour.

Once overarching barriers were identified, specific technical issues were discussed. The six smart manufacturing capability areas presented in Section 2 were investigated along with their associated technology infrastructure needs. The technology infrastructure needs were ranked and prioritized in terms of importance for advancing smart manufacturing and the level of the additional research and development needed. Then, in-depth discussions were held on specific needs and how manufacturing processes could be improved if these needs were met.

Interviewees quantified how meeting these technology infrastructure needs would improve their manufacturing processes in terms of reduced capital, labor, materials, and energy costs, and/or impact their productivity and throughput. This information was used to estimate the economic impact of an improved technology infrastructure supporting smart manufacturing. Firm-level responses were scaled to obtain national industry-level impacts. Interviewees were also asked what role NIST could play in helping meet these needs.

2.2 CONSERVATIVE APPROACH

The quantitative economic impact estimates calculated in this study are considered to be conservative in that they do not capture all the benefits that would result from an improved technology infrastructure. As discussed below, the focus of our analysis is on reductions in manufacturers' production cost that would result from meeting the identified technology infrastructure needs. However, this analysis does not capture all of the potential economic benefits associated with an enhanced technology infrastructure.

For example, a streamlined infrastructure for creating, transmitting, analyzing and communicating design and production data would accelerate the development and commercialization of altogether new product markets. These new products would have increased economic value stemming from enhanced attributes such as

- greater functionality,
- lower maintenance costs, and
- increased life expectancy.

However, valuing new (yet to be defined) products or product attributes is difficult, has great uncertainty, and is beyond the scope of the study.

An improved technology infrastructure will also lead to reduced R&D costs. However, interviewees were not able to quantify R&D savings, saying that the benefits would be a mix of improved/accelerated R&D and enhanced product quality. Hence, these categories of benefits are discussed qualitatively, but not included in the quantitative economic impact estimates.

In general, focusing on manufacturing cost savings implies that the analysis captures primarily gains in producer surplus, and does not capture gains in consumer surplus associated with improved product quality. In addition, the analysis does not capture increases in social welfare from increased output (sales), which result from lower cost and higher demand; nor does the analysis capture increased exports that would result from the enhanced competitive position of U.S. manufacturers.

For these reasons, the economic impacts presented are considered to be conservative, lower-bound estimates.

2.3 INTERVIEW PROCESS

Interviews were selected as the principal mode of primary data collection (rather than a closed-form survey) because of the complexity of the subject matter and the need to be flexible with respect to the respondents' areas of expertise. This approach to data collection provided a richness of information that could not be obtained using survey methods.

We identified potential interview respondents by first identifying firms operating in advanced manufacturing spaces. The focus was on the manufacturing sector as defined by the major two-digit NAICS codes 31–33. Contacts were then identified within firms operating in these manufacturing sectors. High-value respondents were identified and secured by attending industry conferences and trade shows, and reviewing publically available publications and presentations. As part of this process, a large number of informal discussions (not counted as formal

interviews) were conducted. Ultimately, 81 interviews were conducted with 38 developers⁴ and 43 users. Table 2-1 shows the industry sectors covered by the interviews.

End-user interviewees were distributed relatively evenly among discrete parts manufacturers (automotive, aircraft, etc.) and process-oriented manufacturers (chemicals, petroleum, etc.).

Interview participants varied in seniority, from staff engineers to middle management to executives. Job titles of the interviewees included:

- Senior Engineering Manager
- Director, Advanced Manufacturing Technology
- Senior Automation Engineer
- Process Automation Engineer/Process Modeling & Optimization Engineer
- Chief Executive Officer/President
- Founder
- Chief Technical Officer/Chief Technical Advisor
- Global Lead for Manufacturing

2.4 INTERVIEW TOPICS

Interview guides were developed and shared with respondents prior to the interviews. Two separate interview guides were used to differentiate between different positions in the value chain—a guide for firms that develop and sell smart manufacturing technology or services and a guide for firms that use smart manufacturing technology and services. Some firms were hybrid developers/users, and in these cases we asked about both perspectives. To simplify the analysis, industry observers were interviewed from the developer or end user perspective based on their particular experiences and knowledge.

Technology developers provided quantitative responses regarding industry sales growth. They also provided critical qualitative feedback on the specific technologies and infrastructure technologies that NIST can help provide. Sales

⁴ Of the 38 interviewees interviewed from the developer perspective, 5 were industry observers.

Table 2-1. Industry Sectors Covered in the Interviews^a

Industry	NAICS Code
Food manufacturing	311
Fruit and vegetable preserving and specialty food manufacturing	3114
Textile mills	313
Wood product manufacturing	321
Paper manufacturing	322
Pulp, paper, and paperboard mills	3221
Converted paper product manufacturing	3222
Petroleum and coal products manufacturing	3241
Basic chemical manufacturing	3251
Resin, synthetic rubber, and artificial synthetic fibers and filaments manufacturing	3252
Pharmaceutical and medicine manufacturing	3254
Plastics product manufacturing	3261
Other fabricated metal product manufacturing	3329
Agriculture, construction, and mining machinery manufacturing	3331
Industrial machinery manufacturing	3332
Metalworking machinery manufacturing	3335
Engine, turbine, and power transmission equipment manufacturing	3336
Other general-purpose machinery manufacturing	3339
Navigational, measuring, electromedical, and control instruments manufacturing	3345
Household appliance manufacturing	3352
Motor vehicle body and trailer manufacturing	3362
Motor vehicle parts manufacturing	3363
Aerospace products and parts manufacturing	3364

^a The industries represented by the respondents were identified by querying a variety of sources. Some respondents provided a NAICS code for their line of business. Other companies were classified through secondary search of the Hoovers database and Census NAICS Web site searches. NAICS identified at the 3- and 4-digit level were used when scaling individual responses to national impacts.

growth estimates helped identify the impact of public investments in infrastructure technologies on size of the overall market and the extent to which the technologies will be adopted by end users.

End users provided quantitative responses on how smart manufacturing technologies would change their costs in four factors of production—capital, labor, energy, and materials expenses—and ancillary measures such as total throughput, maintenance costs, and the costs of integrating new manufacturing technologies. They also provided critical qualitative feedback on barriers to adoption, key technical pain points, and how advanced manufacturing technologies could improve their products.

The following is an overview of the topics investigated during the interviews. The formal interview guides for developers and end users are in Appendices A and B.

Respondent's background: Respondents were asked to describe their background as it relates to smart manufacturing, and what share of their company's or industry's activities/sales/research they felt comfortable discussing. Respondents were also asked if they were familiar with NIST's activities and/or if they participated in research organizations (standards, calibration and measurement, scientific or data exchange/analysis relevant to smart manufacturing).

Current and planned use of smart manufacturing: Respondents were asked to provide a brief description of their company's current use of smart manufacturing technologies, and what additional areas of smart manufacturing (e.g., automation, sensing/monitoring, data feedback/integration) their company has considered, investigated, or researched for potential future adoption. For example, has the company conducted feasibility studies or developed preliminary cost/benefit models?

Barriers to adoption: Respondents were asked why they decided not to move forward (or are not moving as fast as they would like) with certain investments in smart manufacturing.

A better state of the world: Respondents were asked what capabilities/technologies are needed to promote greater adoption of smart manufacturing and how these enhanced capabilities/technologies would impact their manufacturing activities. Then respondents were asked to rank the importance of these capabilities along with the level of additional development needed.

Economic valuation: Given the enhanced capabilities/technologies cited, respondents were asked about the impact of these technologies on their manufacturing processes, products, and services. They were asked to quantify these impacts in terms of percent reduction in costs and improvements in productivity.

Importance: Respondents were asked to rate the importance of different smart manufacturing capabilities and technologies.

Technology infrastructure needs: Respondents were asked about which areas needed the most research in terms of technology infrastructure, and to identify specific research activities that should be pursued to further enhance smart manufacturing capabilities and functionality.

NIST's potential role: Throughout the interviews, respondents were asked to consider the role NIST might play in supporting the development of an enhanced technology infrastructure. At the end of the interviews, respondents were asked to summarize their thoughts on NIST's role and what activities NIST should prioritize.

2.4.1 Economic Analysis Methodology

Quantitative responses were summarized at the firm level and applied to part or all of the industries represented by the interview respondents. The following sections outline how the quantitative responses are summarized at firm level and industry level given our industry classification scheme previously described. Table 2-2 outlines and briefly describes four analysis components we conducted using information gathered from our interviews.

Firm-level impacts were estimated for each firm that provided quantitative impact data during the interview. We made the effort to estimate impacts only for the relevant portion of the firm as reported by the respondent. Average impacts per

Table 2-2. Economic Analysis Methodology

Stakeholder Group	Scope of Impact Estimate	Description	Section
End users	Firm	Estimate of the impact that enhanced technology infrastructure would have on the individual end users in our sample	2.4.2
Developers	Firm	Estimate of the impact that enhanced technology infrastructure would have on the sales of the individual developers in our sample	2.4.3
End users	U.S. National	Estimate of the impact that enhanced technology infrastructure would have on the U.S. industries that currently use, or will use, smart manufacturing	2.4.4
Developers	U.S. National	Estimate of the impact that enhanced technology infrastructure would have on the sales of U.S. developers of smart manufacturing technologies	2.4.5

expenditures for a given NAICS code were then scaled by national NAICS-level expenditures to obtain national impact estimates.

2.4.2 Firm-Level End-User Impact from the Sample

Respondents provided percent changes to capital, labor, energy, and materials (KLEM) costs (as well as overall production throughput).⁵ Dollar impacts were derived by first estimating the firm-level domestic sales to which the impact estimates applied. We estimated firm-level costs using industry-level cost-to-sales ratios from secondary sources such as the Annual Survey of Manufacturers (ASM) and the Bureau of Labor Statistics (BLS) IO data. Percent change impacts were then applied to these firm-level cost estimates.

Firm-level sales were estimated through a variety of sources including public filings, annual reports, and Hoover's database. Some respondents provided sales estimates that were verified against secondary sources. For larger firms with multiple lines of business where it was clear that the impact estimates only applied to a certain division, division-level sales were estimated using information from annual reports.

To estimate cost-to-sales ratios, we used industry data from national accounts provided by the BLS for industry-level energy and materials cost estimates. Energy costs included the manufacturing industry's purchases of oil and gas extraction (NAICS 211), coal (NAICS 2121), electricity (NAICS 2211), natural gas (NAICS 2212), and refined petroleum (NAICS 324). Materials costs included purchases from other manufacturing industries in the NAICS range 3210–3330, excluding 324 (refined petroleum and coal).

The data provided by BLS give highly aggregated accounts for capital and labor. To better identify capital and labor costs

⁵ Changes in production throughput was used as a proxy for capacity utilization when respondents were not able to provide percent changes for KLEM. However, increased industry growth or sales are not included in the impact estimates; thus, the impact estimates are conservative.

associated with “shop floor” activities, we relied on the 2013 ASM.⁶

Firm-level KLEM cost estimates then equal the estimate of firm or division sales times the relevant industry’s cost-to-sales ratio based on the BLS (energy and materials) or ASM (labor and capital) data. For example, we estimate that production capital is 5.4% of sales in the iron and steel mills industry (NAICS 3311). A respondent at a firm with \$500 million in sales within this industry who reported a 5% reduction in firmwide capital costs would yield a \$1.4 million ($\$500 \times 0.054 \times 0.05$) capital impact estimate for smart manufacturing technology adoption.

Response Assumptions

Some respondents provided a combination of production throughput and capital and labor cost impact estimates. If the respondent provided estimates for capital and labor cost impacts, we used those numbers assuming that the respondent accounted for improvements in product throughput. If the respondent provided no estimates for capital and labor cost impacts, we applied the production throughput improvement as an equivalent percentage improvement in the costs of capital and labor.

Not all respondents were willing to provide quantitative estimates. Some respondents provided a rank order of the impacts or a direction on the impacts, but did not quantify them. We did not include these responses in the quantitative assessment. For respondents who provided an estimate for at least one KLEM category, we assigned zero impact to the categories for which they did not respond.

Impact Applicability

When scaling to national levels, we were careful in determining the appropriate quantity of KLEM expenditures. Applicability factors were calculated to capture both applicable expenditures within a given firm, and the share of firms within the

⁶ Capital costs used in the analysis include capital expenditures on machinery and equipment (CEXMCH, RPMCH), computer and peripheral equipment (CEXMCHC, PCHCMPQ), and other machinery and equipment (CEXMCHO, RPMCH). Labor costs include production workers’ annual wages (PAYANPW) grossed up to include nonwage benefits such as health insurance (BENHEA), retirement (BENPEC, BENPEB), and other fringe benefits (BENOTH).

manufacturing sector for which smart manufacturing impacts are applicable.

These applicability factors (and the percent change impacts) were then applied to national accounts that reflected only a firm's manufacturing activities. For example, only production labor and capital equipment expenditures were used as the basis for scaling impacts to the national level.

Since some respondents provided information specifically about their division's operations, their cost and throughput estimates would not necessarily apply to the firm as a whole. This was particularly true for respondents working for larger, multi-industry or conglomerated firms.

Total sales were estimated based on our identification of the share of firm sales associated with the operation for which the responses were given. For example, we spoke with a respondent from a multinational chemical company who was comfortable answering for a single division of the company that accounted for 20% of the company's sales. Furthermore, approximately 40% of the company's sales took place in the United States. If the firm's revenues were \$100 million, the applicable sales base would be \$8 million ($\$100 \times 0.20 \times 0.40$).

2.4.3 Firm-Level Developer Impacts

End-user demand for smart manufacturing technologies requires commensurate supply from the industries that develop the technologies. Some end users estimated capital cost increases to reflect the purchase of these technologies, but most end users indicated that the bulk of their existing capital would be better optimized through smart manufacturing technologies and enhanced technical infrastructure; thus, on net, most end users cited decreases in capital costs.

Developers were asked what impact an enhanced technology infrastructure would have on their sales of existing and potential new products and services. However, it should be noted that developers' increased sales and end user cost reductions are not additive when calculating economic impact. Sales of supporting smart manufacturing products and services are considered a transfer in the economic accounts. Users accounted for (netted out) additional purchases of these products and services when estimating their benefits (cost reductions).

2.4.4 National-Level End-User Impacts by KLEM

Respondents were given the option to provide a percentage estimate for each quantitative response or a range of impacts. In cases where a respondent provided a range, we took the midpoint of the range when calculating point impact estimate.

We excluded outlying impact estimates that were either unrealistic or likely to heavily bias industry-level impact estimates upward.⁷ We considered several possible ways to summarize the remaining responses within each NAICS code, including:

- Average: A simple average of the impact response for all respondents within a given NAICS code category
- Sales-weighted: A weighted average of impact responses based on the size of the respondent's firm

We used the simple average method because it was less susceptible to being overly influenced by a single response from a very large firm.

Using the industry data on cost-to-sales ratios, we estimated the KLEM cost basis for each 4-digit industry that is represented by responses. We discounted the average cost impacts for each 4-digit industry by the average industry applicability factor. Then we applied the applicability-weighted cost impacts (%) to the KLEM costs for each industry. The total cost impact across industries is the sum of the industry-level impacts.

We received quantitative responses for industries representing nineteen 4-digit level NAICS and four 3-digit level NAICS, which account for 64% of total manufacturing sector sales. Because not all manufacturing industries are likely to benefit from incorporating advanced manufacturing technologies, we recognize that some industries were not captured in the interview process. Thus, national-level impact estimates are likely to be conservative in that some industries with potential benefits are omitted.

⁷ For example, one respondent provided an estimate for all manufacturing sectors that had a significant impact on our average impacts. This response was dropped because the respondent could not be more specific about the industry or sector for which the response was applicable.

Respondents were also asked to provide industry applicability factors for their estimates because not all impact categories are relevant for all companies within a sector. However, for the vast majority of respondents, these factors were 100% (i.e., respondents expected their impact estimates to hold for all firms in the industry). Responses less than 100% were often stated as a fraction of the industry or for a particular type of firm or set of firms within the industry, which required secondary estimates such as market shares from sources like IBISWorld Reports. Applicability factors were then applied by industry to further adjust the industry scaling size.

2.4.5 National-Level End-User Impacts by Capability Gap Area

We apportioned the total cost impact to each of the six capabilities in Table 3-1 by using the average share of importance points awarded to each capability. We used only the importance scores provided by end users (see Section 3.3 on importance scores).

For example, if an interviewee awarded a total of 20 points across the six capabilities, and they provided the highest importance score of 5 to safe HRI and a 2 for objective, low-cost performance characterization, then the shares would be 25% and 10%, respectively. We then averaged these shares across individuals and applied them to the total cost impact.

2.4.6 National-Level Developer Impacts

To estimate the size of the market for developers' advanced manufacturing technologies, we combined estimates of global market revenue from market reports. We then made an assumption about the U.S. market share, using a sample of the largest players in the market for smart manufacturing technologies⁸ as well as an industry report.⁹ These estimates and the U.S. share of the global smart manufacturing technology market are used to scale the sales growth that developers said would result from enhanced technical infrastructure and end-use capabilities. The total value of advanced manufacturing technology purchases (sales) should not exceed its benefit to end users.

⁸ Using a sample of 10 firms, we found that the portion of global industrial automation and control as well as optimization software revenues attributable to the United States was about 35%.

⁹ Cisco, IoE Report. IoE value to the United States was \$4.6 billion, compared with \$14.4 billion globally.

3

Smart Manufacturing Trends and Technology Gaps

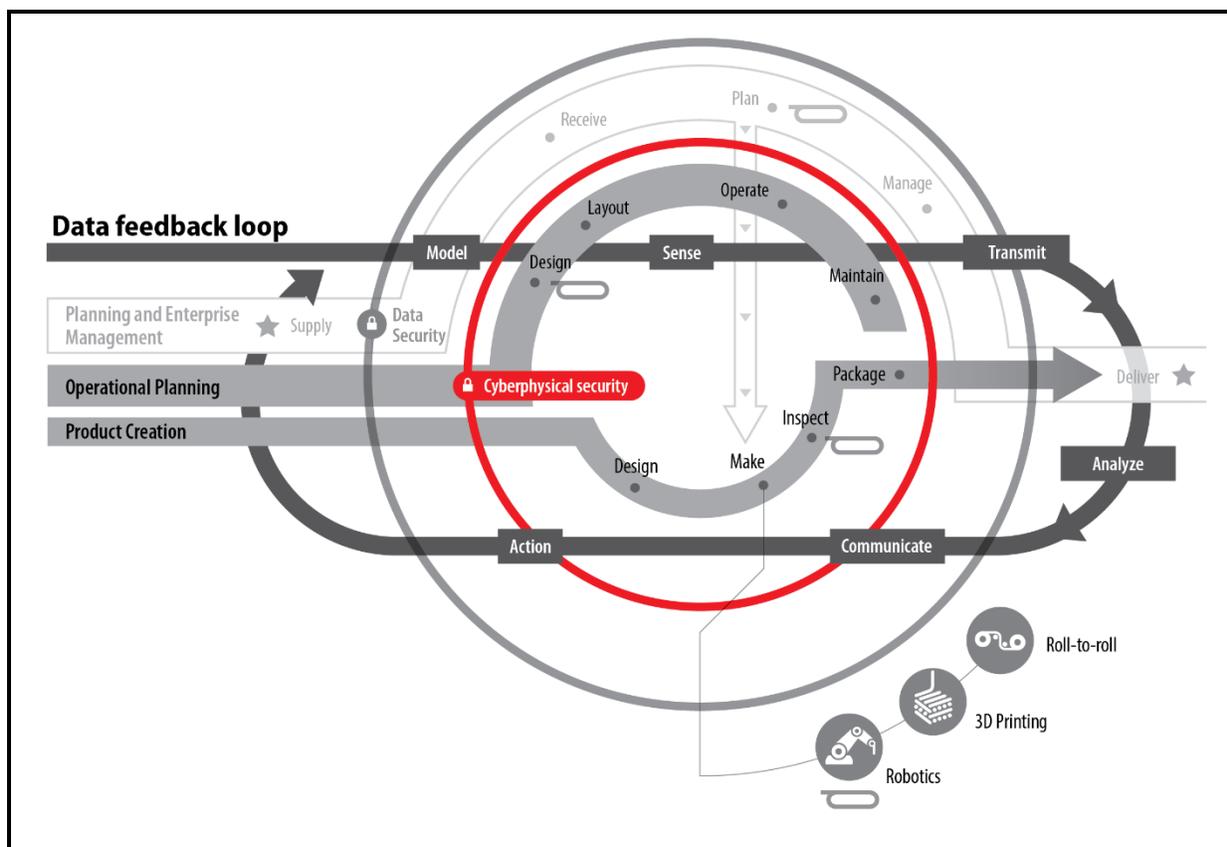
This section provides an overview of the key components of smart manufacturing processes, and discusses current shortcomings and future technology needs. These issues formed the focal point of the stakeholder interviews and set the stage for the quantitative and qualitative findings presented in the following section.

3.1 KEY COMPONENTS OF SMART MANUFACTURING PROCESSES

Smart manufacturing incorporates not only generating and capturing data, but also understanding its implications and taking action as a result of that knowledge. Figure 2-1 captures the processes included within the “smart manufacturing” area and depicts the complexity inherent within the manufacturing system.

In Figure 3-1, three levels of systems that embody smart manufacturing are represented: the enterprise management system, the operations system, and the product creation system. Each of these systems have a data feedback loop that models, senses, transmits, analyzes, communicates, and takes action on data. Smart manufacturing processes are intertwined within the overall manufacturing system, spanning multiple levels of function from product creation to process management to enterprise and supply chain interaction.

Figure 3-1. Overview of Smart Manufacturing Processes and Data Flow



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The potential benefits of smart manufacturing and the associated technology needs described by stakeholders depend on each stakeholder's unique perspective, access to resources, and position in the supply chain relative to the industries they serve. The security aspect of smart manufacturing is all encompassing and represents a significant challenge to adoption. The figure shows a circle where data security is employed, and another circle where cyber-physical security is critical to prevent hostile takeover of equipment.

In its simplest form, smart manufacturing turns data from the manufacturing process into actionable knowledge. Data are generated and input manually into a system through design and simulation, or are captured automatically through sensing environmental measures and process and equipment performance indicators. Data are extracted and communicated in a form that can be analyzed. Software algorithms and models analyze the data and produce actionable intelligence.

The intelligence is communicated to decision makers, either human or machine, and action is taken based on that intelligence.

We grouped smart manufacturing activities and associated technology infrastructure into six categories, which are used throughout the report to facilitate discussion and presentation of results:

- Managing digital data streams through models
- Sensing and monitoring
- Seamless transmission of digital data
- Advanced data and trend analysis
- Communicating information to decision makers
- Determining required action and implementing action

Table 3-1 provides an overview of the smart manufacturing capabilities and the technology infrastructure needed to support these capabilities.

3.1.1 Managing Digital Data Streams through Models

Data are generated in numerous ways within the product manufacturing environment. One way is through the creation of digital models, which are virtual representations of the real-world products and manufacturing systems. Digital models of products entering the build cycle are created using computer-aided design (CAD) tools. Material characteristics and behaviors are modeled to enable simulations of product performance through environmental conditions. The simulations provide models of physical environments, such as temperature and stress, and generate predicted performance data.

Factory floor layouts and process simulations are also digital models. High-fidelity process models are particularly data-intensive and require high-performance computing systems to manage the data calculations. Predictive models, using key performance indicators from equipment and processes, generate and manage data. Models are created for business data, such as operational cost and part lead time, as they affect the operation of the factory.

Table 3-1. Smart Manufacturing Capabilities and Technology Infrastructure Needs

Smart Manufacturing Capabilities	Technology Infrastructure Needed to Support Capabilities	Potential Benefits and Impacts of Enhanced Technology Infrastructure
<p>Managing digital data streams through models:</p> <ul style="list-style-type: none"> • CAD models including material characteristics, • simulation models of part creation and plant layout, and • rapid automated costing functions 	<p>High-fidelity process models, physical model representation for flexible objects, simplified modular applications of CAM software for less sophisticated uses, data standardization, standard and simpler equipment interfaces to facilitate consistent data entry for less-skilled workers, standard terminology for automated part costing</p>	<ul style="list-style-type: none"> • Ability to capture feature-based information in design models • Streamlined simulation of part creation • Enhanced ability to design for manufacturing • Reduced product-development-to-production cycle
<p>Enhanced sensing and monitoring:</p> <ul style="list-style-type: none"> • “state estimation” of critical manufacturing machines (e.g., vibration, acoustics, temperature, tolerances, and pressure), and • real-time monitoring of product attributes as they move through various stages of the production process 	<p>In-process measuring and monitoring for physical processes, self-powered sensors, robust sensors to withstand harsh manufacturing processes, data standardization, methods for calibrating sensing and monitoring systems</p>	<ul style="list-style-type: none"> • More efficient measurement of equipment usage such as overall equipment effectiveness • Reduced scrap • Enhanced in-process product quality • Ability to predict machine issues and intervene with preventive maintenance • Reduced unplanned downtime • Increased sensor reliability • Greater visibility and transparency in manufacturing operations
<p>Seamless transmission of digital information:</p> <ul style="list-style-type: none"> • wireless transmission of digital information without interference from other data channels, • seamless integration of smart sensors, • interoperability between different platforms such as CAD/CAM, and • secure data transmission (wired and wireless) 	<p>Secure data transmission; secure cloud computing and data sharing; standard communication protocols; retrofittable, plug-and-play data communications systems; data interoperability of 3D model parameters and product manufacturing information</p>	<ul style="list-style-type: none"> • Reduced costs in factors of production such as capital, labor, energy, and materials through the increased ability to holistically analyze data, which results in more efficient, optimized production • Energy reductions, active energy management • Reduced downtime, increased uptime • Improved security, reduced risk of IP or safety issues • Reduced integration time (commissioning, debugging, etc.) • Freeing up staff time that is currently spent on connectivity and collating data

(continued)

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Table 3-1. Smart Manufacturing Capabilities and Technology Infrastructure Needs (continued)

Smart Manufacturing Capabilities	Technology Infrastructure Needed to Support Capabilities	Potential Benefits and Impacts of Enhanced Technology Infrastructure
<p>Advances in analyzing data and trends:</p> <ul style="list-style-type: none"> • interpretation and aggregation of data from sensing and monitoring networks, • “Big Data” techniques for manufacturing, • predictive maintenance, • reduction of false positives, and • cloud computing and fee-for-service cloud-based algorithms for product design, simulation, and manufacturing design 	<p>Algorithms to interpret data from disparate sensors and systems; definition of important, relevant, and meaningful data to collect for predictive maintenance</p>	<ul style="list-style-type: none"> • Improved uptime • Enhanced monitoring of in-process quality • Reduction of false positives • Increased overall equipment effectiveness • Better utilization of existing data sources
<p>Efficiently communicating information to decision makers:</p> <ul style="list-style-type: none"> • comprehensive information interfaces, human-computer interaction-based design, and • easy-to-interpret interfaces accessible from any location 	<p>Common taxonomy across platforms and disciplines Standards in interface design for manufacturing equipment</p>	<ul style="list-style-type: none"> • Accelerated development of interfaces by the private sector • More timely, evidence-based decision making
<p>Determining required action and implementing action:</p> <ul style="list-style-type: none"> • real-time feedback of enhanced sensing and monitoring data into factory decision making, • automated optimization-based decision making that functions independently of human interaction, • machine-learning decision-making algorithms for manufacturing, and • reconfigurability of manufacturing systems 	<p>Tested and validated decision models</p>	<ul style="list-style-type: none"> • Optimized manufacturing processes • Greater visibility and transparency in real-time manufacturing operations

Capabilities Needed, Importance and Benefits

Managing digital data streams through models is key for product development and, ideally, would facilitate interoperability across CAD/CAM models and include material characteristics as part of the digital information stored and shared. These models could then be used to streamline simulation for parts creation. Plant layout simulation and rapid automated costing functions are two additional types of data modeling that were mentioned in the interviews.

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One of the challenges of smart manufacturing is the limited development of modeling systems, which leads to the need to set up pilot plants. These small plants are necessary just to make sure that the production process is safe. With the improvement of modeling systems, the very expensive pilot plant implementation should disappear.

Of value would be high-fidelity process models, physical model representation for flexible objects, and simplified modular applications of CAM software for less sophisticated uses. Simpler equipment interfaces to facilitate consistent data entry would also enhance the process and enable less skilled workers.

Simulation models of the manufacturing process and how it behaves is very important from a plant optimization standpoint. Moving forward, simulation models that use real-time data could yield significant benefits. Static or preliminary simulation of factory floor and operations is not always sufficient. There is a need for dynamic simulation as more real-time data become available.

In addition to product and manufacturing information, several respondents discussed the need for capturing more detailed information on material characteristics in design models. Similarly, feature-based designs have databases for features rather than parts.

3.1.2 Sensing and Monitoring

Data are generated not only through models, but also through the sensing and monitoring of physical elements. Temperature, pressure, and humidity of the factory environment are captured to monitor effects on production quality. Measurement of usage (power on/off, idle time, etc.) from machines and equipment captures data for overall equipment effectiveness (OEE). In-process measurement within and during equipment operation provides data that can monitor and control the outcome of the product being produced. For example, measuring temperature within a metal forging operation provides feedback such that the hammer strike can be controlled to deform a part with the correct material properties.

Beyond sensing and measurement of environmental elements, capture of communications data provides another data source within the factory. Human-machine interfaces capture data from operators on the factory floor—data such as the equipment functions they are performing, feedback on the result of those actions, and information on equipment performance. In addition, metadata associated with part build history can be captured for actionable intelligence.

Capabilities Needed, Importance and Benefits

Enhanced sensing and monitoring includes in-process measuring and monitoring for physical processes, self-powered sensors, and robust sensors to withstand harsh manufacturing processes. Overarching examples include:

- “state estimation” of critical manufacturing machines (e.g., vibration, acoustics, temperature, tolerances, and pressure), and
- real-time monitoring of product attributes as they move through various stages of the production process.

Predictive maintenance was commonly cited as an area where improved sensing (and associated data analysis) would provide significant benefits. Downtime is costly for all manufacturing processes, and minimizing downtime is a key objective. Proactive management and maintenance of machines can help to isolate where the problems are being created and minimize planned downtime. One commonly mentioned topic was related to vibration. As sensors for vibration grow more affordable, companies are more interested in using them. The real challenge is how to interpret data: Operators do not have the historical data needed to generate traditional predictive models and companies do not have the in-house expertise to develop theoretic predictive models.

Another growing area is related to tolerances and inspection. Respondents said that more work is needed in this area and that the potential benefits here could be significant. New technologies are needed to support nondestructive tests and measurements.

One specific need cited was related to monitoring humidity. Humidity has a large impact on the efficiency of machines. Currently, there is no good way of understanding humidity effects in real time. One plant, for example, had a poorly performing cooling tower. Had they been able to monitor humidity they would have recognized the problem much earlier and saved on costly repairs. Other plants have machines, pumps, and compressors where their efficiencies are sensitive to humidity. If the humidity were monitored, the company could adjust this equipment’s performance in real-time, thus maintaining the ultimate level of efficient operations.

In process plants, product quality can be greatly improved with enhanced sensing. One process engineer noted that “If you have better control systems, measurement systems, sensors, and better ways to close the loop, you will have more consistent operation and as a result will have a more consistent quality product.” This leads to fewer bad batches and higher throughput.

Currently, many sensors indirectly measure parameters like conductivity, pH, temperature, and flow rates of materials through pipes, and these indirect measures are used to make inferences about the chemical species. What is needed are new sensors that can make direct measurements of the chemical species that are present in a substance while in process (real time). For example, when changing grades in a paper plant, the process is not stopped, but slowed during the changeover, which can last 8 to 10 hours. This paper is junk grade and the fiber is recycled back into the process, which is costly. Better sensors in the plant and greater integration could shorten changeover times and reduce recycling costs.

A commonly cited problem was sensor failure. A sensor may show that something is out of spec—but is it an accurate reading, or did the sensor just fail? In a case such as this, a high level of human intervention is needed, as a senior engineer may be needed to make decisions about process modifications. The value of sensors in a case such as this is diminished. Another concern is that the life cycle of machine tools can be 15 years or more, and the life cycles of process product lines are even greater, but a sensor life cycle is typically much shorter. The durability of sensors needs to be improved to increase their cost effectiveness and reliability.

3.1.3 Seamless Transmission of Digital Data

After the data are captured, they need to be communicated to the appropriate system that can apply computing to generate actionable intelligence. In this step, communications and data protocols are important to ensure that data are transmitted in a seamless manner between software and systems.

Interoperability among CAD systems and between CAD and manufacturing systems ensures that technical data packages from CAD models are communicated appropriately.

Communication protocols, such as MTConnect and Ethernet, ensure that machinery and equipment from different

manufacturers can talk to and understand each other's data. Both wired and wireless communications occur within the factory, and must account for sending and receiving the right data packets in the right formats in synchronized and fast transmissions. Wireless communications must have technology in place to reduce interference. Data security is also a transmission issue. Encryption and other technologies are used to protect data in flight as they travel across the factory.

Location of data storage is another key aspect of the transmission process. Storage of and access to data in the cloud provides cost savings and flexibility, yet has security implications in the storage of, access to, and external transmission of data. External storage can get hacked, access to sites can be denied, and data can be captured in transmission. Security technologies are an important aspect of cloud computing for manufacturing.

Capabilities Needed, Importance and Benefits

Seamless transmission of digital information includes secure data transmission; secure cloud computing and data sharing; retrofitable, plug-and-play data communications systems; data interoperability of 3D model parameters and product manufacturing information; open systems; "information models"; next generation of STEP and MTConnect. Examples cited during the interviews include:

- seamless, real-time integration of large volumes of data from devices such as general-purpose machines and specialized machines, machine tools, smart sensors, and other instrumentation;
- interoperability between different platforms/systems/information models/software applications such as CAD/CAM, ERP, MES, and PLM that are currently "islands of information";
- machine-to-machine communication that includes more classes of machines and can be applied to older machines;
- secure data transmission throughout the facility network (wired and wireless), across the firm, and across the supply chain, including secure cloud storage and cloud computing;
- the convergence of information technology (IT) and operations technology (OT) or control networks; and

- wireless transmission of digital information without interference from other data channels.

3.1.4 Advanced Data and Trend Analysis

Once data are captured, there is a need to process and interpret the data so that the information becomes actionable. To fully realize the potential of smart manufacturing, analysis capabilities are needed to extract and express insights from large amounts of data. These insights can then be used to spur immediate action, such as addressing operational downtime issues. They can also be used for future action, such as improving operational efficiency based on causal information, or scheduling maintenance on equipment that is predicted to fail at a specified time in the future.

Condition-based maintenance is a technology that monitors and evaluates many different parameters of machinery that affect performance and maintenance. In a simple system, few parameters need to be analyzed; however, for multiple parameters affecting wear and tear on machines, models are created using pattern-recognition software that predicts success and failure by evaluating parameters such as amperage fluctuation, vibrations, reset frequency, and temperature/humidity.

To meet the intelligence needs of factory managers, research and analysis algorithms determine which performance indicators of equipment are needed to determine failure modes and which operator and process measures indicate efficiencies and issues. Models are created and applied to the appropriate data, using predictive analytics and machine learning algorithms to analyze and understand the data in a context of importance to the decision makers. Similarly, parts designers can learn and adapt their designs based on trends and functions determined by production data captured along the part build process.

Capabilities Needed, Importance and Benefits

Advances in analyzing data and trends includes the ability to interpret data from disparate sensors and systems for uses. This capability would support:

- enhanced interpretation and aggregation of data from sensing and monitoring networks;

- a better understanding of which data points are the most important and which can be disregarded, given the proliferation of data;
- “big data” mining techniques and algorithms for manufacturing, which includes more data scientists and mathematicians interested in manufacturing;
- enhanced ability to correlate upstream factors, such as material properties, with product quality;
- enhanced monitoring of in-process quality;
- reduction of false positives;
- rapid cloud/parallelized computing for complex discrete event or process models/simulations and cloud-based fee-for-service algorithms for product design, simulation, and manufacturing design; and
- new forms of computing such as edge/distributed computing.

Improved predictive maintenance was cited as the most important benefit associated with advances in data analysis. Equipment is always going to fail and when it does, it is costly. Being able to detect or forecast failure events would be extremely advantageous. In addition, monitoring a process and being able to detect when something is going off spec, off-grade, or generally in the wrong direction would allow equipment operators to make timely decisions about equipment use, but this requires real-time analysis capabilities.

From a more generic perspective, dynamic contextualization is needed—that is, a system capability to adjust the algorithm depending on the question asked. For example, “What is the best way to quickly look at the output of 100,000 variables in terms of what is important?”

3.1.5 Communicating Information to Decision Makers

Interfaces allow individuals to access and understand the information being collected efficiently in real time. Data are only useful if they are readily accessible and can be interpreted easily. Visualization of data such that meaningful information is conveyed to plant managers and operators alike helps to optimize efficiency and solve problems quickly within the factory.

Virtualized information devices are used for training and maintenance on the factory floor. Mobile devices that provide

repair instructions along with visual depictions of a model shorten the learning curve for maintenance personnel and mitigate errors in the repair procedure.

Capabilities Needed, Importance and Benefits

Efficiently communicating information to decision makers would involve:

- comprehensive information interfaces with human–computer interaction-based design,
- consistent, easy-to-interpret, real-time interfaces accessible from any location,
- interactive information interfaces with various levels of aggregation suitable to different users, and
- interfaces that can efficiently filter and sift through large amounts of information to support decision making.

Companies do not always have the ability to bring domain-specific problems occurring in a plant quickly to the attention of domain experts. Benefits from more traditional human–machine interaction (HMI) could be enhanced by making the interaction more intuitive.

Simpler and more consistent interface structures for operators would generate value. There is a need for consistency across the industry and within companies' interfaces to accommodate workforce transformation around smart manufacturing, the increased level of automation, and the increasingly varied level of employee capabilities. One respondent suggested leveraging research from pilot cockpit and air traffic control systems/studies.

Another area where improvement is needed is in communication between manufacturing operators and the design community. Feedback from the manufacturing process through the supply chain should be much greater. Manufacturers' ability to influence the design specifications of new products would reduce the "guesswork" and the uncertainty associated with new product development and certification.

3.1.6 Determining Required Action and Implementing Action

Data are generated and gathered, analyzed, and communicated to decision makers who can take action. Manufacturing execution systems (MES), enterprise resource planning (ERP),

product lifecycle management (PLM), and supervisory control and data acquisition systems (SCADA) all provide intelligence and enable decision makers to act. However, too much information can overwhelm systems operators; information overload can be mitigated by using specially adapted machine learning algorithms that detect responses to information and provide guidance on only the most important information.

Machine learning also enables automated actions, taking the human out of the loop. For example, a learning system on a welder using sensors to detect mistakes can self-adjust to prevent future errors. This self-optimization system determines the required action from data detected from sensors and analyzed to provide intelligence, then implements the action. To truly achieve the full potential of smart manufacturing techniques in optimizing manufacturing processes, improvements in artificial intelligence are needed.

Capabilities Needed, Importance and Benefits

Determining required action and implementing action would enable real-time feedback of enhanced sensing and monitoring data into factory decision making through advanced control.

Desired capabilities cited include:

- automated optimization-based decision making that functions independent of human interaction, including machine-to-machine communication and decision making,
- machine learning decision-making algorithms for manufacturing such as adaptive tool planning,
- reconfigurability and flexibility of manufacturing systems, and
- computational horsepower to deal with large amounts of data and complex systems.

Supporting tools would include physics-based models, virtual models, and discrete event models for the plant floor that will help make decisions faster. One end user stated that “In many instances, decisions could be made in half the time of our factory, which would lead to significant cost reductions.” Currently, some discrete event models take days to produce and analyze results. Cloud computing has the potential to shorten analysis time, but large companies are not comfortable exposing their data outside internal firewalls.

Modifying/segmenting the data structure is a potential solution for protecting IP in a secure environment.

Another challenge facing manufacturers is the limited development of modeling systems, which leads to the need to set up pilot plants. These small plants are necessary just to make sure that the production process is safe. With the improvement of modeling systems, the need for the very expensive pilot plant implementation should disappear.

Decisions about replacement could be easier in a smart manufacturing environment. Maintenance and machine throughput will be more visible, and the decision on ROI will be much easier when evaluating continued operation versus reinvestment. Companies need to be aware of all the costs associated with continued operation of older machines.

3.2 STAKEHOLDERS

Stakeholders included in the study were grouped into three major categories: smart manufacturing product developers and service providers, end users, and observers, described in detail below.

3.2.1 Smart Manufacturing Product Developers and Service Providers

Product developers and service providers (referred to as developers) are those companies that make products to enable smart manufacturing processes and provide the services for installation/integration. Developers encounter barriers to implementation of their technologies on a regular basis as they seek to sell their products to manufacturers. Developers include the following categories of vendors and providers.

- **Consultants and Service Providers:** These companies provide services such as engineering design; design for manufacturing; process engineering; modeling; simulation; and analysis, prototyping, and machine tool and robotic programming. These service providers are hired by both large and small companies to fill capability gaps in these organizations. They are hired to implement new technology in factory settings, and in doing so they are exposed to the issues faced by their customers.
- **Design, process, and automation software suppliers:** These suppliers support product design and

simulation and offer traditional CAD/CAM systems. This group also includes companies that focus on the integration of product design and product simulation systems and process modeling systems.

- **Network infrastructure and information systems providers:** This category includes companies that provide the systems-level software to support the management and operations of the factory and supply chain. This software includes infrastructure involved in cloud-based computing, network support, sensor communication, and software interfaces.
- **Equipment and hardware manufacturers:** This group includes suppliers that make the machine tools and equipment that support the build of the product. CNC machines, punch presses, material handling equipment, coordinate measurement machines, and programmable logic controllers are a few examples of the hardware made by these manufacturers.

3.2.2 Smart Manufacturing End Users

End users are companies that are the customers of the developers' products and services. They have much to say about why they adopted specific technologies, the ongoing issues they have with those technologies, and the factors preventing them from implementing other technologies. In addition to seeking the perspectives of large manufacturers, which generally have both the financial and human resources to implement new technology, we sought the perspective of small manufacturers, which are often unaware of new technologies or do not have the in-house capabilities to implement them. End users are described below.

- **Large manufacturers:** This group includes both large product and process manufacturers typically focusing on high-value, customized products as well as continuous process operations, where network systems and data can lead to large efficiency gains in areas such as electricity and heat use.
- **Small and medium enterprises (SMEs):** These companies primarily form the multiple-tiered supply chain for the industries, but also include a growing number of companies generating final products with new advanced manufacturing techniques.

Within the end-user group, manufacturers are segmented into two broad groups: (1) discrete parts and assembly manufacturers and (2) batch and continuous process

manufacturers. Table 1-1 (see Section 1.3) provides a list of major industry sectors included in each group.

- **Discrete parts and assembly manufacturers** include traditional assembly sectors such as the automotive and aerospace industries along with their supply chain of fabricated metal, electronic, plastic, and component parts. Discrete parts manufacturers also include appliances, furniture, and other factory-floor industries. Technology infrastructure needs for discrete manufacturers focus on the life cycle of products or parts, which includes product design, prototype development, testing, scale-up, and production. The exchange of electronic data throughout the value chain is key to increasing efficiency in both product design and manufacturing projects.
- **Batch and continuous process manufacturers** focus on the life cycle of the process. They work toward optimizing the life cycle to increase energy efficiency and minimize product waste/process failures (“bad batches”). Historically, many process manufacturers have been more vertically integrated than discrete parts manufacturers, which would have multiple-tiered supply chains. As a result, for process manufacturers, technology needs focus less on supply chain interoperability issues. However, as globalization increases, some aspects of the process sector are becoming increasingly specialized, leading to more subcontracting and increasing the need for better communication across companies.

3.2.3 Smart Manufacturing Observers

Observers represent those working in the field but that have a broader perspective beyond the day-to-day operations of a specific company. Organizations in the observer category are people working in consortia, universities, and federal laboratories who are focused on solving problems and developing new smart manufacturing technologies. Observers interface with many people in the industry and are often working to solve the industry's problems. They have a more global view and see the landscape of issues and opportunities.

A few of the most relevant consortia for smart manufacturing are described below.

- **Smart Manufacturing Leadership Coalition (SMLC)**, located at the University of California at Los Angeles. With 37 university, federal, and industry members, the

SMLC is “committed to overcome barriers to the development and deployment of Smart Manufacturing (SM) Systems through an implementation agenda for building a scaled, shared infrastructure called the Smart Manufacturing Platform” (Smart Manufacturing Leadership Coalition, 2014).

- **Digital Manufacturing and Design Institute (DMDI)**, located in Chicago, Illinois. The DMDI will focus on the life cycle of digital data interchanged among design, engineering, manufacturing, and maintenance systems and across supply chain networks. Its members comprise leading players in the field, with 41 companies, 23 universities, and 9 supporting organizations.
- **Industrial Internet Consortium (IIC)**, located in Needham, Massachusetts. The IIC was founded in 2014 by AT&T, Cisco, General Electric, IBM, and Intel. It was formed to accelerate the development and adoption of interconnected machines and devices. The IIC is now an open-membership organization that coordinates the priorities and enabling technologies of the Industrial Internet.
- **Internet of Things Consortium (IoTC)**, located headquartered in San Francisco, California, with business development offices in New York City. IoTC members include hardware, software, and analytics companies across a variety of sectors including automation and virtual reality. The IoTC educates stakeholders about the value of IoT and supports the growth of the IoT marketplace.
- **Manufacturing Enterprise Solutions Association (MESA) International**, located in Chandler, Arizona. MESA International is a global organization of manufacturers, IT hardware and software suppliers, system integrators, and consultants. Member companies cover the range of operations from discrete to process. MESA strives to help manufacturers achieve real-time visibility into the production process and through the optimized implementation of IT and other management best practices.
- **Control System Integrators Association (CSIA)**. CSIA’s mission is to advance the industry of control system integration so that industries everywhere have access to safe and successful applications of automation technology.

3.3 TRENDS THAT WILL INFLUENCE SMART MANUFACTURING

Several megatrends are shaping the future of smart manufacturing.

3.3.1 Connected Factories

Connected factories provide decision makers greater visibility into real-time information about production, inventories, and workers which allows for greater optimization of existing resources and better planning for the future.

GE, Cisco, and other multinational companies are developing and deploying industrial internet technologies. Industry experts have envisioned a factory operating platform and an online marketplace for industrial apps.

As more and more devices and machines are built and retrofitted with internet connectivity, it will become increasingly economically advantageous for factories to invest in more robust communications networks. These machines and devices will not only capture and stream data that can be used in higher level analyses, but they will also communicate directly with other machines and respond autonomously to incoming data streams.

3.3.2 Big Data Storage and Analytics

As factories become more connected and sensors more prevalent, manufacturers will need to efficiently collate large amounts of digital information and to apply more complex data analysis techniques such as machine learning and data mining in addition to more established analysis techniques.

Sensors are moving from discrete output to continuous output, which ultimately provides more value but in the short term is a challenge for manufacturers as they try to determine the appropriate frequency with which to store and analyze sensor data. Additionally, there will be other data streams feeding in from the supply chain, machines, and workers that will need to be managed and used to optimize production systems.

Cloud computing is an enabling technology that could make big data storage and analytics more accessible for SMEs. To take advantage of big data analytics, manufacturers will not necessarily have to purchase and maintain their own data storage and data processing equipment. Instead,

manufacturers can rent it on an as needed basis from cloud service providers. Although there are potentially large economic benefits associated with cloud computing, perceived risks about data security and IP protection may inhibit its use.

3.3.3 Demand-Driven Supply Chain Optimization

Enabled by improvements cloud-based processing speeds and the digitization of supply chain information, demand driven supply chain optimization is becoming more of a possibility. Using real-time information about downstream changes in the supply chain, supply chain partners can better adapt to unexpected changes in demand. This can yield benefits such as reducing inventory, improving forecasting, reducing transportation costs, and improving customer satisfaction.¹⁰ While supply chain optimization is beyond the scope of our study, it is nonetheless an important overarching trend that will shape smart manufacturing within the factory walls.

Distributed manufacturing, perhaps a more futuristic trend, related to demand driven supply chain optimization. Distributed manufacturing, also referred to as the localization of production, describes a manufacturing paradigm in which raw materials and production processes are decentralized and final products are manufactured very close to the end customer.¹¹ Distributed manufacturing will require large amounts of computing power and advanced optimization techniques that do not currently exist today.

Additive manufacturing could be a potential enabler of distributed manufacturing, although only certain types of products can currently be manufactured using additive methods.¹² Proponents of distributed manufacturing approaches believe that it may yield less waste compared with more centralized production, however raw materials like plastics and metals will still need to be transported across the world in order for distributing manufacturing to take place. Furthermore, the economics of distributed manufacturing may only work for certain kinds of products.

¹⁰ <http://www.bcg.com/documents/file106861.pdf>

¹¹ <http://www.weforum.org/agenda/2015/03/emerging-tech-2015-distributed-manufacturing/>

¹² See the NIST companion study on additive manufacturing for additional discussion.

3.3.4 Increasing Awareness of and Interest in Smart Manufacturing

The prevalence of industry consortia that are starting to coalesce around smart manufacturing issues indicates that there is increasing private sector awareness of and interest in smart manufacturing around the world. Government-funded initiatives such as the SMLC and DMDI in the United States and Industry 4.0 initiatives in Europe show that the public sector is also playing an active role in supporting the development and adoption of smart manufacturing technologies.

3.3.5 Other Disruptive Manufacturing Technologies

Advanced robotics technology and additive manufacturing technology are expected to be disruptive for manufacturing.¹³ As these technologies gain widespread adoption, manufacturers will need to consider how to more effectively leverage these technologies within a smart manufacturing approach.

3.4 NEED FOR ADDITIONAL DEVELOPMENT OF TECHNOLOGY INFRASTRUCTURE TO SUPPORT SMART MANUFACTURING

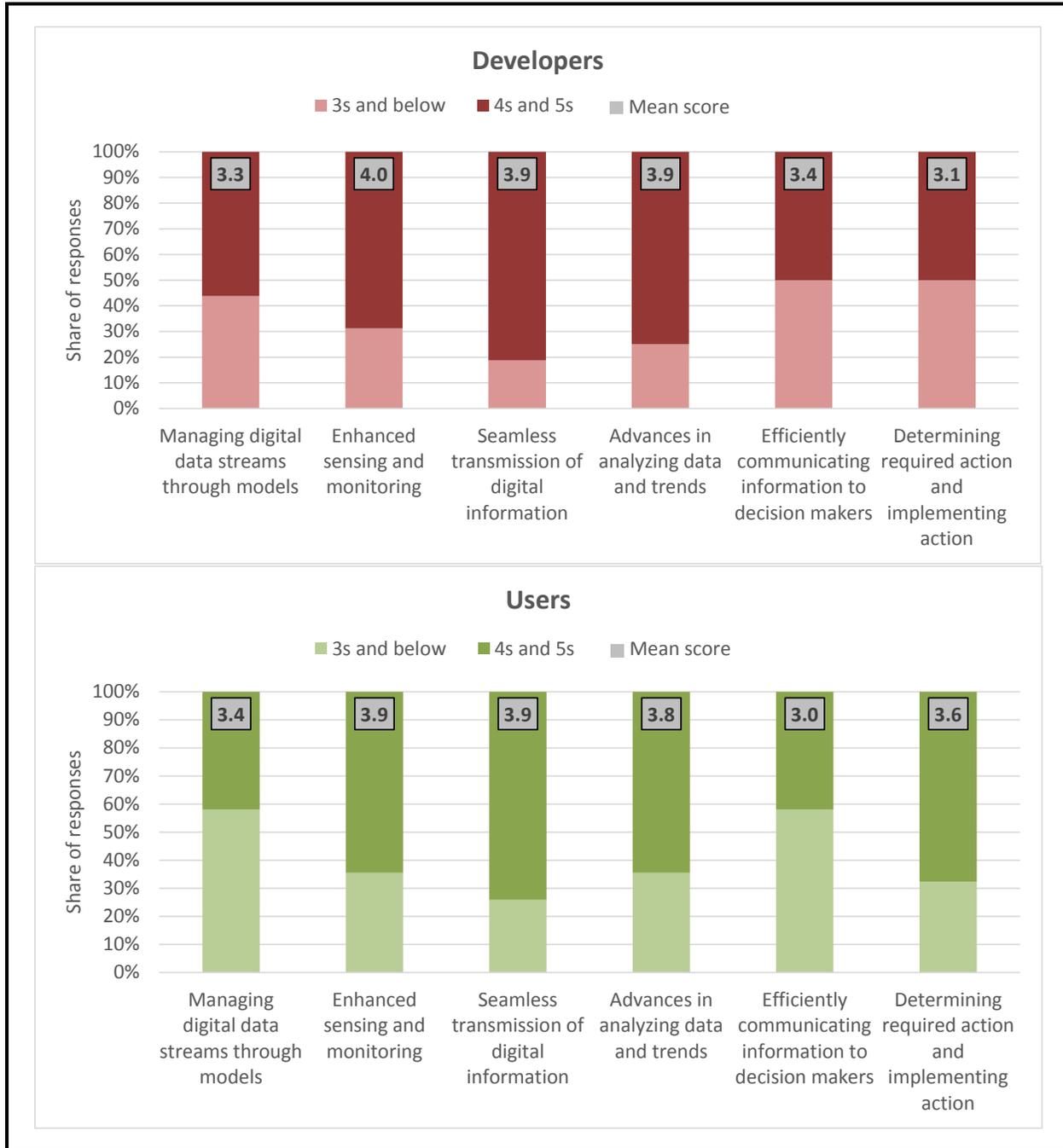
This section discusses the relative importance of smart manufacturing capabilities and identifies the areas where additional development is needed in the six smart manufacturing capability areas outlined in Section 2. Section 5 through Section 10 focus individually on the six capability areas, providing greater detail on specific technical needs, market barriers to their development, and roles for NIST. Appendix C includes two vignettes that provide examples of specific needs and opportunities.

3.4.1 Relative Importance of Capabilities

Respondents were asked a series of questions to elicit their opinion on the most important capabilities related to the use of smart manufacturing technologies and processes. They ranked the capabilities groupings on a scale of importance of 1 to 5, with 5 being most important. Figure 3-2 shows the scoring for all respondents and for developers and users separately.

¹³ See the NIST companion study on robotics for additional discussion.

Figure 3-2. Average Importance of Each Smart Manufacturing Capability, by Type of Respondent



This publication is available free of charge from: <http://dx.doi.org/10.6028/NIST.GCR.16-007>

Interviewees said that enhanced sensing capabilities are needed but will only add value if they are accompanied by cost-effective and secure transmission of the information. Similarly, the growth and availability of real-time digital information on manufacturing activities is only as valuable as the ability to analyze the information. Thus, in many ways the value of smart manufacturing systems is a function of the weakest link in the chain.

Respondents scored all of the categories as important (as judged by an average above 3.0), with the highest scores given to sensing and monitoring and seamless transmission of digital information. The next highest scored was the need for advances in capabilities to analyze data and trends.

Responses were relatively similar across developers and users—with the exception that developers focused more on the importance of communicating information to decision makers, and users focused more on how to use the information to generate implementable actions.

The relatively high scores for importance across all of the capability areas supporting smart manufacturing highlight how interdependent the different functionalities are across the spectrum of smart manufacturing activities. Interviewees said that enhanced sensing capabilities are needed but will only add value if they are accompanied by cost-effective and secure transmission of the information. Similarly, the growth and availability of real-time digital information on manufacturing activities is only as valuable as the ability to analyze the information. Thus, in many ways the value of smart manufacturing systems is a function of the weakest link in the chain.

3.4.2 Barriers to the Adoption of Smart Manufacturing Technology

Respondents were asked to identify the barriers to adopting smart manufacturing and realizing the full benefits of the capabilities described in this section. The barriers named were associated with adopting existing smart manufacturing technologies as well as implementing the necessary enhancements in the technology infrastructure to make smart manufacturing technologies more viable, functional, and cost effective in the future.

Table 3-2 provides the categories of barriers most frequently identified during the interviews. Frequency of response is provided for all interviews as a single group, as well as separately for developers and users. Users are further broken out into discrete and process manufacturers.

Financial issues were the most commonly cited barrier to adoption of smart manufacturing technologies and processes. One end user stated that financial returns are paramount

unless his firm is forced by regulations or customer specifications to adopt new technologies. In general, users cited low ROI—in part driven by cost issues associated with legacy systems, vendor lock in, and age of plants—as the greatest barrier to adoption.

A direct challenge to ROI expressed by one chemical process manufacturer was that “benefits have to be continuously greater than maintenance costs, and [smart manufacturing] instruments consume resources for supporting and maintaining.” In other cases, while adequate ROI may be feasible, users mentioned that uncertainty about new technologies makes it difficult to understand and justify ROI, and this aversion to uncertainty acts as a barrier to adoption. A small machine tool company suggested that other SMEs may find it hard to justify investment in smart manufacturing technologies unless their companies are confident that they will be manufacturing a significant amount of repeat products in the future.

Table 3-2. Percent of Sample Citing Each Barrier to Adoption, by Type of Respondent

Barrier	Percent				
	All	Developers	Users	Users – Discrete	Users – Process
ROI, lack of financial resources (low margins)	46	30	59	60	60
Legacy systems, vendor lock in, age of plants	33	17	45	40	53
Lack of technical resources and knowledge	31	22	38	40	33
Small business, size of plant	27	30	24	13	33
Cultural and organizational barriers	27	43	14	13	20
Uncertainty, risk	19	17	21	27	13
Technical issues	15	9	21	33	7
Data security (malicious and IP issues)	15	13	17	20	13
Long machine-plant lifetimes, cost of retrofit	13	9	17	7	27
Logistical, downtime, “hassle” factors	12	4	17	20	13

Standards issues	8	9	7	7	7
Regulation	8	13	3	0	7
Market structure, market issues	6	0	10	20	0
Safety	4	4	3	0	7
Future growth industries and applications	4	9	0	0	0
Lack of government support	2	4	0	0	0
Product mix	2	0	3	7	0

Concerns about financial issues were followed by a lack of technical resources and knowledgeable staff needed for implementation. One process manufacturer noted, “I spend so much of my time in upkeep, migrating and supporting systems. There is really no allotment of my time to how can we look for technology that might be a step-change improvement.” Other users pointed out that personnel with specialized knowledge are scarce because of the aging/retiring workforce and the lack of multidisciplinary engineering programs. For smaller manufacturers in particular, the lack of technical resources and knowledgeable staff appears to be a major barrier.

Top barriers cited were relatively consistent across discrete parts and process manufacturers, with legacy systems and age of plants being more of a barrier to adoption in the process industries.

In contrast, developers did not see financial and legacy issues as significant barriers; they had a more optimistic view of their products’ cost effectiveness and ease of adoption. Developers commonly cited cultural and organizational barriers to adopting new technologies and processes—more specifically, internal company politics, inertia of older workers and their resistance to change, and a hesitancy to invest in technology that may supplant some types of jobs.

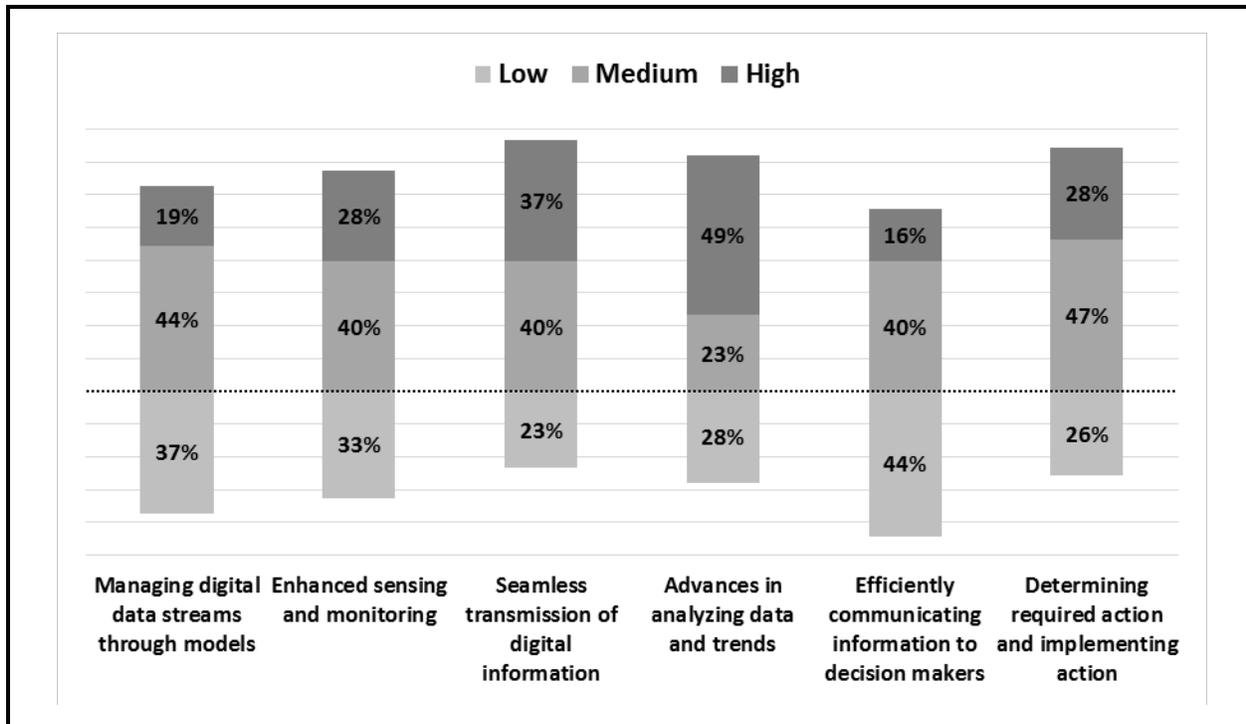
Specific examples of barriers limiting adoption, as well as the underlying market failures, are provided in the following sections discussing the individual capability areas.

3.4.3 Need for Additional Technology Infrastructure Development

To identify potential areas where NIST could effectively collaborate with and complement industry, interviewees were asked to characterize the level of additional development needed for each of the six smart manufacturing capability areas and corresponding infrastructure technologies. Interviewees were asked to classify each capability according to a scale of “low,” “medium,” or “high” level of additional development needed. Figure 3-3 summarizes the responses to the level of additional development needed, by capability.

As shown in the figure, advances in analyzing data and trends was characterized by 49% of interviewees as needing a *high* level of additional development. Next, 37% of interviewees rated seamless transmission of digital information as needing a *high* level of additional development. Relative to the other needs, the least important need for further development was communicating information to decision makers—only 16% of interviewees gave it a *high* rating.

Figure 3-3. Level of Additional Technology Infrastructure Development Needed for Smart Manufacturing Capabilities



Note: All columns sum to 100%.

Developers placed the highest need for additional development on seamless transmission of digital information, whereas end users placed the highest need on advances in analyzing data and trends.

Another way to consider these responses is by adding together the *medium* and *high* levels of additional development, thus excluding any *low* ratings for additional development needed. When considering the data in this manner, the majority of interviewees stated that each capability required a *medium* or *high* level of additional development.

The perceived level of additional development varies based on position in the value chain. Table 3-3 focuses on the percentage of interviewees who characterized each capability as needing a *high* level of additional development, broken out by technology developer perspective and end-user perspective. End-user responses are further segmented into process manufacturers versus discrete parts manufacturers.

Developers placed the highest need for additional development on seamless transmission of digital information, whereas end users placed the highest need on advances in analyzing data and trends. In general, developers struggle to get their equipment to talk with other developers' equipment, and this consumes much of their focus. Developers' customers, the end users, also want seamless communications, but are more concerned with better data analytics to obtain greater value from their smart manufacturing investment.

Process manufacturers and discrete manufacturers tended to agree in general; however, discrete manufacturers cited a

Table 3-3. Percentage *High* Level of Additional Development Needed, Developers versus End Users

Interviewee Type	Percent, %					
	Managing Digital Data Streams through Models	Enhanced Sensing and Monitoring	Seamless Transmission of Digital Information	Advances in Analyzing Data and Trends	Efficiently Communicating Information to Decision Makers	Determining Required Action and Implementing Action
Developers	6	25	44	38	13	25
End users	26	30	33	56	19	30
Process	8	38	31	62	15	23
Discrete	40	27	33	53	20	33
Overall	19	28	37	49	16	28

much higher level of development needed for managing digital data streams through models. This reflects the fact that process manufacturers do not operationalize product information in the same way that discrete parts manufacturers do. Specifically, the 3D modeling and parts focus of this capability was less relevant for process industries. Simulation models of plant layouts seemed to be more relevant to process manufacturers. One industrial gas process manufacturer simply stated that “CAD models are not resonating with me.” However, a building materials process manufacturer expanded, “This is not as relevant as it would be to a discrete industry ... this is less important for process industries. However, simulation models of the manufacturing process and how it behaves is very important from a plant optimization standpoint.”

4

Economic Impacts

Total economic impacts associated with meeting technology infrastructure needs for smart manufacturing are estimated to be \$57.4 billion. This represents, on average, a 3.2% reduction in the shop floor cost of production. Note that benefits of adopting smart manufacturing processes, in general and not just for those tied to technology infrastructure gaps, would provide even more economic value for the economy.

Section 4 describes how impacts were calculated. It also includes a discussion of the relative importance of smart manufacturing capability, barriers to adoption, and areas where additional technology infrastructure development is needed. Later sections explore key areas of need in greater detail.

4.1 FIRM-LEVEL END-USER IMPACTS

During the interviews, respondents were asked to estimate the percent change in inputs (capital, labor, energy, and materials, referred to as KLEM) and the effects on outcomes (throughput, utilization, and product quality) resulting from the potential adoption of improved smart manufacturing technologies and processes.

These impacts were said to be a result of greater ability to holistically analyze data, which leads to more efficient, optimized production. Examples of benefits included:

- freeing up staff time that is currently spent on connectivity and collating data together;
- reduction in energy use through active energy management;
- reduced downtime and increased uptime, resulting in increased throughput and productivity;
- improved security, reduced risk of IP or safety issues; and

- reduced integration time (commissioning, debugging, etc.).

4.1.1 Estimates of Average Impact by Factors of Production (KLEM)

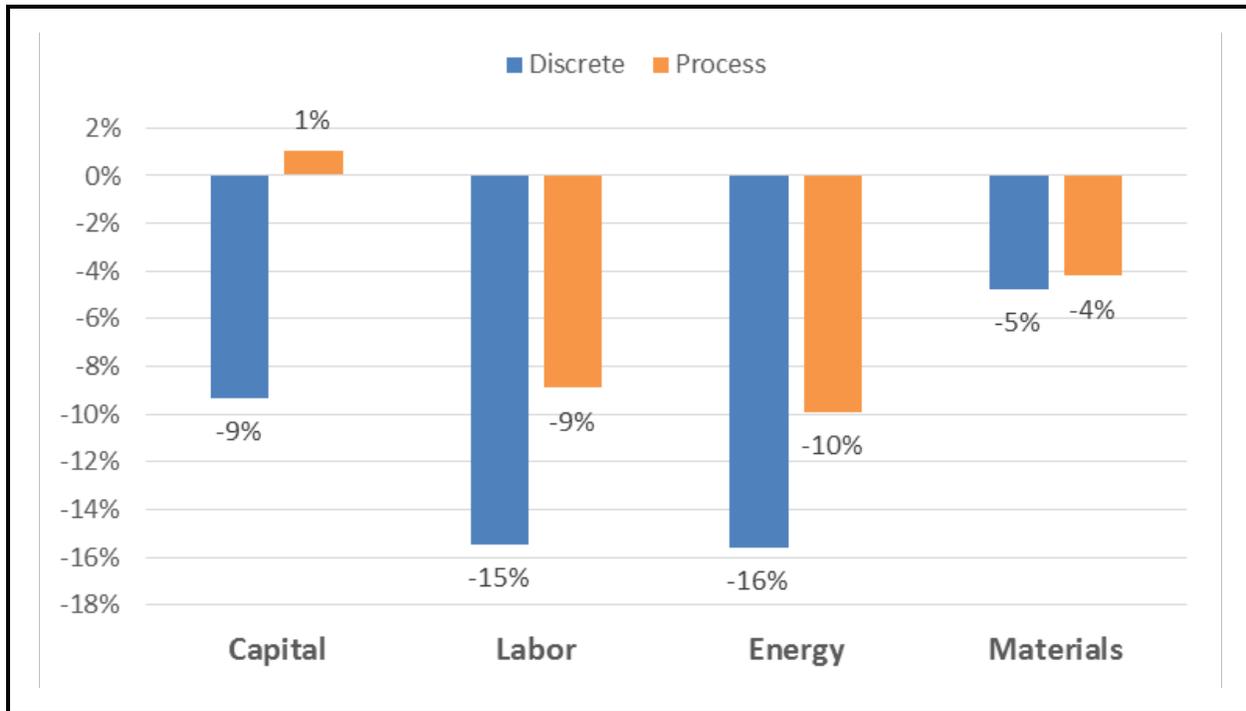
Table 4-1 shows the average percent change in factor inputs provided by respondents. All users indicated that the greatest potential for cost savings would be in labor (at 12%) and energy (at 13%). Capital and materials potential savings were estimated at up to 5% each. Note that the percent change in capital costs reflects net capital expenditures, which include both additional capital expenditures to implement smart manufacturing and capital savings due increased capital utilization and life expectancy.

Figure 4-1 shows percent changes in factor inputs for discrete and process manufacturers. The results indicate that, compared with process industries, discrete industries have the potential for greater percent change impacts, likely because process industries tend to be more mature, with older facilities and longer equipment life expectancies. In addition, process industries typically have less flexibility in making modifications because of the rigid nature of their systems. Note that the average change in capital expenditures was shown to increase slightly for process industries, reflecting legacy issues from adopting smart manufacturing technologies.

Table 4-1. Average Percent Change in Factor Inputs

Factor Input	Mean Impact
K: Capital	-5%
L: Labor	-12%
E: Energy	-13%
M: Materials	-5%

Figure 4-1. Average Percent Change in Factor Inputs: Discrete versus Process Industries



4.1.2 Distribution of Impacts across Respondents

Figure 4-2 shows the responses from the interviews broken out by each factor of production. Furthermore, each bar is color-coded based on whether the response came from a discrete manufacturer (blue) or a process manufacturer (orange). Whereas the y-axis varies across the panel of graphs, one can quickly glean these points: although labor, energy, and materials are unambiguously unchanged or reduced due to enhanced smart manufacturing technology infrastructure, the impact on capital is more varied, with some users—both process and discrete—citing net capital cost increases due to increased adoption of smart manufacturing technology.

4.2 NATIONAL-LEVEL END-USER IMPACTS

Average percent change impacts for discrete parts and process manufacturers were then applied to national factor expenditures (KLEM) to calculate potential national-level impacts.

Respondents were asked about the share of their industry to which the smart manufacturing benefits they described are applicable. As shown in Table 4-2, respondents view smart manufacturing as applicable for the majority of firms in their industry.

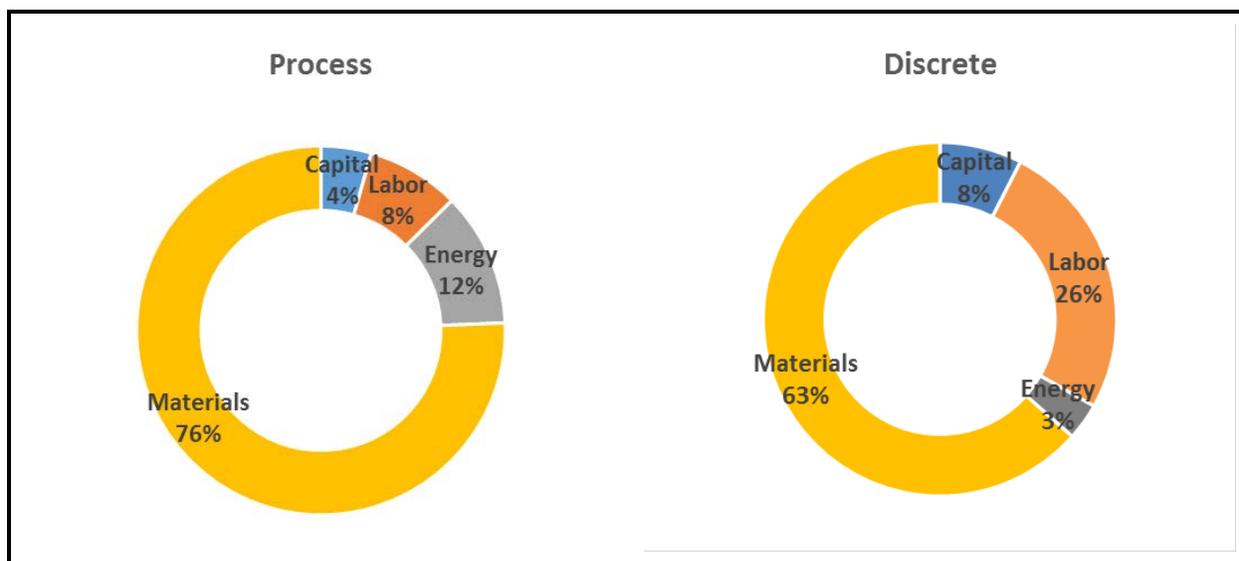
4.2.1 National Expenditures on Factors of Production (KLEM)

Figure 4-4 shows the distribution of national factor expenditures by factor of production for process and discrete industries. Materials make up the majority of national factor expenditures for process and discrete industries, with 76% and 63% of total expenditures, respectively. Compared with discrete industries, process industries require more than three times the energy as a percentage of total factor expenditures costs. On the other hand, at 26%, labor is also a substantial cost component. Capital costs are important to both process and discrete industries; however, they will make up a much smaller percentage of the total costs. Using the discrete parts industries as an example, 1% cost savings for material will have a much larger absolute dollar impact than a 1% cost savings for capital or labor.

Table 4-2. Industry Applicability Factor

Measure	Discrete Parts Manufacturers	Process Manufacturers	All Users
	Mean Impact	Mean Impact	Mean Impact
Industry Applicability Factor	93%	95%	94%

Figure 4-4. KLEM Share of Cost Basis for Process and Discrete Industries



Note: Only national accounts related to manufacturing activities were used in the analysis.

4.2.2 National Impact Estimates by KLEM

National impact estimates are calculated at the four-digit NAICS level. Industries included are listed in Table 2-1. Industry-level percent changes are applied to KLEM expenditures for each industry to calculate national impact estimates.

Following the procedures outlined in Section 3, we scaled out firm-level impacts to the national-level using a series of informed assumptions about how the responses in our sample mapped to U.S. industries. Table 4-3 illustrates our calculations with a stylized example for a particular NAICS code. These same calculations were carried out for the NAICS codes in our sample. The estimates for each NAICS code derived in Step #5 in Table 4-3 were then summed together to obtain estimates of national economic impacts.

Table 4-4 provides impact estimates aggregated to process industries and discrete parts industries.

Table 4-3. Stylized Example of Scaling Sample Impacts to the National Level, End User

Step	Description	Figures and Calculation(s)
Step #1—Begin with KLEM percentage impact responses.	Percentage changes in KLEM factor inputs are recorded during the interview.	K: +25% L: -10% E: +10% M: -5%
Step #2—Calculate applicability-weighted cost impacts.	Multiply the industry applicability factor from the interview with the percentage changes in KLEM factor inputs to derive the applicability-weighted cost impacts.	Applicability factor = 50% K: +25% x 50% = +12.5% L: -10% x 50% = -5% E: +10% x 50% = +5% M: -5% x 50% = -2.5%
Step #3—Assign an industry code and average responses from the sample.	Assign a 3- or 4-digit NAICS code based on the interviewee's company and average the applicability-weighted cost impacts from Step #2 with other responses from the sample that are categorized with the same NAICS code, if applicable.	The NAICS code that best describes this interviewee's company is NAICS 3329 Other fabricated metal product manufacturing. No other responses in the sample have the same NAICS code, so the average responses are simply the figures from Step #2. K: +12.5% L: -5% E: +5% M: -2.5%
Step #4—Estimate KLEM expenditures for the industry.	Using ASM and BLS data on KLEM-to-sales ratios, estimate the KLEM expenditures for the 3- or 4-digit NAICS code. Sum the individual KLEM expenditures to estimate the total national factor expenditure for the NAICS code.	2013 Industry Sales from ASM = \$75.4 billion K: 2.8% x \$75.4 billion = \$2.1 billion L: 13.3% x \$75.4 billion = \$10.0 billion E: 1.7% x \$75.4 billion = \$1.3 billion M: 31.1% x \$75.4 billion = \$23.5 billion Total KLEM national factor expenditure = \$36.9 billion
Step #5—Calculate KLEM expenditure impacts and composite cost impact on national factor expenditures.	Calculate KLEM expenditure impacts using average percentage impacts from Step #3 and KLEM expenditures from Step #4. Sum together each KLEM expenditure impact from Step #5 to estimate the composite cost impact.	K: +12.5% x \$2.1 billion = +\$265 million L: -5% x \$10.0 billion = -\$502 million E: +5% x \$1.3 billion = +\$63 million M: -2.5% x \$23.5 billion = -\$586 million Composite cost impact = -\$760 million
Step #6—Calculate composite cost impact in percentage terms.	Divide the composite cost impact from Step #5 by the total national factor expenditure from Step #4.	Percentage composite cost impact = -\$760 million/\$36.9 billion = -2.1%

Table 4-4. Annual Economic Impact Summary, Process versus Discrete

Type of Industry	Industry Data, 2013		Cost Impacts, \$ Billions					Percentage Savings in Shop Floor Production Costs
	Sales, \$ Billions	KLEM National Factor Expenditure, \$ Billions	K	L	E	M	Total	
Process	2,423.3	1,281.1	-1.1	-4.9	-3.9	-16.7	-26.6	-2.1%
Discrete	1,320.5	537.0	-5.1	-17.2	-1.8	-6.7	-30.8	-5.7%
Total	3,743.9	1,818.1	-6.2	-22.1	-5.7	-23.5	-57.4	-3.2%

Note that KLEM expenditures used in the analysis represent approximately one-third of the industry sales, reflecting that smart manufacturing technologies and processes are applicable for only a portion of the manufacturing sector activities.

Total Annual economic impacts associated with smart manufacturing are estimated to be approximately \$57.4 billion, and will accrue for many years. This represents, on average, approximately 3.2% reduction in the shop floor cost of production. Discrete parts manufacturing accounts for \$30.8 billion and process manufacturing \$26.6 billion. Discrete parts industries had larger potential impacts, although process industries represented a larger share of the manufacturing sector.¹⁴

Figure 4-5 shows cost savings for each factor of production, by discrete parts and process manufacturers, and Figure 4-6 the relative distributions. The largest impact was associated with labor savings in discrete manufacturing sectors. In the process industries, the greatest savings was in materials (feedstock), followed by energy and labor.

¹⁴ End users were also asked about the impact that smart manufacturing capabilities and associated technology infrastructure would have on their sales. Most interviewees were not able to draw an inference between the capabilities and increases in their sales so we did not attempt to quantify a sales impact.

Figure 4-5. Annual Cost Savings by Factors of Production (millions of USD) for Process and Discrete Industries

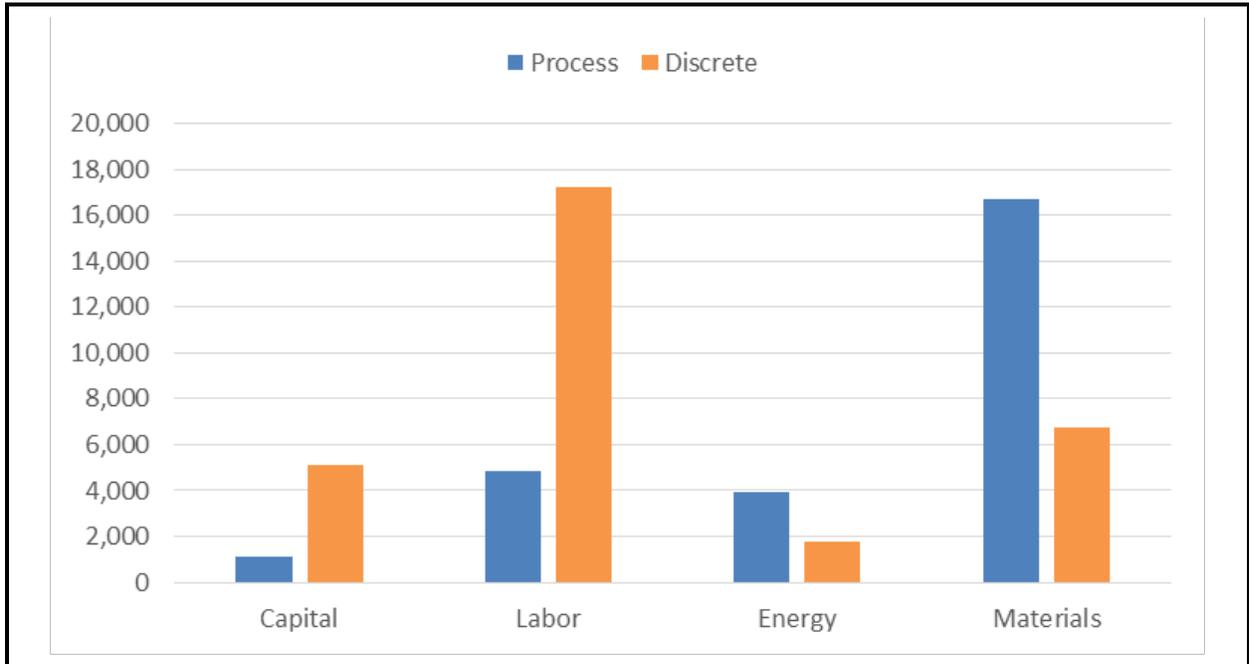
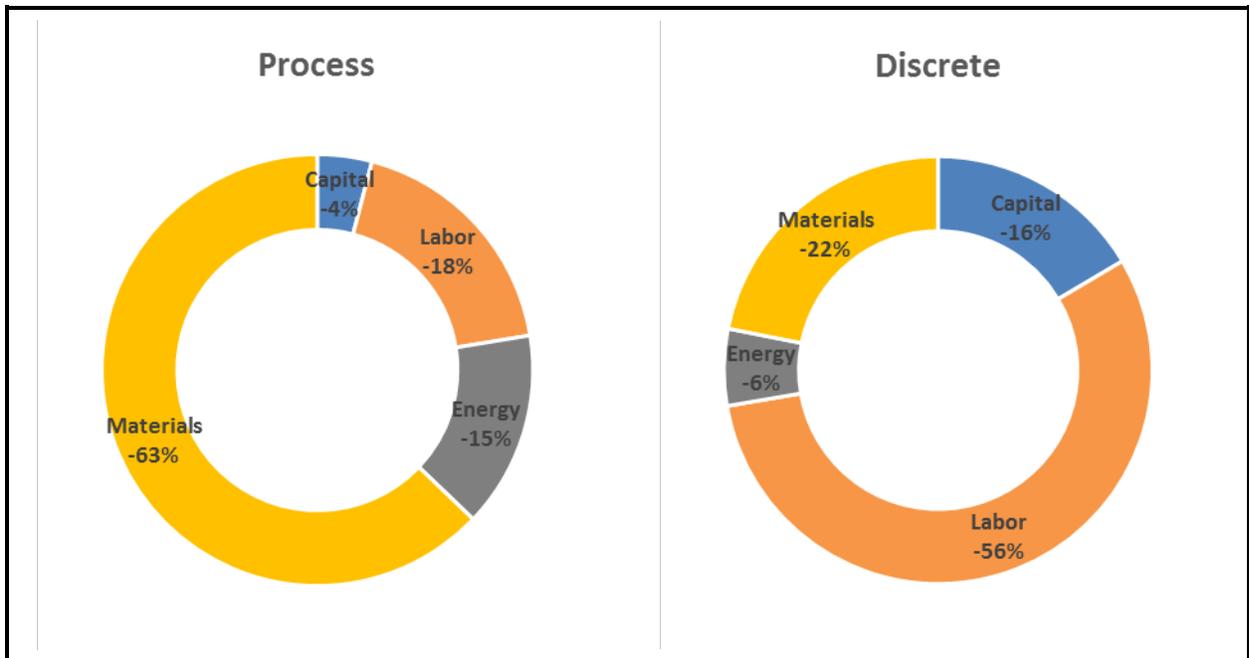


Figure 4-6. KLEM Shares of Composite Cost Impact for Process and Discrete Industries



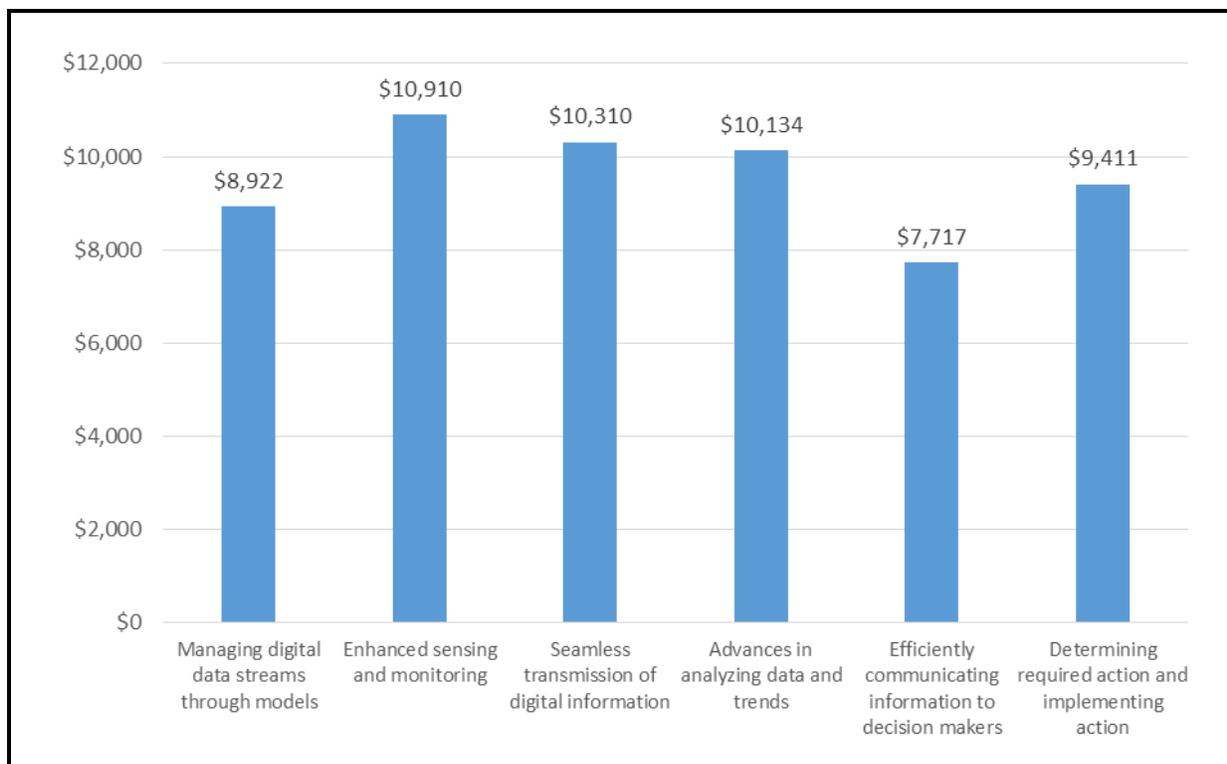
This publication is available free of charge from: <http://dx.doi.org/10.6028/NIST.GCR.16-007>

4.2.3 National Impact Estimates by Capability Gap Analysis

Figure 4-7 shows the distribution of total KLEM impacts apportioned to each of the six capabilities. The distribution of impacts reflects the average importance scores provided by end users. Enhanced sensing and monitoring, seamless transmission of digital information, and advances in analyzing data and trends all have potential annual impacts greater than \$10 billion. All of the identified capability areas were estimated to have annual benefits of over \$7 billion, reflecting the generally overall importance score of all the categories.

The relative magnitude across all the categories is evidence that there are strong complementarities or “interaction effects” among the capabilities. For example, it was stated that enhanced sensing and monitoring was only as important as the ability to transmit, analyze, and communicate the information.

Figure 4-7. Total Annual Cost Impact, by Capability (Millions of 2013 USD)



4.3 NATIONAL-LEVEL DEVELOPER SALES IMPACTS

Developers were asked about the impact on their sales and the value of the products and services they provide in a future scenario with an enhanced technology infrastructure for smart manufacturing. Most developers responded that sizable increases in sales were not likely, in large part because manufacturing companies (users) did not have the budgets to boost spending on smart manufacturing.

However, developers did say that their products and services would be better and would provide added value for their customers, which, ultimately, could translate into additional revenue and profits.

This section quantifies the market size for developers of smart manufacturing products and services in the United States. Our findings on average percent changes in sales were applied to the market sales figure to obtain an estimate of potential market growth.

4.3.1 Market Size

We estimated the size of the U.S. smart manufacturing technology market using a series of market reports on the smart factory market, industrial control and automation, and the industrial internet (see Table 4-5). Our interviews revealed that these markets are highly interrelated and overlap substantially. Therefore, we interpreted each of these market reports as within the scope of smart manufacturing technology. One of these reports was from 2012, but we included this one to be conservative since there has likely been some growth in the market since that 2012 report was published. Furthermore, we took an average of these reports to be conservative about the size of the market for smart manufacturing technology.

Given that the market size estimates are global in scope, we used two distinct data points for determining the share of the global market that can be attributed to the United States. The first data point came from a Cisco report on how value from the IoE will be distributed across countries. The U.S. value at stake was 32.4% of the global value at stake. This is a rough proxy for how smart manufacturing technologies are distributed globally. A more direct method, which yielded a remarkably

Table 4-5. Market Reports on Global Smart Manufacturing Revenues

Market	Global Market Size, \$/billion	Year	Source
Smart factory market	50.1	2015	MarketsandMarkets
Industrial control and factory automation market	146.2	2015	MarketsandMarkets
Global factory automation and industrial control solutions	156.9	2015	Mordor Intelligence
Spend on industrial internet technology	20.0	2012	Wikibon

similar percentage, involved gathering sales, product, and geographic information for a dozen of the largest smart manufacturing players in the world. This allowed us to estimate that approximately 35% of global smart manufacturing sales occur in the United States. We averaged these two data points together to obtain 33.7%, which is the number we applied. This yielded a U.S. smart manufacturing market of \$31.5 billion.¹⁵

4.3.2 Total Industry-Level Impacts for Developers

Of the 20 developers that we spoke with, 16 provided quantitative estimates of the impact that enhanced technology infrastructure would have on sales. Of the four individuals who did not provide quantitative estimates, three said that sales would be directly impacted, but that it was too difficult to quantify. Therefore, our estimate is likely conservative because we excluded these respondents.

Of the 16 quantitative answers, the distribution was skewed toward zero impact on sales, as 13 developers did not believe the enhanced technology infrastructure would lead to an increase their sales of smart manufacturing products and services. However, several developers said that although their sales might not increase significantly, an enhanced technology infrastructure would enable them to provide greater value-added activities. They would be able to move beyond basic

¹⁵ We also explored a more direct approach for determining the smart manufacturing market size. Using the sales, product, and geographic information gathered for a dozen of the largest players in the market, we calculated a lower bound estimate for the market for U.S. smart manufacturing technologies of \$27.6 billion. Therefore, we are confident that our estimate of \$31.5 billion for the market size is conservative, because it is not much larger than this lower bound.

interoperability/communications issues and focus on enhanced functionality, which if increasingly valued by used, could lead to new products and markets. However, most developers were reluctant to speculate/quantify what the impact might be on sales.

Three respondents provided quantitative estimates. However, one response was a severe outlier, so we removed it from our analysis. Of the final 15 quantitative answers, the average increase was 16% and the median was 0%.

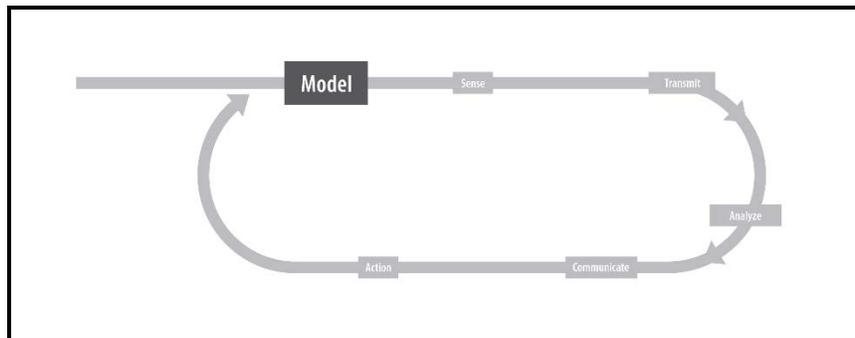
Using the market value of \$31.5 billion calculated in Section 4.3.1 as a baseline for the total value of smart manufacturing technology in the United States, we multiplied by the average percentage increase of 16% to yield a \$5.0 billion increase in sales for the U.S. smart manufacturing technology market that is associated with enhanced technology infrastructure.

Assuming that the purchases of smart manufacturing technology are proportional to estimated benefits, we expect that the discrete parts industries will buy \$3.3 billion of the new technology and the process industries will buy the remaining \$1.7 billion. We also investigated if benefits varied based on the size of industries or the size of vendors. However, we found no evidence of any such trends, in part due to the limited sample size.

5

Managing Digital Data Streams through Models

Figure 5-1. Smart Manufacturing Data Feedback Loop: Model



As discussed in Section 2, the core of smart manufacturing is the data feedback loop that runs through each level of the factory systems—product creation, operational planning, and enterprise management (see Figure 3.1). Sections 5 through 10 individually discuss industry needs expressed for each of these steps in the feedback loop. This section examines the modeling phase of the data feedback loop (Figure 5-1).

Data models are used to represent material behavior, product design, and process flow digitally to simulate and test different scenarios before actually building a product or arranging a factory floor. Data models hold key information that is transmitted electronically so that products can be manufactured. Machinery and corresponding maintenance guides are “virtualized” and placed on mobile devices, allowing quick and easy access to maintenance instructions. Predictive models, using key performance indicators from equipment and processes, generate and manage data.

Industry characterized data model creation as the second lowest capability in terms of importance score. Needs varied by industry and by segment of the supply chain. Electronic data exchange for CAD/CAM has been the focus of industry (and NIST) for the past decade, and developers indicated that they were working on products that accommodated multiple data formats. However, respondents still identified this area as a continued source of frustration. In general, there is tension between competitive positioning with proprietary systems or formats versus the move toward open-source system, which support competition and ease of entry into the modeling market.

5.1 BARRIERS TO ADOPTION AND ASSOCIATED MARKET FAILURES

The length of time and difficulty in developing high-fidelity process models can be a barrier to the use of process simulation. Creating realistic high-fidelity process models can take up to a year, and can be so complex that they require PhD-level employees to create them and high-performance computing systems to run them; moreover, in many instances, the end product still fails to provide accurate modeling.

End users indicated that models need not be “too realistic,” and in many instances simpler models are sufficient. For example, it was suggested that if a model could capture 90% of behavior, it would be preferred over more complex models that capture 95%. In some instances, higher-fidelity process models may not be quickly adopted because they are more difficult to manage. It is easier for someone to pass on if it is simpler. There is a need for a metric for model efficiency. For example, how well does the model reproduce the data relative to how complex the model is or the amount of time it takes for adoption? In addition, minimizing the number of parameters would be preferable. Models with “parameters without limit becomes a thing that no one can really understand.”

Industry also needs more open-source platform development to allow large and small companies alike to rapidly innovate, express needs, and develop common platforms. Most large software companies want to sell end-to-end automation packages and pursue this approach as a competitive strategy. However, this limits flexibility. A marketplace is needed to

encourage startups in this space and related big data application. SMLC has the vision to create an open source cloud infrastructure to allow people to create code and solutions that are plug and play. Enabling multiple businesses to create modeling or other manufacturing software on an open source platform provides buyer choice, which drives competition and lowers product costs.

5.2 TECHNOLOGY INFRASTRUCTURE NEEDS

Interviewees were asked to comment on the areas that needed additional development. We summarize interviewee comments in tables that describe the percentage of interviewees that identified a need (Table 5-1). These tables summarize open-ended conversations about the technology infrastructure needs, and therefore should be interpreted as a guide to the critical issues rather than a strict prioritization. The most commonly cited category are discussed below.

5.2.1 Identified Needs

Standards

Respondents indicated that there was a need for a broker, coordinating with organizations such as ISO and intervening in standards groups when multiple camps start to form. The rationale is that everyone benefits from technology agnostic standards but that companies often try to shape standards in a way that maximizes their own welfare, which may or may not be aligned with the public interest. In some cases, such actions can ultimately slow down the adoption of standards. A respondent from the aerospace industry thought that managing digital data streams through models was not currently a major

Table 5-1. Identified Needs Related to Managing Digital Data Streams through Models

Identified Needs
Standards
Quality/metrology
New features of CAD/CAM models
Costing capabilities
Metrics
Interoperable models

“It would be interesting to generate a mismatch of the machining process and digital expectation. ...How close is the actual product to the digital model?”

limitation, but noted that a common standard for 2D and 3D model representations could be helpful.

Quality/Metrology

It was suggested that there was a need for developing techniques for measuring the quality of as-built products and parts in terms of their variance from underlying digital models. Quantifying variance in this context would require the systematic comparison of 3D models with their physical offspring/reproductions. This concept was mentioned in the context of CAD/CAM models for discrete parts manufacturing. As the end user stated, “It would be interesting to generate a mismatch of the machining process and digital expectation. ...How close is the actual product to the digital model?”

In contrast, it was also noted that tolerance and inspection were important issues, but that industry would likely take a lead in solving any challenges in these areas, suggesting only a supporting role for NIST in helping industry address these issues.

New Features of CAD/CAM Models

Several ideas emerged for how CAD/CAM technology could be even more powerful than it is currently. A startup company noted a need for better methods for generating 3D representations of an entire manufacturing environment. Currently, such representations are typically in point-cloud format, but something more akin to solid models would be more powerful because of the metadata that are paired with geometric data.

A developer of machine tools and machine tool software suggested a need for a method of tracking materials properties that can sync up with tool settings in a smart way.

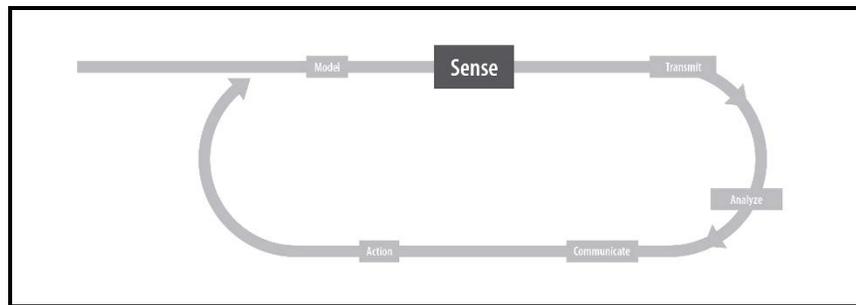
Other Capability Needs

Several other comments centered on automated costing as a helpful tool, but did not offer specific details in this area. Integrating automated or rapid costing functions in the design process could greatly lower the materials and manufacturing costs. However, to enable automated costing requires a standardized and accepted vocabulary linking physical attributes and manufacturing techniques to materials and production costs.

6

Enhanced Sensing and Monitoring

Figure 6-1. Smart Manufacturing Data Feedback Loop: Sense



Sensors are being integrated into most new machines produced today. Although a broad range of sensor capabilities is available, in many instances manufacturers are not fully taking advantage of these technologies. All study respondents said that state estimation of critical machines is an area industry is continually pursuing. Manufacturers believe that existing sensors are adequate for many applications, and that the most crucial need lies in improvement of data analysis capabilities. Nevertheless, we found that the industry still lacks many sensing and monitoring capabilities, and that the existing technologies need significant improvement. In addition, integrating sensing capabilities into older legacy systems is costly, and is often limited by technical constraints. This section examines these issues in more detail, and Figure 6-1 illustrates the position of sensing in the data feedback loop.

6.1 BARRIERS TO ADOPTION AND ASSOCIATED MARKET FAILURES

For many industries, the availability of simple, low-cost sensors is not an issue. Many of the laser, acoustic, and vibration

sensors needed are commercially available. The challenge is associated with the communications standards, interference, security (wireless being a security issue), and data processing (analysis of big data). The areas of need associated with the advanced sensors focus on operation in extreme environments (extreme heat or pressure). For these environments, the capabilities of specialized sensors could be improved.

Self-powered sensors that can harvest energy from temperature gradients or vibrations are needed. They would enable truly wireless applications (eliminating both communications and power supply hard-wiring), lowering the cost of implementation and increasing the potential for factory flexibility.

For existing process facilities, access and cost of installation are issues. Installation of new sensors as part of routine maintenance cycles is possible, but must be well coordinated. Often, access to the appropriate location for installation can be difficult, and retrofits are always more expensive than installing sensors at the time of original construction. It was cited

that emerging countries like China, which are building large numbers of new plants, have an advantage because they are able to build in extensive monitoring capabilities at low cost, enabling their plants to operate more efficiently. This places the United States at a competitive disadvantage—where it is almost impossible to site a new refinery or petrochemical plant—hence, creating cost and feasibility issues associated with legacy

The Need for Open-Source Communications Platforms

In the electric utility industry, the price of a generation turbine ranges from \$20 million to \$80 million; thus, predictive capabilities to help avoid catastrophic failure could have a significant economic benefit. There is no shortage of companies producing the required sensors, analysis software, and reporting packages.

However, the open-source communications protocols to link individual products do not exist. As a result, turbine manufacturers have been able to dominate the market by providing dedicated vertical systems that integrate the sensing, communication, and analysis. However, these custom systems tend to be expensive (about \$250,000 each), which has greatly limited their adoption. If open-source communications platforms were available, flexible systems could be developed at a much lower cost (potentially as low as \$10,000) using readily available components from specialized developers. See Appendix C for a more detailed discussion.

systems. Research, information, and/or case studies on how to most efficiently upgrade existing plants would be helpful.

Manufacturers said that solutions are needed which are lower risk, economically feasible, and have fewer of calibration and false-positive issues. If there were standards for reliability, it would significantly reduce the risk. Manufacturers feel that, currently, standards are loose and should be more stringent. For example, if a sensor has too much fluctuation, the time period in which the sensor is accurate needs to be extended. Tolerances of sensors needs to be improved. If standards were produced (and enforced), then developers would be forced to comply and publish the tolerance rates; users would then know what they are buying at various cost points. Users individually conduct testing in their labs, which is very costly and inefficient from a social perspective.

In general, sensor developers and vendors are well positioned to design, produce, and market new advanced sensors and monitoring equipment. However, with manufacturers not fully aware or convinced of the benefits, there can be significant technical risk for developers in investing in the required R&D. In addition, in some instances the developers do not have the fundamental technical expertise needed for the enhanced sensing capability and/or would not be able to fully appropriate the social benefits due to the infrastructure nature of the technology development.

Similar manufacturers, in many instances, do not have the in-house capabilities to fully realize the benefits from enhanced monitoring and sensing, even though they have in-depth knowledge of their manufacturing processes. For example, one company respondent said that:

Wireless sensing is extremely interesting, but we have to think about how do we put the information in the right context? Where does its implementation belong within our organization? Where does it make sense to store the data? How do you want to store the data? What is the ideal sensing frequency? Why should we do this—because we can? We have to learn what the value of that information is and how it can benefit us. At the moment that is all blurry.

6.2 TECHNOLOGY INFRASTRUCTURE NEEDS AND ROLES FOR NIST

A common theme from the interviews was that individual sensors and sensing devices are relatively advanced, but at the systems level, common typology, architecture, protocols, communication, and data structures are “all over the map.”

Almost one-third (28%) of all interviewees indicated a *high* need for additional development of sensing and monitoring capabilities. Developers and end users appeared to give roughly equal weight to this capability, although process manufacturers tended to think there was greater room for development than discrete parts manufacturers. Table 6-1 lists specific needs identified by respondents in general order of importance.

6.2.1 Sensors

Interviewees cited the need for technology infrastructure to support development of novel sensors. A pharmaceutical expert thought that the industry has a major need for noncontact, nondestructive sensors that can measure attributes such as density, cohesiveness, uniformity, potency, strength, and compressibility. A machine tool developer said that his industry needs sensors that can measure coolant concentrations on machine tools. And, there was common agreement on the need for increased accuracy of sensors—if not self-calibrating, then they should at least have the capability to detect when calibration is off and recalibration is needed. NIST has engaged in this type of work in the past when developing sensors for monitoring pipelines (NIST, 2008).

As the costs of sensors start to fall and they become more ubiquitous, there will be significantly more data for manufacturers to process. Hence, there will be a need for manufacturers to manage and analyze sensor data in a way that maximizes the value of rapidly expanding sensor networks. This highlights the interrelated technology infrastructure needs across many of the capability areas.

6.2.2 Standards

The need for standards supporting sensing and monitoring was mentioned by several companies. Companies pointed out the need for sensor interoperability. Sensors from any manufacturer should be compatible with the full range of data transmission and analysis systems.

Table 6-1. Identified Needs Related to Enhanced Sensing and Monitoring

Identified Needs
Sensors
Standards
Best practices
Data on fixtures
Predictive maintenance
Security
Wireless

Developers considered security a barrier for enhanced sensing and monitoring, noting that there was a need for generating better data standards that account for the level of security needed in different contexts. One developer stated, “Maybe there should be standards for how secure each type of data has to be. Sensing data may not need to be as secure because it is a different network.”

Enhanced sensing and monitoring will not only make companies more efficient, but as a developer posited, more invention will happen in the private sector if standards for sensing and perception were put in place.

6.2.3 Other Needs

Best practices need to be established for setting up wireless sensing and tools/models to enable predictive maintenance. Companies suggested that there was a need for algorithms to enable more widespread implementation of predictive maintenance in the manufacturing sector.¹⁶

In addition, there is a need for miniaturized, noncontact, nondestructive sensors that measure more diverse parameters. For example, in the pharmaceutical industry, for producing powders the processes are monitoring temperature and speed of mixing, but are really trying to control density, cohesiveness, and content uniformity of the powder. These are the attributes that impact product quality for the customer. The industry is

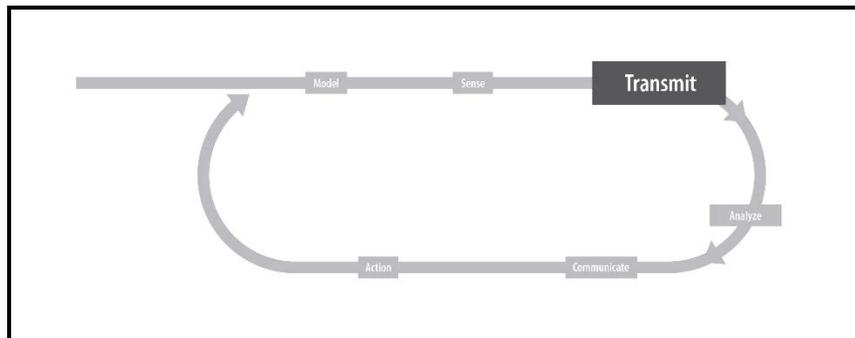
¹⁶ Predictive maintenance (or “state estimation”) was considered by some interviewees as belonging in enhanced sensing and monitoring and by others interviewees as belonging in advances in analyzing data and trends. This example illustrates the fact that the six technical areas have a significant degree of overlap.

interested in specialty sensor devices that can perform real-time monitoring of strength, physical structure, and compressibility of powders, to determine whether the compound will meet the required quality attributes. Better optimization of formulation would reduce the time to market and minimize the production of throw-away batches.

7

Seamless Transmission of Digital Information

Figure 7-1. Smart Manufacturing Data Feedback Loop: Transmit



Interoperability between platforms is not a new issue, but one that study respondents still cited frequently as a significant source of ongoing inefficiency. Standards developments, such as the Standard for the Exchange of Product (STEP), have definitely improved interoperability in several areas, but more advances are needed. Figure 7-1 illustrates the position of the transmit phase of the data feedback loop.

7.1 BARRIERS TO ADOPTION AND ASSOCIATED MARKET FAILURES

The most commonly cited technology-specific barriers cited during the interviews included networking/communications between machines and equipment from different vendors and different eras. Significant time is spent setting up machines and equipment to talk to a network. Even equipment with an “Ethernet-enabled” label is a source of frustration because companies do not use a standard communications protocol.

Specific to CAD/CAM systems, the ability to transfer not just geometric data but also the associated metadata would be very useful. The metadata design history would be particularly useful for assembling systems digitally when a large number of individual parts need to be integrated.

Although MTConnect was mentioned as a potential standard that could receive widespread adoption, the cost of implementing MTConnect could run from \$10,000 to \$30,000 per machine—a substantial cost barrier for large manufacturers with a lot of equipment. Also, one company commented that MTConnect was not able to replace data from operations down at the PLC level. One respondent commented, “Everyone has a different way of implementing MTConnect, and it is remarkably inconsistent. Each machine has a different way to get the program. Any standards here would be great. A lot of people are still using USB sticks because they can’t figure out another way to do it.”

Moreover, use of MTConnect is limited to certain classes of machines, and several users suggested that it would be helpful if its use could be extended to additional classes of machines. Illustrating the lack of interconnectivity between machines and monitoring equipment is the common practice of moving files between machines via the “sneakernet” (removing electronic data and manually walking it to its destination), simply because it is easier than doing it electronically. In many instances, the cost of achieving interconnectivity is still too high.

Respondents indicated that it has been a struggle to get manufacturers to adopt solutions such as MTConnect. Original equipment manufacturers (OEMs) and user communities have concerns about using this technology, and smaller companies are not familiar with the standard. More OEMs need to build the capabilities into their equipment, but small OEMs do not have the staff capabilities to develop the software to integrate the standards into their equipment’s sensing capabilities. In addition, some application developers are concerned that this will impact/eliminate a large part of their service market. Their market is to write and install software to solve communication problems. In response, proponents of solutions such as MTConnect indicate that the software will not solve all the problems; there will still be issues to address, but these solutions can help streamline the basic communication issues,

enabling service providers to promote and sell more advanced applications.

The technology of transmitting data via wireless technology was cited as an issue by some, but not all, respondents. Concerns centered on interference between transmissions of several data channels from multiple pieces of equipment. Neither quality nor cost of bandwidth were mentioned as issues. However, security was often cited as a concern. Hard (copper) wiring sensors are costly and cumbersome. To maximize the use and benefits of sensors, wireless communication is optimal. However, sending sensitive information wirelessly opens up a wide range of security issues that, as mentioned previously, include both physical security (sabotage, random disturbances) and intellectual property (IP) security. IP security includes protecting internal IP as well as the IP of customers.

For example, an interviewee from a petrochemical plant compared their production facility to a finely controlled “potential bomb,” stating that if someone could gain control of the monitoring system they could influence operation in a way that could lead to catastrophic failure and/or explosion. One industry observer thought that the high security issue was acting as an artificial barrier to the increased adoption of smart manufacturing technology, masking more basic issues of “status quo mentality,” risk aversion, and lack of skilled/motivated staff. This person stated, “Is high security really worth the opportunity costs that SM optimization provides?” and went on to describe ways that truly sensitive data could be decoupled from potentially less secure flows of information.

The most common concerns associated with wireless communication across all industries were loss of IP and competitiveness. Chemical companies said that the inability to stop communications from being transmitted beyond the factory gates was a serious concern, and that it influenced how they implement their sensing and monitoring systems. This concern also applied to how they view future potential use of cloud computing.

Cloud computing, data management, and software sharing were frequently mentioned as sources of cost reduction and increased availability of smart manufacturing solutions, but security was the main barrier to adoption. Different industries

and companies have different views on security concerns related to the cloud, ranging from loss of IP to the legal implications of disclosure of customers' personal financial and health data. Improved security protocols are needed, as is certification of existing security products and services.

However, several respondents indicated that data security concerns were overstated and, in some instances, were being used as an excuse for not adopting wireless communications. The typical comment was, for example, "Yes all data is at risk and anything can be hacked. But what is really the cost of the lost data—who is targeting it? What will they do with it?" They questioned whether high security outweighed the opportunity costs that smart manufacturing optimization provides, and stated that it is simple to disconnect truly sensitive data (IP) from logistics or basic operating sensing and monitoring. These respondents were proponents of using the cloud—but not for everything. It was thought that 80% of storage and large computing needs could be served by the cloud without any security concerns.

Cost and uncertainty of benefits associated with connectivity continue to be barriers, and markets have not been able to adequately address these barriers. The total investment costs of connecting assets are high, and it is often difficult to guarantee or demonstrate the benefits/return. Differences across plants and older, legacy equipment make plug-and-play solutions difficult to develop. In addition, entrenched vendors continue to promote proprietary software and solutions that inevitably increase costs and limit adoption.

7.2 TECHNOLOGY INFRASTRUCTURE NEEDS AND ROLES FOR NIST

More than one-third of the interviewees stated that seamless data transmission required a *high* level of additional development. There were many substantive comments on how NIST could play an active role in this area.

Table 7-1 lists particular areas of research that need to be advanced to accelerate the development and realization of truly seamless transmission of digital information. Data formats,

Table 7-1. Identified Needs Related to Seamless Transmission of Digital Information

Identified Needs
Data formats, standards, and protocols
Interoperability of systems
Machines
Data security protocols
Bridging information technology with operations technology
Typology, architectures, standards, structures
Facilitate consortia
Sensors
Closed-loop systems
Test beds
Programming tools

standards, and protocols, along with related interoperability issues, were the most commonly cited areas in which NIST could play a role.

7.2.1 Data Formats, Standards, and Protocols

The most critical need in this area involves the structure of data streams coming from distributed and disparate sources. Currently, it takes substantial amounts of skilled labor to collate data from systems, machines, and devices that are physically spread across factory floors. Currently, no single organization has the private sector has the capability or incentive to provide critical technical inputs and guidance on the standardization of data formats, protocols, and configurations. One end user in the heavy equipment sector pointed out the difficulty in bringing together different forms of data: “In the past we had a lot of point data. Now, we’re collecting 2D data from radars, and we have 3D data from reverse-engineering tools and computed tomography (CT)¹⁷ data. It is more than just seamless transmission. Data structure is the key.”

“In the past we had a lot of point data. Now, we’re collecting 2D data from radars, and we have 3D data from reverse-engineering tools and computed tomography (CT) data. It is more than just seamless transmission. Data structure is the key.”

¹⁷ Computed tomography, or CT, is just one of several 3D scanning technologies that can be used in the reverse-engineering process. For more information, refer to <https://www.asme.org/engineering-topics/articles/modeling-computational-methods/the-rise-of-reverse-engineering>.

Several interviewees pointed out the early success of the MTConnect standard. Although, thus far, adoption has been limited to the machine tool industry, MTConnect has potential for expansion to other arenas.

Several interviewees compared the current manufacturing environment to the early days of the Internet when there were dozens of different networking protocols before TCIP became the widely accepted internet protocol. One developer put it aptly: "What needs to happen is an equivalent collapse of these things into a consistent, ubiquitous protocol."

Several interviewees pointed out the early success of the MTConnect standard. Although, thus far, adoption has been limited to the machine tool industry, MTConnect has potential for expansion to other arenas.

Respondents commented that individual firms cannot solve the data standards challenge on their own. Firms do not want to invest in developing these systems. "We have all sorts of different systems all around the world. So, it is important to get more commonality. He who figures out those key relationships, causal relationships, that identification and recognition will be pivotal." Another developer described itself as a willing collaborator. One of the challenges faced by standards-setting bodies is that the market for smart manufacturing technologies is highly fragmented and proprietary, which would require cooperation from a large number of companies, although there is a more limited number of large players that could potentially move the market.

Several interviewees compared the current manufacturing environment to the early days of the Internet when there were dozens of different networking protocols before TCIP became the widely accepted internet protocol. One developer put it aptly: "What needs to happen is an equivalent collapse of these things into a consistent, ubiquitous protocol."

7.2.2 Interoperability of Systems

Another critical area is the interoperability of systems, which is related to the data format issue but with some differences. Several individuals described islands of information that exist in different factory systems that perform different functions. These systems cannot easily be integrated because they do not always talk to each other very well. Even different vintages of the same system can create version issues. One SME pointed out that "the interoperability of platforms can be improved. When a CAD version changes, then everyone else has to catch up and update their stuff." Manufacturing environments can have 10 to 20 different systems, ranging from supply systems to production systems. Standards are needed at key connection points between systems so that islands of information can be tied together. An industry observer stated that standards are needed to "support the full chain all the way through ERP systems."

STEP is currently being used to translate dimensions and tolerances. However, more manufacturing attribute definitions need to be added. These definitions would include manufacturing features such as concentricity, smoothness, hardness of material, and stress relief requirements. The problem is that every CAD vendor characterizes these attributes differently, so common definitions would improve interoperability. A developer pointed out that there should be standards for simulation-readiness of STEP files. As much as 30% to 40% of the data in a STEP file can be represented by a 3D company logo, which adds no value at all to the simulation process and, in fact, can slow down processing. The comments we gathered about STEP standards show the interrelationship between managing data streams through models and advances in analyzing data and trends. One approach for improving interoperability is for platforms to have built-in capabilities to communicate with multiple commercial software products. For example, Windchill is a PLM tool with built-in capabilities to work with multiple CAD options, including Autodesk, Microsoft, Adobe, I-Deas, Unigraphics, and Dassault CATIA. Expanded development of such platforms could lower the cost of accessing specialized applications/functions across a wide range of products.

Currently, interoperability issues can require substantial investments of staff time that could otherwise be spent on other value-added tasks.

There is a real opportunity cost associated with these interoperability challenges. Currently, interoperability issues can require substantial investments of staff time that could otherwise be spent on other value-added tasks. As one developer explained, “A lot of our time is spent implementing solutions to get connectivity [which is] wasted time that could be spend on optimization.” The good news is that systems appear to be opening up, albeit at a slow pace.

A consortium was recommended as a way to solve interoperability issues. Industry partners could share particular pain points and find common ground, with companies willing to collaborate on these issues at low risk to losing competitive advantage.

7.2.3 Machines

Two main themes emerged related to machines: (1) there is a need to continue to build on MTConnect to enhance machine-to-machine communications and (2) guidance is needed on

best practices for retrofitting machines to enable smarter use of factory assets.

The ability to integrate machine tools, robotics, and sensors is an example that was raised. Another respondent noted the need for a common protocol, and that currently there are too many options. Another developer suggested that industry should build on the success of MTConnect by extending it to additional classes of machine such as CNC machines, autoclaves, and ply-cutters as well as older machines that can be retrofitted.

7.2.4 Data Security Protocols

Another area where industry believed that the technical infrastructure needs to be enhanced is data security. One potential solution to cyberphysical security concerns is to develop carefully defined monitoring communication protocols that are decoupled from control communication protocols. It was mentioned that for predictive maintenance of turbines, wireless sensors transmit real-time vibration data in a one-way fashion to the control room, but in a way that is completely separate from control communications that are wired.

Without effective and trusted security protocols, factories have limited capability for seamless and integrated data analysis. As the importance of cloud computing grows to handle massive datasets, companies will face an increasing need to transmit data offsite for processing. However, some manufacturers are hesitant to let data out because of potential IP risks.¹⁸ Furthermore, inadvertently providing access to control systems can expose factories to malicious security threats from third parties.

7.2.5 Bridging Information Technology with Operations Technology

The information technology–operations technology (IT–OT) gap is essentially the challenge of getting IT systems and staff to efficiently interoperate with OT systems and staff. The IT–OT gap is not unique to the manufacturing sector, but it is intensified in manufacturing because many factories have operations technologies that were developed decades before IT protocols and practices were implemented.

¹⁸ One interviewee even mentioned their company's hesitancy to hire outside consultants because of IP concerns.

A process optimization software developer spoke of the value of sensor data and some of the technical challenges associated with the IT–OT gap: “There is a lot of value in getting the information [from sensors] that doesn’t put the control networks and operations at risk. Traditionally, sensors were out there were for control loops. A lot of sensing going on now is for higher order monitoring and analytics. The challenge with a lot of our customers as low-cost sensors go in is that information is still incredibly valuable back in the control network and operations space.” The developer went on to describe that customers are worried about feeding the sensor data from the IT network into operations systems because that may introduce cyber security vulnerabilities.

The IT–OT gap is as much an organizational and cultural challenge as it is a technical challenge.

The IT–OT gap is as much an organizational and cultural challenge as it is a technical challenge. A food manufacturer spoke about the organizational challenge: “The issue that we’ve had is traditionally there are two separate streams: (1) manufacturing, then (2) enterprise/corporate IT structure. IT people aren’t familiar at all with process computers, and vice versa. There are some security concerns. For example, concerns about transmitting to a vendor to help troubleshoot equipment which can involve special private VPNs, not standard protocols.” One end user suggested that degree programs in IT–OT or advanced certification programs could supply industry with appropriately skilled people to bridge the gap. Cisco Systems has launched the Industrial Networking Specialist certification specifically toward that end (Cisco.Com, n.d.).

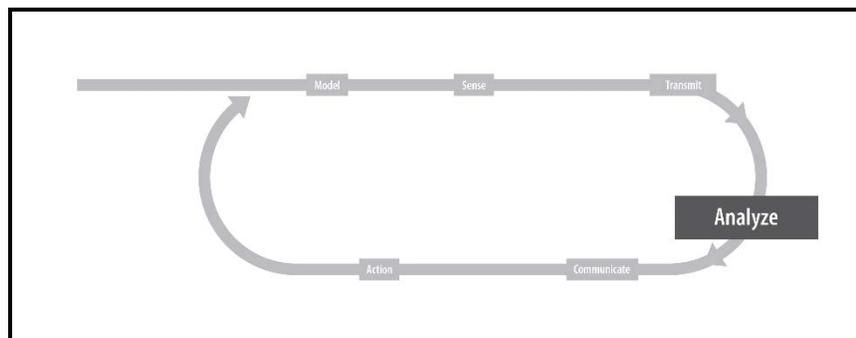
7.2.6 Other Needs

Other needs mentioned related to interoperability include developing new sensors (discussed in the previous section), programming tools, typologies, and architectures; providing test beds; and acting as a facilitator through consortia or other mechanisms.

8

Advances in Analyzing Data and Trends

Figure 8-1. Smart Manufacturing Data Feedback Loop: Analyze



The analysis of big data is a rapid-growth sector. However, most manufacturers in our study thought that the manufacturing sector was not receiving sufficient attention from data analysis service providers. Most of the data analysis firms are better positioned to serve the financial service sector or marketing departments. They lack the engineering or chemicals expertise to support much of the manufacturing sector. It was suggested that consortia and long-term partnerships need to be fostered to bring the multidisciplinary teams together to solve the analysis problems that would advance smart manufacturing. Figure 8-1 illustrates the position of the analysis phase in the data feedback loop.

8.1 BARRIERS TO ADOPTION AND ASSOCIATED MARKET FAILURES

The cost associated with computing power and analysis software can be significant, and represents a barrier to

adoption of smart manufacturing, especially to SMEs. One interviewee said that up to 70% of their factory's network infrastructure was "nonvalue," meaning that it was associated with the infrastructure need—not with the customized/task-specific software that was generating the benefit. Some people noted that, from this perspective, the cloud has the potential to greatly reduce the overhead cost associated with smart manufacturing capabilities by making shared resources available. One company described cloud computing as a "tidal wave" for the industry, but that it had experienced particular challenges implementing cloud computing because of security and concerns about complying with export controls.

In general, we found significant disagreement with respect to future use of cloud computing. For some, the concept did not resonate at all due to security concerns related to proprietary data and protection from hacking. However, for others the benefits of the cloud's low-cost computing power and storage outweigh the risks. Typical comments were that a company "does not have to put the most sensitive information on the cloud. It is good for what it's designed for."

Companies talked about not only shared computing power but also the need for a new model of shared software resources for analyzing big data or accessing customized, complex programs. If a company is going to use a

Reducing Costs for SMEs

Virtual simulation of manufacturing production systems can increase innovation and help more efficiently manage the entire product life cycle. However, the current market is primarily limited to large manufacturers that are able to justify the high fixed cost of a new software package and the required computational power based on economies of scale/ROI.

It is difficult for most SMEs to justify the high fixed costs of licensing these types of software in the traditional manner or purchasing the computers needed to run the simulations. Decreasing the cost of software plus the cost of implementation would increase market penetration and adoption of these technologies among SMEs, which could yield substantial economic benefits. A more centralized approach where software tools and computing capacity were hosted in the cloud and rent access available would decrease the direct software costs incurred by any single manufacturer and potentially decrease the indirect implementation costs. See Appendix C for a more detailed discussion.

customized design or simulation software only a few times a year, it is very expensive to purchase and maintain software for such a limited need. However, if licensing mechanisms can be developed to allow access for a fee, a cloud-based service sector could greatly lower the cost of many of the digital advances in product design, simulation, and manufacturing design. Sharing resources is not a technical research topic per se, but it is a structural issue that professional associations might address.

Also associated with the need for improvement of analysis capabilities is the reduction of false positives. False positives can be very costly if they lead to unnecessarily shutting down a line or delaying restart.

Following costs, the second most common barrier mentioned related to data analysis is that staff do not have graduate degrees in engineering. Senior staff are more likely to be long-term employees with on-the-job experience and expertise. Thus, skill level is an issue in utilizing analysis systems that are very complex. Several companies said they have been advocating for bringing more computer scientists and mathematicians into manufacturing. In general, the concern is that data can be misleading as they are currently aggregated and reported, and taking disparate data and aggregating them across the different data formats and structures leads to errors.

8.2 TECHNOLOGY INFRASTRUCTURE NEEDS AND ROLES FOR NIST

Most interviewees stated that data analysis required at least a *medium* level of additional development. Table 8-1 shows the major needs identified by interviewees for advancing the analysis of manufacturing data and trends.

8.2.1 Best Practices and Techniques for Data Analysis

Best practices and techniques for data analysis emerged as the top technology infrastructure need in this area. Prediction, particularly predictive maintenance, was a big theme. In addition, advances in algorithm testing and development were needed to provide guidance on how to interpret data from different sensors and determine which data are most important, relevant, and meaningful to collect for predictive maintenance. To the extent that it is possible to develop standard algorithms

“There is so much data to pull out of machines, which are the leading indicators of predictive failure, and how will you know that? What are those models, how should they be structured?”

that can be customized by end users, this approach would be ideal. Another term for predictive maintenance is analysis of failure modes, which is a big gap, according to some. One developer noted, “There is so much data to pull out of machines, which are the leading indicators of predictive failure, and how will you know that? What are those models, how should they be structured?”

Table 8-1. Identified Needs Related to Advances in Analyzing Data and Trends

Identified Needs
Best practices and techniques for data analysis
Virtual factories and simulation
Metrology
Standard and test beds
New architectures for information technology–operational technology (IT–OT)

Other technical challenges include time calibration of data streams and what information should be used when pulling from particular types of sensors. For example, for vibration sensors, guidance on the optimal time domain and frequency domain is needed.

8.2.2 Virtual Factories and Simulation

Currently, industry appears to lack sufficient technology infrastructure to enable virtual factories and simulation to support the analysis of data and trends. Several interviewees commented that simulation standards have not been as widely adopted as hoped because they are not “complete enough.” For example, if STEP standards were more comprehensive, OEMs would expand use for communicating to suppliers (especially build to print).

A chemical manufacturer suggested that more model complexity is not always necessary. This concept is analogous to model selection techniques in statistics that quantify the incremental predictive power of adding another variable into a statistical model.

Another compelling idea called for the need for a common way to quantify model usefulness versus complexity. A chemical manufacturer suggested that more model complexity is not

always necessary. This concept is analogous to model selection techniques in statistics that quantify the incremental predictive power of adding another variable into a statistical model.¹⁹ The need for model selection in manufacturing environments is driven by an information asymmetry issue between developers and end users. According to the same chemical manufacturer, “Service providers are always trying to sell their latest and greatest complex model to establish a niche and follow-on services. Similar academics are looking to push the frontier and hence are not interested in developing simple/usable, less accurate models.”

Finally, modular applications and expanded data libraries were mentioned as infrastructure technologies that could lower development costs and improve the accuracy of simulation models. Increased information for process flows, material characteristics, and simulation platforms could improve efficiency and lower the required skill level for modeling tasks. Providing these building blocks could increase the use of simulation modeling, especially for SMEs.

A fundamental platform such as a standard factory operating system that ties together modular applications and data libraries with existing systems in the manufacturing environment could be transformative. Other groups, such as the SMLC, are leading efforts to develop a real-time manufacturing platform, so close coordination with the SMLC would be vital to determine the support needed for technical inputs.

8.2.3 Other

Additional roles for NIST include informing and shaping standards, creating test beds, and providing leadership in metrology to support advanced data analysis.

Developers noted that the information technology–operational technology (IT–OT) gap (discussed at length in Section 7) is a barrier to data analysis because it prevents the fluid flow of information from the shop floor to engineering groups that can provide a different perspective.

¹⁹ For example, the Akaike information criterion (AIC) and Bayesian information criterion (BIC) are two criteria that statisticians consider when a model.

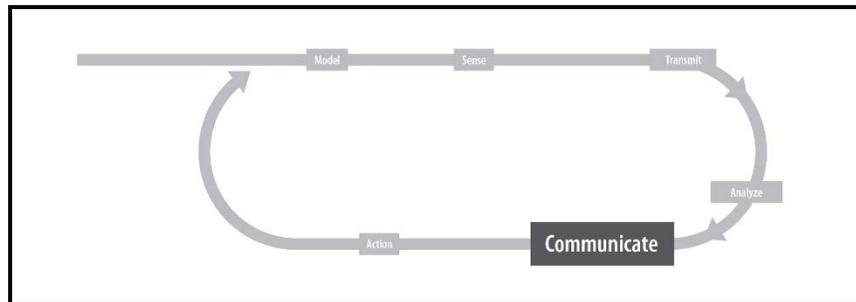
Centrally hosted cloud-based applications could make analyzing big datasets more accessible to SMEs. Big data tools such as Hadoop tend to be cost prohibitive for SMEs, but cloud computing can make applications and computing power much more accessible for them. A discrete parts manufacturer stated that the cloud could offer a scalable solution to this problem; a large OEM or another group could host services in the cloud, which could reduce the cost of the individual licenses for smaller shops.

Despite the fact that there were many ideas shared for how NIST can play a role, several interviewees stated that they did not see a role for NIST in advanced analysis of data and trends, viewing it as an industry-driven technology. However, there seemed to be confusion over the distinction between NIST developing the technology infrastructure and making it available to the public sector to support the development of commercial products, and NIST developing open-source software that would be made available to the public and potentially crowd out certain products and services currently being offered by product and service providers. Several companies seemed threatened by NIST involvement due to concerns about competition, and hence were not enthusiastic.

9

Efficiently Communicating Information to Decision Makers

Figure 9-1. Smart Manufacturing Data Feedback Loop: Communicate



Respondents interviewed were most familiar with activities related to physical components, data exchange, and related standards. However, the “softer” side of smart manufacturing, which includes efficiently communicating information to decision makers, was also cited as an area needing further research. For example, the value of smart manufacturing data and activities would be increased through research to develop simpler, user-friendly communication interfaces that would be customized for smart manufacturing and integrate statistical methods for establishing thresholds to trigger decisions. Figure 9-1 shows the position of the communication phase in the data feedback loop.

9.1 BARRIERS TO ADOPTION AND ASSOCIATED MARKET FAILURES

Many industries encounter issues related to efficient and concise information interfaces. “Ease of use paradigms” are needed. Plant staff members need to be able to access and understand software and information in a manageable way. Mobile access with tablets would be a key selling factor; however, the wireless aspect of tablets introduces security issues.

A key concern is that everyone wants information differently and thinks about issues differently. It is difficult to develop one interface that fits. Examples such as OPC GE and OMAC exist, where it was shown that developing common interfaces is very difficult.

In many instances, users get too involved with a particular piece of machine or family of machines. What is needed is a higher level approach to more generally think about the science of communication. This is closer to basic research (one respondent referred to it as “textbook” method) and reflects investments that would have a broad impact on the manufacturing sector. The distinction is that not all investments should be machine specific. Higher level, public-good research is needed in this area.

A related overarching barrier to adoption discussed by respondents is that existing, older staff members are frequently uncomfortable with electronic information interfaces—and, in contrast, younger staff who are comfortable with electronic information interfaces do not have the level of technical background/experience to quickly interpret the results and identify solutions.

9.2 TECHNOLOGY INFRASTRUCTURE NEEDS AND ROLES FOR NIST

Two-thirds of interviewees stated that this capability required at least a *medium* level of additional development. Table 9-1 lists the areas identified. Interviewees provided very few specific technical areas, possibly due to the elusiveness of the concept or its broad nature. The few comments that were provided were evenly spread across a range of ideas about enhancements needed.

Table 9-1. Identified Needs Related to Efficiently Communicating Information to Decision Makers

Identified Needs
Common taxonomy
How and when to use a directed closed-loop system
Information representation
Metrics

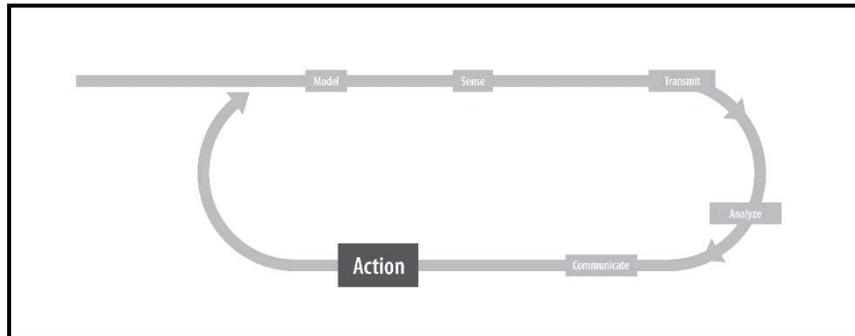
“Another way to think about human–computer interaction is how you integrate closed-loop systems with a human in the loop. What are the best ways to design integration between automated systems and people who implement advice? Direct close-loop versus having humans in the loop. When is each best?”

One particularly poignant comment from a developer described how industry could approach the topic of communicating information to decision makers: “Another way to think about human–computer interaction is how you integrate closed-loop systems with a human in the loop. What are the best ways to design integration between automated systems and people who implement advice? Direct close-loop versus having humans in the loop. When is each best?” One end user offered a different perspective by pointing out that efficiently communicating information to decision makers is about the metrics used to communicate with decision makers rather than the design of interfaces. Overall equipment effectiveness (OEE) is one example of a high-level metric that has gained some traction in industry but is not consistently defined.

Another developer stated that, although it would be difficult to determine how to standardize the representation of information for decision makers, he would be eager to see some level of standardization because it would, in theory, enable rapid development.

10 Determining and Implementing Required Action

Figure 10-1. Smart Manufacturing Data Feedback Loop: Action



The ability to determine and implement required action was referred to as the "... ultimate capability. Without it, the other of the capabilities are of no use." Most manufacturers expressed the need for enhanced decision support tools that would help make decisions much faster, including information and analysis tools targeted at both manufacturing operators and upper management. Using artificial intelligence and learning systems to identify and direct the most appropriate actions based on data analysis would help toward building an automated and more flexible factory. A challenge commonly cited for determining and implementing required action is communicating meaningful information to management, where many of the investment and high-level operating decisions are made. This challenge demonstrates that some of the capabilities are interrelated. Figure 10-1 illustrates the position of the action phase in the data feedback loop.

10.1 BARRIERS TO ADOPTION AND ASSOCIATED MARKET FAILURES

Improvements in decision systems will require continued research on statistical methods for analyzing big data (pattern recognition, trends, and correlations) and the intelligence to make critical decisions based on risk assessment and optimization modeling. This is a multidisciplinary research area in which coordination must be improved across the different sectors pursuing these enhanced capabilities.

The ability to easily reconfigure manufacturing systems was discussed as a need in several interviews, but very few specific technologies that would facilitate in-process flexibility and reconfiguration were mentioned. One product on the market is Lynx, a mobile conveyer belt that can be deployed to any location in the factory and can work safely alongside humans, avoiding collisions by using real-time path planning. The benefits in terms of cost and speed of implementation hinged on developing analysis systems that could function independent of human interaction.

The lack of a specialized workforce is one of the critical components limiting the development of decision support tools. Educators are working to catch up their offerings in this area, and organizations such as the National Science Foundation (NSF) have conducted workshops to highlight the need. In general, smart manufacturing intelligence systems require a highly multidisciplinary workforce. Europe, which is more advanced in this area, encourages courses specifically designed to supply qualified students trained to “understand data, how to capture it, how to model it, and how to use it.” Employees who work in the manufacturing factory of the future will have to be highly trained in understanding digital data, how to work with the machine, and achieve better integration of the human resources with the digital resources.

An example was provided from the paper industry. Within the paper industry, the workforce is generational. On average, staff are not highly educated and typically work their way up, gaining a wealth of practical experience. Control rooms are not very sophisticated. Controllers have been working with the same processes for years, leveraging tacit knowledge about what the output should be saying to make product that meets specification. This operating model does not lend itself well to

the introduction a smart manufacturing technology, and represents a barrier to adoption.

10.2 TECHNOLOGY INFRASTRUCTURE NEEDS

Again, two-thirds of interviewees stated that this capability required at least a *medium* level of additional development. Similar to efficiently communicating information to decision makers, there were few substantive recommendations for areas in which to implement required action. Table 10-1 summarizes those needs.

Large process manufacturers commented that it would be helpful to have closed-loop systems, but offered no specific guidance on what technology infrastructure was needed to develop these systems. A major developer of industrial automation and control systems suggested that industry could better deal with uncertainty and risk when determining and implementing actions. The same respondent suggested that there are standardization needs for control models. Finally, a respondent from a manufacturing simulation software company stated the need for a standard virtual factory operating system.

Overall, respondents thought that substantial opportunities to enhance the technology infrastructure in this area were needed and are possible, but respondents did not offer specific recommendations.

Table 10-1. Identified Needs Related to Determining Required Action and Implementing Action

Identified Needs
Standards
Closed-loop systems
Dealing with uncertainty

11 Conclusions and Summary Needs

With the increasing complexity of manufacturing processes, smart manufacturing has the potential to increase efficiency and productivity. Through the generation and capture of data, the understanding of its implications, and the ability to take timely action as a result of that knowledge, smart manufacturing can increase the U.S. manufacturing sectors' competitive position globally.

Although the term *smart manufacturing* means different things to different industries, there is a growing consensus that significant cost savings can be realized through optimizing product design and production systems at the equipment, factory, and enterprise levels. At the core of this technology is the integration of cyber and physical systems, which can enable innovative production processes and new product systems.

However, barriers exist to the adoption of all but the simplest of smart manufacturing technologies. Enhancements in the technology infrastructure are needed to develop the next-generation smart manufacturing technologies. Advances in the technology infrastructure, which provides the underpinning for advances in smart manufacturing, can drive product and process improvements that are just in the conceptual stages today. Improvements in the technology infrastructure will lower the cost and increase the benefits from adopting existing and future smart manufacturing technologies.

The following insights and recommendations are based on more than 80 interviews and many additional informal conversations with individuals representing a variety of smart manufacturing product and service providers, smart manufacturing end-user companies, and industry observers.

11.1 CAPABILITY NEEDS AND BARRIERS TO ADOPTION

11.1.1 Capability Needs

Respondents indicated the importance and need for research on a broad range of capability areas supporting smart manufacturing. These areas ranged from product design to data collection and transmission, and from data analysis to decision support tools. This finding illustrates how interdependent the different functionalities are across the spectrum of smart manufacturing activities. For example, interviewees said that enhanced sensing capabilities are needed, but will only add value if they are accompanied by cost-effective and secure transmission of the information. Similarly, the growth and availability of real-time digital information on manufacturing activities is only as valuable as the ability to analyze the information. Thus, in many ways the value of smart manufacturing systems are a function of the weakest link in the chain.

11.1.2 Barriers to Adoption

Financial issues were the most commonly cited barriers to adoption of smart manufacturing technologies and processes—however, this is likely a symptom of underlying issues and market failures. In general, users cited low ROI—in part driven by cost issues associated with legacy systems, vendor lock in, and age of plants—as the greatest barrier to adoption. In other cases, while adequate ROI may be feasible, users mentioned that uncertainty about new technologies makes it difficult to understand and justify ROI, and this aversion to uncertainty acts as a barrier to adoption.

Concerns about financial issues were followed by a lack of technical resources and knowledgeable staff needed for implementation. End users pointed out that personnel with specialized knowledge are scarce because of the aging/retiring workforce and the lack of multidisciplinary engineering education programs. For smaller manufacturers in particular, the lack of technical resources and knowledgeable staff appears to be a major barrier.

11.2 ECONOMIC IMPACTS

Interviewees were asked what impact enhanced smart manufacturing capabilities could have on their manufacturing processes if technology infrastructure needs were met. Table 11-1 shows the average percent change in factor inputs provided from the interviews. Manufacturers indicated that labor costs could be reduced by an average of 12%, and energy savings of 13% could be achieved. Capital and materials potential savings were estimated to be, on average, 5% each.

Changes in factor inputs were then scaled to national levels to estimate the economic impacts associated with an enhanced technical infrastructure for smart manufacturing. Table 11-2a shows that economic impacts are estimated to be approximately \$57.4 billion. This represents, on average, an approximately 3.2% reduction in the shop floor cost of production, which is on the lower end of the spectrum compared to other studies evaluating the potential benefits of smart manufacturing. Discrete parts manufacturing accounts for \$30.8 billion, and process manufacturing \$26.6 billion. Discrete parts industries had larger potential impacts, but process industries represented a larger share of the manufacturing sector. Materials accounts for the largest share of savings, accounting for approximately two-thirds of manufacturing production costs.

Economic impacts were also estimated by capability area based on the level of importance provided by respondents. As shown in Table 11-2b, enhanced sensing and monitoring, seamless transmission of digital information, and advances in analyzing data and trends all have potential annual impacts greater than \$10 billion. All of the identified capability areas were estimated to have annual benefits of over \$7 billion, reflecting the overall interdependency across all the capability areas.

Table 11-1. Average Percent Change in Factor Inputs

Factor Input	Mean Impact
K: Capital	-5%
L: Labor	-12%
E: Energy	-13%
M: Materials	-5%

Table 11-2a. Economic Impact Summary, Process versus Discrete

Type of Industry	Cost Impacts, \$ Billion					KLEM National Factor Expenditure, \$ Billions	Percentage Savings in Shop Floor Production Costs
	K	L	E	M	Total		
Process	-1.1	-4.9	-3.9	-16.7	-26.6	1,281.1	-2.1%
Discrete	-5.1	-17.2	-1.8	-6.7	-30.8	537.0	-5.7%
Total	-6.2	-22.1	-5.7	-23.5	-57.4	1,818.1	-3.2%

Table 11-2b. Economic Impacts by Capability Area

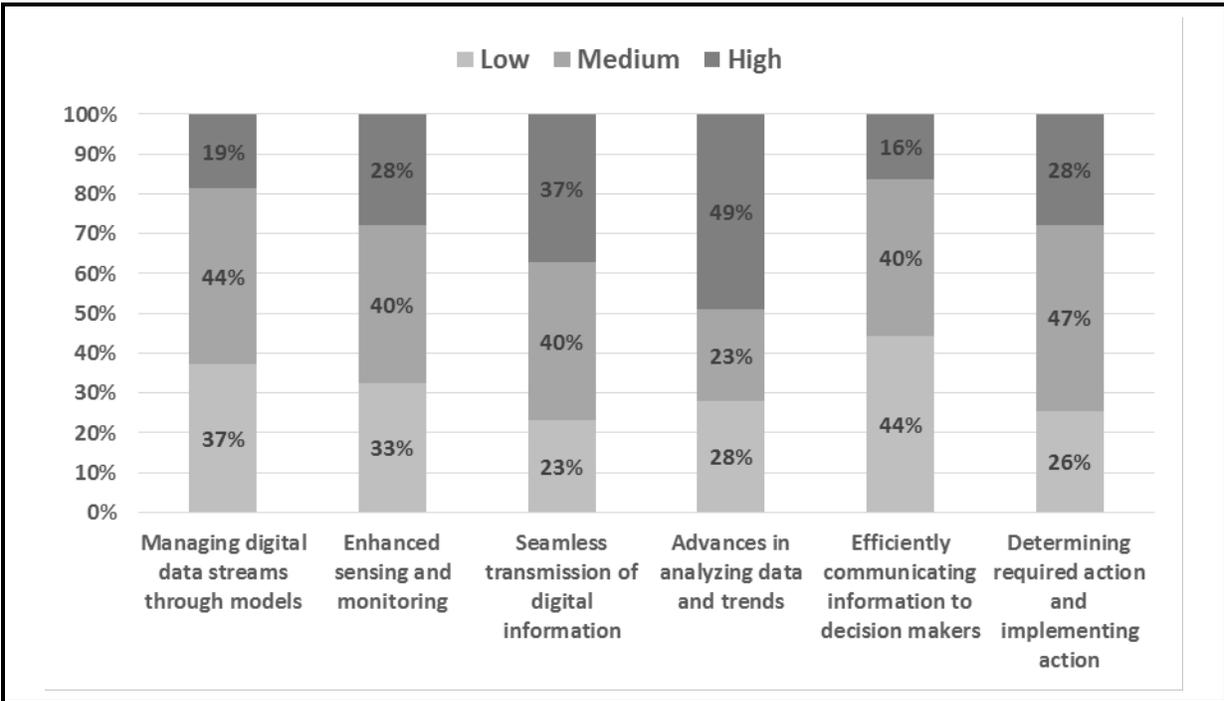
Capability Area	Economic Impact (\$ Billion)
Managing digital data streams through models	8.2
Enhanced sensing and monitoring	10.9
Seamless transmission of digital information	10.3
Advances in analyzing data and trends	10.1
Efficient communication of information to decision makers	7.7
Determining required actions and implementing action	9.4
Total	57.4

Note, that as discussed in Section 2.2, the economic impact estimates presented are considered to be conservative in that they focus on reductions in manufacturer's production cost that would result from meeting the identified technology infrastructure needs. Not included in the economic impact calculations is the economic value associated with reduced R&D costs, improved product attributes, increased sales, or accelerating the introduction of new products to market.

11.3 TECHNOLOGY INFRASTRUCTURE NEEDS

As shown in Figure 11-1, respondents indicated that there is a need for technology infrastructure development across all of the capability areas supporting smart manufacturing. Although advances have been made over the past decade, seamless transmission of digital information was ranked as the area in which the most research was needed. This was followed by decision support tools to determine and implement action, and advances in analyzing data and trends. The implication is that NIST may have a potential role in contributing to the technology infrastructure for most of these capabilities.

Figure 11-1. Percentage of Interviewees Indicating the Need for Additional Reach in Smart Manufacturing Capability Areas



11.3.1 Communication Standards and Conformance Testing

All interviewees said that government should continue to support standards and communications protocols that span the capabilities and functionality of smart manufacturing; a crucial need was cited for research on the structure of data streams coming from distributed and disparate sources. Currently, substantial amounts of skilled labor are needed to collate data from systems, machines, and devices that are physically distributed across entire factories. Research is needed to better understand the critical technical inputs on the standardization of data formats, protocols, and configurations.

Other technical challenges include the area of calibration. Self-calibrating machines, or ones that could detect when calibration was off, would be very helpful. In addition, methods for time calibration of data streams and best practices regarding what information should be used from particular types of sensors are needed. For example, for a vibration sensor, guidance is needed on the optimal time domain and frequency domain.

Security Issues

Security concerns related to wireless communications, data storage, and access to computational power were consistently cited as issues limiting the adoption of smart manufacturing technology. Security concerns included both protection of sensitive IP as well as physical plant security and worker safety. Data encryption and security protocols tailored for the manufacturing sector are needed, as well as approaches for decoupling sensitive IP data from routine process monitoring data. However, several interviewees thought the security concerns were overstated, and that cloud computing and data storage were applicable (safe) for over 80% of the smart manufacturing needs.

Data Analysis and Intelligent Systems

Best practices and techniques for data analysis emerged as the top technology infrastructure need. Prediction, particularly predictive maintenance, was cited as an area with large potential benefits. For example, it was stated that government organizations, with their expertise in algorithm testing and development, could provide guidance on how to interpret data from different sensors and determine which data are most important, relevant, and meaningful to collect for predictive maintenance. An area of focus, suggested by respondents, was the development of standard algorithms that can be customized by manufacturers; in this category, analysis of failure modes was cited a major gap.

Coordinating with Other Organizations and Industries

Interviews clearly pointed to a demand for, and enthusiasm about, partnering with government organizations, such as NIST, to address some of the challenges discussed in this work. Companies feel strongly that the public sector should help coordinate activities with private organizations that are involved in the smart manufacturing space, so that all stakeholders clearly articulate the value of smart manufacturing. Many interviewees believe that NIST involvement would add much-needed credibility to initiatives to support smart manufacturing.

In general, it is difficult to engage industry in an open discussion and to expect them to share information. However, this is essential for identifying the pain points and developing solutions that will be acceptable to a broad cross section of manufacturers. There are network externalities to be leveraged

through coordinated efforts if resources can be pooled and focused.

Building Human Capital through Education and Training

A common theme that emerged from the interviews was the importance of human capital in the successful application of smart manufacturing technologies. Whether directly (through funding) or indirectly (through endorsements) contributing to degree and/or certification programs or simply documenting best practices, government has a role to play in ensuring that skills keep up with the pace of technological advancement. With the attrition of the aging U.S. manufacturing workforce, the manufacturing sector will be looking for skilled and talented people to fill the need for new workers.

Supporting SMEs

Several interviewees pointed out that NIST's Manufacturing Extension Partnership (MEP) program could be an excellent mechanism for supporting smart manufacturing. They said that MEPs engage SMEs in an array of training, innovation, and process improvement activities, so there are existing avenues through which smart manufacturing could be reinforced. Manufacturers suggested that the MEP program could also help connect users with developers of smart manufacturing technologies by creating platforms that allow regional offices to direct SMEs to new marketplaces.

A common theme that emerged from the interviews was the importance of human capital in the successful application of smart manufacturing technologies.

11.4 CONCLUSION

Enhanced technology infrastructure for smart manufacturing can help U.S. manufacturers gain cost efficiencies on the order of billions of dollars (compared with the current baseline trajectory of smart manufacturing technology). The substantial economic benefits quantified as part of this study are likely to be conservative because we focus primarily on efficiency gains and production cost savings, rather than quantifying the value of increased product quality, increased sales, and exports. These benefits, combined with the market failures and barriers to adoption, suggest opportunities for public policy to encourage and support industry in addressing these barriers and, ultimately, increasing total social benefits.

Our interviews with industry identified specific areas where the technology infrastructure needs to be improved and advanced.

Interview findings demonstrate that companies in the manufacturing sector appreciate and welcome NIST's traditional role as a standards coordinator and leader in metrology; however, additional important areas where the public sector can help include data analysis, cyber security, human capital, and interoperability of systems, machines, and other data streams. Our findings clearly point to a broader role for the public sector in making the U.S. manufacturing sector more innovative, efficient, and competitive.

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Appendix A: NIST Advanced Manufacturing Strategic Planning Study

A.1 INTERVIEW GUIDE: PERSPECTIVES OF USERS OF SMART MANUFACTURING PROCESSES

The National Institute of Standards and Technology (NIST) in the U.S. Department of Commerce has contracted with RTI International to conduct an economic analysis of standards, measurement, and general purpose technology needs that inhibit efficient development and adoption of advanced manufacturing in the United States.

The objectives of this critical strategic planning study are to

- identify current and emerging needs related to standards and measurement,
- estimate the economic impact of meeting these needs, and
- review public policy and investment options.

The study has a particular focus on 4 aspects of advanced manufacturing: (1) robotics and automation, (2) smart manufacturing processes, (3) 3D Printing (additive manufacturing), and (4) roll-to-roll manufacturing. The focus of our conversation is smart manufacturing.

Your perspective will help guide NIST's planning and investment process. Participation in this analysis is confidential; only aggregated information will be included in any deliverables or communications. Your name and your company's name will not be disclosed. We do not wish to discuss specific products, strategies, or technologies; but rather your thoughts about how investments in standards and measurement technologies would affect your company and companies like yours.

Our research products will be an economic analysis, final report, and presentation materials. All deliverables will be publicly available in late 2015 and these will be shared with you as soon as they are released.

If you have questions, please contact:

- Mike Gallaher, Case Study Lead, RTI, 919-541-5935 or mpg@rti.org
- Alan O'Connor, Principal Investigator, RTI, 919-541-8841 or aconnor@rti.org

- Gary Anderson, NIST Project Officer, NIST, 301-975-5238 or gary.anderson@nist.gov

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Respondent Contact Information

Name	
Title	
Division	
Company	
Industry	
Phone	
Email	
Location	

For our conversation today we are defining smart manufacturing to include

The creation, communication and use of electronic information, as well as the interface of these information systems with the human element, for data-driven decision support. This includes how data and information generated during the production process is communicated and used to improve the design, engineering, and production phases of the product cycle.

1. Does this definition cover the relevant areas you typically include under "smart manufacturing?" If not, what else do you include in "smart manufacturing"?

2. Please describe your background as it relates to smart manufacturing. How did you come to be in your current position?
3. Are you familiar with NIST's activities? If so, please give a brief description of any ways that NIST currently impacts your work (through, e.g., any standards, calibration and measurement, scientific and engineering data relevant to your work).

Company Background and Level of R&D

4. How would you describe your company's primary line of business (e.g., industry classification)? What kinds of products/services does your firm produce/provide and which are currently – or in the future could – benefit from smart manufacturing technology/techniques?
 - a. Approximately what percentage of your company's sales revenue is associated with your division, or the division for which you are responsible? A range is fine.
5. Is the amount of R&D your company spends as a percentage of revenue similar to that of other companies in in your industry? If there are important differences, can you describe why your company may be more/less R&D-intensive than others? As a proportion of revenue in a typical year, how much does your company invest in R&D?
6. Does your company conduct R&D related to the use/enhancement/implementation of smart manufacturing technology or techniques? If so, what are the broad objectives of that R&D (e.g., cost reduction, quality improvement, other)?

If Yes to question 6 -

7. Roughly what proportion of your company's total R&D is related to the use of smart manufacturing? Would you expect other companies in the same lines of business to say roughly the same?

8. As far as you are aware, is your division or company engaged with any industry consortia, standards organizations, or governing bodies specifically for smart manufacturing? If so, in which bodies do you participate and what are the underlying drivers for participation?

Current Use of Smart Manufacturing and Barriers to Adoption

9. Please provide a brief description of your company's use of smart manufacturing technologies in your manufacturing processes.
10. What additional areas of smart manufacturing (automation, sensing/monitoring, data feedback/integration) has your company considered, investigated or researched?
 - a. Have you conducted feasibility studies? Please describe.
 - b. Have you developed preliminary cost/benefit models? Please describe.
11. Why did you decide not to move forward (or are not moving as fast as you would like) with certain investments in smart manufacturing?
 - a. Financial benefits were not large enough
 - b. Technology not mature enough
 - c. Risk to product quality or delivery schedule
 - d. Limited resources such as investment capital and/or knowledgeable staff
 - e. Limited technical resources such as guidelines, tools, software or test cases
 - f. Legacy systems and entrenched staff and management practices
 - g. Cost of software
 - h. Logistical, down time, or hassle factors

Potential Future State of Smart Manufacturing

Table A-1 describes a better state of the world in which a bundle of capabilities and technology infrastructure is available throughout the manufacturing industry. Industry needs are in the left hand column, and NIST-provided technology infrastructure that is needed to develop and diffuse the capabilities is in the right hand column.

Table A-1. Better State of the World: Capabilities and Technology Infrastructure Available

Smart Manufacturing Capabilities	Infrastructure Technology to Help Meet Needs
<p>Managing digital data streams through models:</p> <ul style="list-style-type: none"> • CAD models including material characteristics, • Simulation models of part creation and plant layout, and • Rapid automated costing functions. 	<p>High-fidelity process models, physical model representation for flexible objects, simplified modular applications of CAM software for less sophisticated uses, data standardization, standard and simpler equipment interfaces to facilitate consistent data entry for less-skilled workers, standard terminology for automated part costing.</p>
<p>Enhanced sensing and monitoring:</p> <ul style="list-style-type: none"> • “State estimation” of critical manufacturing machines (for example: vibration, acoustics, temperature, tolerances, and pressure), and • Real-time monitoring of product attributes as they move through various stages of the production process 	<p>In-process measuring and monitoring for physical processes, self-powered sensors, robust sensors to withstand harsh manufacturing processes, data standardization, methods for calibrating sensing and monitoring systems.</p>
<p>Seamless transmission of digital information:</p> <ul style="list-style-type: none"> • Wireless transmission of digital information without interference from other data channels, • Seamless integration of smart sensors, • Interoperability between different platforms such as CAD/CAM, and • Secure data transmission (wired and wireless). 	<p>Secure data transmission; secure cloud computing and data sharing; standard communication protocols; retrofittable, plug-and-play data communications systems; data interoperability of 3D model parameters and product manufacturing information</p>
<p>Advances in analyzing data and trends:</p> <ul style="list-style-type: none"> • Interpretation and aggregation of data from sensing and monitoring networks, • “Big data” techniques for manufacturing, • predictive maintenance, • Reduction of false positives, and • Cloud computing and fee-for-service cloud based algorithms for product design, simulation, and manufacturing design. 	<p>Algorithms to interpret data from disparate sensors and systems; definition of important, relevant, and meaningful data to collect for predictive maintenance</p>
<p>Efficiently communicating information to decision makers:</p> <ul style="list-style-type: none"> • Comprehensive information interfaces human-computer interaction-based design, and • Easy-to-interpret interfaces accessible from any location. 	<p>Common taxonomy across platforms and disciplines Standards in interface design for manufacturing equipment</p>
<p>Determining required action and implementing action:</p> <ul style="list-style-type: none"> • Real-time feedback of enhanced sensing and monitoring data into factory decision making, • Automated optimization-based decision making that functions independent of human interaction, • Machine learning decision making algorithms for manufacturing, and • Reconfigurability of manufacturing systems. 	<p>Tested and validated decision models</p>

This publication is available free of charge from: <http://dx.doi.org/10.6028/NIST.GCR.16-007>

12. Based on your role as a user of smart manufacturing processes, are there any additional capabilities or technology infrastructure needs that you feel are not captured in the table above?
13. Using the below scale, please indicate (a) the importance of each of the capabilities listed in the table and (b) the level of additional development needed.

Capabilities	(a) Importance					(b) Level of additional development needed		
	1	2	3	4	5	Low	Medium	High
Managing digital data streams through models								
Enhanced sensing and monitoring								
Seamless transmission of digital information								
Advances in analyzing data and trends								
Efficiently communicating information to decision makers								
Determining required action and implementing action								

1 being low; 5 being high

Potential Benefits of Enhanced Smart Manufacturing Capabilities

The following questions ask about the impact to your company's product design and manufacturing processes if these enhanced manufacturing capabilities were available:

14. To enable us to combine your responses with the responses of others and provide NIST with a sense of potential impacts at the industry level, could you quantify the impacts we have discussed in terms of the following metrics? A range is fine.

Production Costs		+/- % Change
a	Cost of materials	%
b	Cost of energy/electricity	%
c	Cost of labor	%
d	Cost of capital equipment	%
	Costs of maintenance	%

<u>Production Costs</u>		<u>+/- % Change</u>
	Costs related to integrating manufacturing technologies	%
e	Production throughout	%
f	Overall cost of production	%

15. Would you say that your answer to the question above is representative of your industry (of companies in similar lines of business), or of only a subset? Please explain briefly how, if at all, the anticipated impacts for your company may be different from the industry as a whole, or how different industry segments may be affected differently.
16. Switching from thinking about costs to thinking about product quality or new product offerings, could you describe what changes could be expected if these capabilities were all met today? A range is fine.
- Changes in the performance of existing products?
 - Changes in the amount of customization within existing product lines?
 - Introduction of new products or product lines?
 - Other
17. To enable us to combine your responses with the responses of others and provide NIST with a sense of potential impacts at the industry level, could you quantify these impacts on product quality or new product offerings in terms of a relative change in your company's sales? A range is fine.

Impact on Sales	%
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18. Would you say that your answer to the product quality question above is representative of your industry (of companies in similar lines of business), or of only a subset? Please explain briefly how, if at all, the anticipated impacts for your company may be different from the industry as a whole, or how different industry segments may be affected differently.
19. Would you expect any changes in your company's investment patterns or risk tolerance, if the types of technologies discussed above were made available? If so, what types of changes?

Potential Roles for NIST

20. Reflecting back on the barriers to adoption for smart manufacturing technologies discussed earlier, which would be the most important infrastructure technologies NIST could support to promote adoption?

21. Are there near term activities NIST could engage in that would help promote the adoption of existing (or close to market) smart manufacturing technologies and techniques (activities having impact over next 3–5 years)?
22. Are there longer terms research agendas NIST could undertake/coordinate/fund that would increase the benefit of smart manufacturing in the future (activities having impact over the next 5–10 years)?
23. Is there anything else that we should have asked you or that you would like to mention?
24. Could you recommend any developers or end-users that we could reach out to for this study?

We Greatly Appreciate Your Time and Input

Appendix B: NIST Advanced Manufacturing Strategic Planning Study

B.1 INTERVIEW GUIDE: PERSPECTIVES OF USERS OF SMART MANUFACTURING PROCESSES

The National Institute of Standards and Technology (NIST) in the U.S. Department of Commerce has contracted with RTI International to conduct an economic analysis of standards, measurement, and general purpose technology needs that inhibit efficient development and adoption of advanced manufacturing in the United States.

The objectives of this critical strategic planning study are to

- identify current and emerging needs related to standards and measurement,
- estimate the economic impact of meeting these needs, and
- review public policy and investment options.

The study has a particular focus on 4 aspects of advanced manufacturing: (1) robotics and automation, (2) smart manufacturing processes, (3) 3D Printing (additive manufacturing), and (4) roll-to-roll manufacturing. The focus of our conversation is smart manufacturing.

Your perspective will help guide NIST's planning and investment process. Participation in this analysis is confidential; only aggregated information will be included in any deliverables or communications. Your name and your company's name will not be disclosed. We do not wish to discuss specific products, strategies, or technologies; but rather your thoughts about how investments in standards and measurement technologies would affect your company and companies like yours.

Our research products will be an economic analysis, final report, and presentation materials. All deliverables will be publicly available in late 2015 and these will be shared with you as soon as they are released.

If you have questions, please contact:

- Mike Gallaher, Case Study Lead, RTI, 919-541-5935 or mpg@rti.org
- Alan O'Connor, Principal Investigator, RTI, 919-541-8841 or oconnor@rti.org

- Gary Anderson, NIST Project Officer, NIST, 301-975-5238 or gary.anderson@nist.gov

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Respondent Contact Information

Name	
Title	
Division	
Company	
Industry	
Phone	
Email	
Location	

For our conversation today we are defining smart manufacturing to include

The creation, communication and use of electronic information, as well as the interface of these information systems with the human element, for data-driven decision support. This includes how data and information generated during the production process is communicated and used to improve the design, engineering, and production phases of the product cycle.

1. Does this definition cover the relevant areas you typically include under “smart manufacturing?” If not, what else do you include in “smart manufacturing”?
2. Please describe your background as it relates to smart manufacturing. How did you come to be in your current position?
3. Are you familiar with NIST’s activities? If so, please give a brief description of any ways that NIST currently impacts your work (through, e.g., any standards, calibration and measurement, scientific and engineering data relevant to your work).

Company Background and Level of R&D

4. How would you describe your company’s primary line of business (e.g., industry classification)? What kinds of products/services does your firm produce/provide and which are currently – or in the future could – benefit from smart manufacturing technology/techniques?
 - a. Approximately what percentage of your company’s sales revenue is associated with your division, or the division for which you are responsible? A range is fine.
5. Is the amount of R&D your company spends as a percentage of revenue similar to that of other companies in your industry? If there are important differences, can you describe why your company may be more/less R&D-intensive than others? As a proportion of revenue in a typical year, how much does your company invest in R&D?
6. Does your company conduct R&D related to the use/enhancement/implementation of smart manufacturing technology or techniques? If so, what are the broad objectives of that R&D (e.g., cost reduction, quality improvement, other)?

If Yes to question 6 -

7. Roughly what proportion of your company’s total R&D is related to the use of smart manufacturing? Would you expect other companies in the same lines of business to say roughly the same?
8. As far as you are aware, is your division or company engaged with any industry consortia, standards organizations, or governing bodies specifically for smart manufacturing? If so, in which bodies do you participate and what are the underlying drivers for participation?

Current Use of Smart Manufacturing and Barriers to Adoption

9. Please provide a brief description of your company's use of smart manufacturing technologies in your manufacturing processes.
10. What additional areas of smart manufacturing (automation, sensing/monitoring, data feedback/integration) has your company considered, investigated or researched?
 - a. Have you conducted feasibility studies? Please describe.
 - b. Have you developed preliminary cost/benefit models? Please describe.
11. Why did you decide not to move forward (or are not moving as fast as you would like) with certain investments in smart manufacturing?
 - a. Financial benefits were not large enough
 - b. Technology not mature enough
 - c. Risk to product quality or delivery schedule
 - d. Limited resources such as investment capital and/or knowledgeable staff
 - e. Limited technical resources such as guidelines, tools, software or test cases
 - f. Legacy systems and entrenched staff and management practices
 - g. Cost of software
 - h. Logistical, down time, or hassle factors

Potential Future State of Smart Manufacturing

The Table B-1 describes a better state of the world in which a bundle of capabilities and technology infrastructure is available throughout the manufacturing industry. Industry needs are in the left hand column, and NIST-provided technology infrastructure that is needed to develop and diffuse the capabilities is in the right hand column.

Table B-1. Better State of the World: Capabilities and Technology Infrastructure Available

Smart Manufacturing Capabilities	Infrastructure Technology to Help Meet Needs
<p>Managing digital data streams through models:</p> <ul style="list-style-type: none"> • CAD models including material characteristics, • Simulation models of part creation and plant layout, and • Rapid automated costing functions. 	<p>High-fidelity process models, physical model representation for flexible objects, simplified modular applications of CAM software for less sophisticated uses, data standardization, standard and simpler equipment interfaces to facilitate consistent data entry for less-skilled workers, standard terminology for automated part costing.</p>
<p>Enhanced sensing and monitoring:</p> <ul style="list-style-type: none"> • “State estimation” of critical manufacturing machines (for example: vibration, acoustics, temperature, tolerances, and pressure), and • Real-time monitoring of product attributes as they move through various stages of the production process 	<p>In-process measuring and monitoring for physical processes, self-powered sensors, robust sensors to withstand harsh manufacturing processes, data standardization, methods for calibrating sensing and monitoring systems.</p>
<p>Seamless transmission of digital information:</p> <ul style="list-style-type: none"> • Wireless transmission of digital information without interference from other data channels, • Seamless integration of smart sensors, • Interoperability between different platforms such as CAD/CAM, and • Secure data transmission (wired and wireless). 	<p>Secure data transmission; secure cloud computing and data sharing; standard communication protocols; retrofitable, plug-and-play data communications systems; data interoperability of 3D model parameters and product manufacturing information</p>
<p>Advances in analyzing data and trends:</p> <ul style="list-style-type: none"> • Interpretation and aggregation of data from sensing and monitoring networks, • “Big data” techniques for manufacturing, • predictive maintenance, • Reduction of false positives, and • Cloud computing and fee-for-service cloud based algorithms for product design, simulation, and manufacturing design. 	<p>Algorithms to interpret data from disparate sensors and systems; definition of important, relevant, and meaningful data to collect for predictive maintenance</p>
<p>Efficiently communicating information to decision makers:</p> <ul style="list-style-type: none"> • Comprehensive information interfaces human-computer interaction-based design, and • Easy-to-interpret interfaces accessible from any location. 	<p>Common taxonomy across platforms and disciplines Standards in interface design for manufacturing equipment</p>
<p>Determining required action and implementing action:</p> <ul style="list-style-type: none"> • Real-time feedback of enhanced sensing and monitoring data into factory decision making, • Automated optimization-based decision making that functions independent of human interaction, • Machine learning decision making algorithms for manufacturing, and • Reconfigurability of manufacturing systems. 	<p>Tested and validated decision models</p>

This publication is available free of charge from: <http://dx.doi.org/10.6028/NIST.GCR.16-007>

12. Based on your role as a user of smart manufacturing processes, are there any additional capabilities or technology infrastructure needs that you feel are not captured in the table above?
13. Using the below scale, please indicate (a) the importance of each of the capabilities listed in the table and (b) the level of additional development needed.

Capabilities	(a) Importance					(b) Level of additional development needed		
	1	2	3	4	5	Low	Medium	High
Managing digital data streams through models								
Enhanced sensing and monitoring								
Seamless transmission of digital information								
Advances in analyzing data and trends								
Efficiently communicating information to decision makers								
Determining required action and implementing action								

1 being low; 5 being high

Potential Benefits of Enhanced Smart Manufacturing Capabilities

The following questions ask about the impact to your company's product design and manufacturing processes if these enhanced manufacturing capabilities were available:

14. To enable us to combine your responses with the responses of others and provide NIST with a sense of potential impacts at the industry level, could you quantify the impacts we have discussed in terms of the following metrics? A range is fine.

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<u>Production Costs</u>		<u>+/- % Change</u>
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15. Would you say that your answer to the question above is representative of your industry (of companies in similar lines of business), or of only a subset? Please explain briefly how, if at all, the anticipated impacts for your company may be different from the industry as a whole, or how different industry segments may be affected differently.
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Potential Roles for NIST

- 20. Reflecting back on the barriers to adoption for smart manufacturing technologies discussed earlier, which would be the most important infrastructure technologies NIST could support to promote adoption?
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Appendix C: Example Vignettes

The following are two examples of technology infrastructure needs identified during stakeholder interviews and the approach to estimating the economic benefits.

C.1 CLOUD-BASED SOFTWARE AND COMPUTING FOR SMALL AND MEDIUM-SIZED MANUFACTURERS

RTI spoke with several software companies that are currently looking to license digital manufacturing software packages to companies in a variety of sectors, including industrial equipment, automotive, aerospace, and shipbuilding. In the terminology described above, these software companies can be considered technology developers supporting users in the discrete manufacturing sectors.

The software enables SMEs and OEMs to more efficiently manage the entire life cycles for their products. Among the many capabilities these software packages offer, one key capability is virtual simulation of manufacturing production systems. Being able to accurately and flexibly simulate the production of new products in a digital environment has the first-order effect of decreasing the costs of prototyping and testing, which has traditionally been done in the physical environment and can lead to substantial costs. The second-order effect of virtual simulation is increased innovation, because the marginal costs associated with bringing new products to fruition can be orders of magnitude smaller.

The current market is primarily limited to large manufacturers that are able to justify the high fixed cost of a new software package and the required computational power based on economies of scale/ROI. It is difficult for most SMEs to justify the high fixed costs of licensing these types of software in the traditional manner or purchasing the computers needed to run the simulations. Given that the current market is mainly constrained to large firms, decreasing the cost (cost of software plus the cost of implementation) would increase market penetration and adoption of these technologies among SMEs, which could yield substantial economic benefits.

To estimate the economic benefits associated with the cloud-based licensing of manufacturing software and computing power, we would need information on both the cost reduction of existing R&D activities and the value creation of new

products/processes enabled by enhanced simulation capabilities. From a market perspective, we are modeling the product or service the SME is selling, hence we need information on the following:

- Change in production costs (shift in the supply function)
 - Cost reduction of the software (\$/use) relative to the old market model
 - Decreased cost of prototyping and testing new products (percentage change in the average cost/product)
- Change in produced value/quality (shift in the demand function)
 - Value of increased levels of innovation and improved product attributes resulting from using the simulation (users' increased willingness to pay)

With these shifts, adoption may increase as a result of the lower cost and increased demand. The quantity being modeled in this supply-demand framework can either be the number of SMEs using simulation capabilities or the number of products being designed using simulation capabilities. In the latter, the new simulation capabilities would streamline the process, leading to companies redesigning their product offerings more frequently, which would provide increased value to OEMs as products evolve and improve at a faster rate.

One software company that RTI spoke with envisions a model in which NIST's MEPs would host their software tools in the cloud and rent access to the software to regional manufacturing companies. This more centralized approach to software ownership would decrease the direct software costs incurred by any single manufacturer and potentially decrease the indirect implementation costs. In addition to software ownership, MEPs could provide ongoing training and support for the cloud-based software. While NIST would want to consider such a model based on the merits of particular software packages, the idea could be applied more broadly to an open protocol manufacturing platform, and MEPs could purchase and license plug-in applications developed by the private sector. As mentioned in the Technology & Industry Report, a specific technology infrastructure need for smart manufacturing processes is high-fidelity process models. If successfully

developed, NIST could distribute these process models using the MEP network.

C.2 PREDICTIVE MAINTENANCE IN THE ELECTRIC UTILITY INDUSTRY

One large electric utility company is actively expanding the sensing/monitoring performance of its gas turbines and then centralizing the data analysis at its office headquarters. The price of an electricity generation turbine ranges from \$20 million to \$80 million; thus, predictive capabilities to help avoid catastrophic failure could have a significant economic benefit. In addition, predictive analysis systems could help coordinate routine maintenance and minimize equipment downtime.

There is no shortage of companies producing the required sensor, analysis software, and reporting packages. However, the open-source communications protocols to link individual products do not exist. As a result, turbine manufacturers have been able to dominate the market by providing dedicated vertical systems that integrate the sensing, communication, analysis, and reporting on equipment vibration and other key parameters. However, these custom systems tend to be expensive (about \$250,000 each), which has greatly limited their adoption (hence potential benefits).

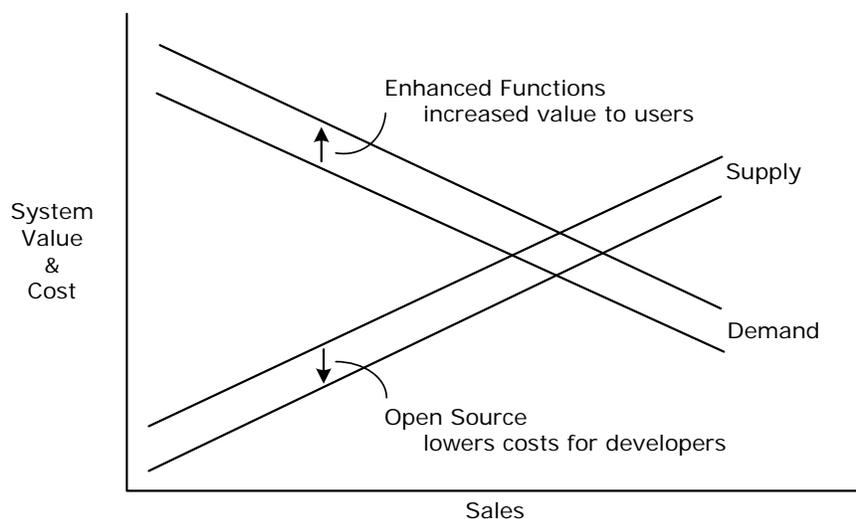
If, however, open-source communications platforms were available, flexible systems could be developed at a much lower cost using readily available components from specialized developers (potentially as low as \$10,000). The following outcomes might result:

1. The cost of delivering the sensing, analysis, and reporting capabilities needed for predictive maintenance might decrease. This change can be viewed as a downward shift in the supply curve that lowers the cost per system (keeping capabilities of the system constant for the time). This lower cost generates a producer surplus for the technology developers, lowering production cost and greatly increasing the number of units sold (adoption).
2. The electric utilities as the users of the system now are able to realize the benefits from predictive maintenance, which are represented as the area under the demand curve. Benefits could include:

- extended life expectancy of turbines due to a reduction in catastrophic failures,
- reduced repair and routine maintenance costs, and
- higher overall capacity utilization rate (less need for redundant excess capacity).

In the above example, because the capabilities of the system did not change, the demand curve does not shift; users benefit from greater adoption and the realization of the benefits (because the cost of adoption has decreased). However, if additional capabilities are now available (e.g., in addition to monitoring vibration, the system is now capable of monitoring bearing wear and hot spots), this would shift the demand curve because the overall value of the system to the electric utility has increased (see Figure C-1).

Figure C-1. Market for Smart Sensing/Monitoring Systems



To estimate the economic benefits associated with the technology infrastructure (protocols) needed to support the open-source communications system, we would need the following information:

1. Cost reduction of the new systems (\$\$/system)
2. Potential increased adoption resulting from the cost reductions (number of additional systems)
3. Value of the benefits (listed above) to the electric utility
 - a. Holding capabilities the same and/or
 - b. with expanded/enhanced capabilities

In this example, a single electric utility has launched an initiative to solve the open-source protocol barriers in conjunction with a team of sensor and software suppliers. This example illustrates the magnitude of the potential benefit to the utility. However, respondents indicated that what was more urgently needed was a larger initiative that would include additional utilities, suppliers, and standards organizations such as NIST.