Implementing 21st Century Smart Manufacturing

Workshop Summary Report

DRAFT

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Prepared by

SMLC

Smart Manufacturing Leadership Coalition

About this Report

This report describes a framework for a proposed path forward for Smart Manufacturing in a number of priority areas. The report reflects the views of a national cross-section of industry leaders involved in planning the future of the process industries, vendors supplying technology solutions for manufacturing operations, and academic researchers engaged in a range of associated systems research. The report is based on information generated during the workshop on Implementing 21st Century Smart Manufacturing held in Washington, D.C. in September 2010, and from subsequent discussions among members of the Smart Manufacturing Leadership Coalition. A complete list of participants who contributed their valuable ideas at the workshop is shown on the facing page.

About the Smart Manufacturing Leadership Coalition

The Smart Manufacturing Leadership Coalition (SMLC) is an organization of manufacturing practitioner, supplier, and technology companies; manufacturing consortia; universities; and government laboratories committed to the goals of Smart Manufacturing. The coalition has collectively developed and is pursuing a comprehensive technology and business roadmap to develop and implement Smart Manufacturing capabilities that will enable next-generation economic, energy, sustainability and EH&S manufacturing performance and competitiveness.

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Executive Summary

21st Century Smart Manufacturing applies information and manufacturing intelligence to integrate the voice, demands and intelligence of the 'customer' throughout the entire manufacturing supply chain. This enables a coordinated and performance-oriented manufacturing enterprise that quickly responds to the customer and minimizes energy and material usage while maximizing environmental sustainability, health and safety, and economic competitiveness. Innovations that allow diverse devices, machines, and equipment to communicate seamlessly are opening the door for much wider use of system simulation and optimization software in the operation and control of advanced manufacturing systems. Today, smart tools and systems that both generate and use greater amounts of data and information are being used to innovate, plan, design, build, operate, maintain, and manage industrial facilities and systems in dynamic ways that significantly increase efficiency, reduce waste, and improve competitiveness.

While industry is making progress in developing and using smart manufacturing, the infrastructure and capabilities needed to deliver the full potential of this knowledge-based manufacturing environment have yet to be developed. Challenges include incorporating and integrating customer intelligence and demand dynamics and the needs for greater affordability, operator usability, protection of proprietary data, systems interoperability, and cyber security.

To identify and prioritize the actions needed to overcome some of these challenges in smart manufacturing, a workshop on Implementing 21st Century Smart Manufacturing was held in Washington, D.C., on September 14-15, 2010.

Figure ES-1. Proposed Outcomes and Goals for Smart Manufacturing

Goals to Achieve Outcomes

- Lower the cost for applying advanced data analysis, modeling, and simulation in core manufacturing processes.
- Lower the cost of pre-competitive infrastructure, including data and information networks, interoperable hardware and software, and shared business data.
- Establish an industry-shared, community-source platform that provides access to customizable open-access software, serves as an applications or "apps" store and clearinghouse and facilitates innovation.
- Create and provide broad access to next-generation sensing technologies and the digital infrastructure for the enterprise application of manufacturing intelligence, (e.g., disposable sensors, data fusion, wired and wireless networks which combine data from different sources to achieve greater measurement accuracy and more intelligence).
- Establish national test beds or accessible user facilities for smart manufacturing concepts and make them available to companies of all sizes.
- Develop virtual factory and supply chain tools (e.g., real-time simulation and visualization, virtual test beds, dynamic risk analysis, dynamic supplier involvement) for real-time planning and point-in-time tracking/traceability of materials and products.
- Apply dashboard performance tools (e.g., key performance indicators, dynamic monitoring, dynamic visualization of critical data, like a car dashboard) across the enterprise to manage dynamic production, use, and storage of essential resources (energy, water, air) sustainability and EH&S.

Overarching Outcomes

Technology Innovation and Economic Health
Highly integrated smart systems provide pathways for competitively manufacturing materials and products.

Agility
Agile processes in highly optimized manufacturing plants and supply networks enable rapid response to changes in customer demands.

Resource Efficiency
Ready access to manufacturing intelligence allows factories to run more efficiently and minimize use of resources.

Safety and Confidence
Products and processes are guaranteed safe and reliable through tracking of sustainable production and real-time handling of materials.

Next Generation Workforce
A manufacturing workforce with advanced skills and talent maximizes the benefits of manufacturing intelligence.

Sustainability
Smart processes minimize environmental impacts and improve sustainability of critical sectors (clean energy, defense, homeland security).

This report summarizes the results of the workshop. It reflects the consensus of a national cross-section of industry leaders involved with planning the future of the process industries, vendors of technology solutions for manufacturing operations, and academic researchers engaged in a range of associated systems research. The overarching goals and outcomes for SM, as identified at the workshop, are shown in Figure ES-1. The outcomes illustrate the broad potential benefits to be gained through greater use of smart manufacturing concepts in U.S. factories and supply chains.

Ten actions were identified as priorities to move SM into a broader spectrum of the industrial sector and enable the use of SM in a range of plant sizes and companies. Although these 10 actions (shown in Figure ES-2) emerged from discussions of three distinct operational structures (batch, continuous, and discrete), these actions generally apply to most of the manufacturing sector. Proposed implementation plans for each of these priority actions are described in Section 3 of this report.

Figure ES-2. Ten Priority Actions for Smart Manufacturing

Industrial Community Modeling and Simulation Platforms for Smart Manufacturing

1. Create community platforms (networks, software) for the virtual plant enterprise	2. Develop next generation toolbox of software and computing architectures for manufacturing decision-making	3. Integrate human factors and decisions into plant optimization software and user interfaces	4. Expand availability of energy decision tools (energy dashboards, automated data feedback systems, energy 'apps' for mobile devices) for multiple industries and diverse skill levels

Affordable Industrial Data Collection and Management Systems

5. Establish consistent, efficient data methods for all industries (data protocols and interfaces, communication standards)	6. Develop robust data collection frameworks (sensors/ data fusion, machine and user interfaces, data recording and retrieval tools)

Enterprise-wide Integration: Business Systems, Manufacturing Plants, and Suppliers

7. Optimize supply chain performance through common reporting and rating methods (dashboard reports, metrics, common data architecture and language)	8. Develop open platform software and hardware to integrate and transfer data between small and medium enterprises (SMEs) and original equipment manufacturers (OEMs) (data sharing systems and standards, common reference architectures)	9. Integrate product and manufacturing process models (software, networks, virtual and real-time simulations, data transfer systems)

Education and Training in Smart Manufacturing

10. Enhance education and training to build workforce for smart manufacturing (training modules, curricula, design standards, learner interfaces)

1. Introduction

Overview of Smart Manufacturing

Intense global competition, uncertainties in energy cost and supply, and exponential growth in information technology are shifting industries toward agile, just-in-time processing, high-performance manufacturing, and accelerated introduction of new products. Business performance is increasingly linked to sustainability and environmental, health, and safety (EHS) issues. Companies can use smart manufacturing (SM) to help meet objectives associated with these issues and improve overall economy, safety, and competitiveness.

From an engineering standpoint, smart manufacturing is the intensified application of advanced intelligence systems to enable rapid manufacturing of new products, dynamic response to product demand, and real-time optimization of manufacturing production and supply chain networks. SM connects all aspects of manufacturing, from intake of raw materials to the delivery of finished products to market. It creates a knowledge-rich environment across a spectrum of products, operations, and business systems–spanning factories, distribution centers, companies, and entire supply chains.

Over the last decade, the evolution in digital computing and communications has fundamentally changed the way manufacturing plants operate. Digital plants are creating new opportunities for the adoption of smart manufacturing techniques to support more agile operations and accelerated product and business cycles. Today, smart tools and systems are being used to innovate, plan, design, build, operate, maintain, and manage industrial facilities in significantly improved ways. Figure 1-1 suggests a few of the many potential applications.

While industry is making progress in developing and using smart manufacturing, the systemic infrastructure and capabilities needed to deliver and mobilize a knowledge-based manufacturing environment remain to be developed. The cost of developing and implementing open source software and technologies remains high, creating a significant barrier to entry—particularly for small- and medium-size enterprises (SMEs). Limitations in operator usability, protection of proprietary data, systems interoperability, and cyber security also continue to impede progress.

Figure 1-1. Current and Potential Applications of Smart Manufacturing

- Digital control systems with embedded, automated process controls, operator tools, and service information systems can optimize plant operations and safety.
- Asset management using predictive maintenance tools, statistical evaluation, and measurements could maximize plant reliability.
- Smart sensors could detect anomalies and help avoid abnormal or catastrophic events.
- Smart systems integrated within the industrial energy management system and externally with the smart grid could enable real-time energy optimization.

Industry has some compelling reasons to explore the use of smart manufacturing, as shown in Figure 1-2. The effective integration of these SM components could enable unprecedented manufacturing productivity. Widespread application of smart, virtual plant enterprise tools have the potential to more quickly move new products from concept to commercialization. In addition to cost and time savings, SM can optimize energy use, improve carbon footprints, and promote environmental sustainability. Further benefits include reduced plant maintenance costs and improved safety. Potential improvements in supply chain interaction could dramatically reduce inventories, increase product customization, and enhance product availability while facilitating traceability throughout the manufacturing process.

Figure 1-2. Benefits of Smart Manufacturing

- Reduces time to market
- Leverages dynamic demand-driven economics
- Drives higher export markets
- Provides global competitive edge
- Enables progress toward zero incidents and emissions performance
- Takes advantage of integrated energy management and the smart grid
- Enables agile response to consumer demand

Figure 1-3. Essential Technologies for Smart Manufacturing

- **Networked sensors**–Data for communications, automated controls, planning and predictive models, plant optimization, health and safety management, and other functions will be provided by large numbers of networked sectors.
- **Data interoperability**–Seamless exchange of electronic product, process, and project data is enabled through interoperable data systems used by collaborating divisions or companies and across design, construction, maintenance, and business systems.
- **Multi-scale dynamic modeling and simulation**–Business planning and scheduling can be fully integrated with operations via multi-scale models that support enterprise-wide coordination and enable large-scale optimization across companies and supply chains.
- **Intelligent automation**–Automated, learning systems are vital to SM but must be effectively integrated with the human learning and decision environment.
- **Scalable, multi-level cyber security**–System protection from cyber vulnerabilities (without compromise of functionality) is needed throughout the manufacturing enterprise.

Source: Smart Process Manufacturing: An Operations and Technology Roadmap, November 2009.

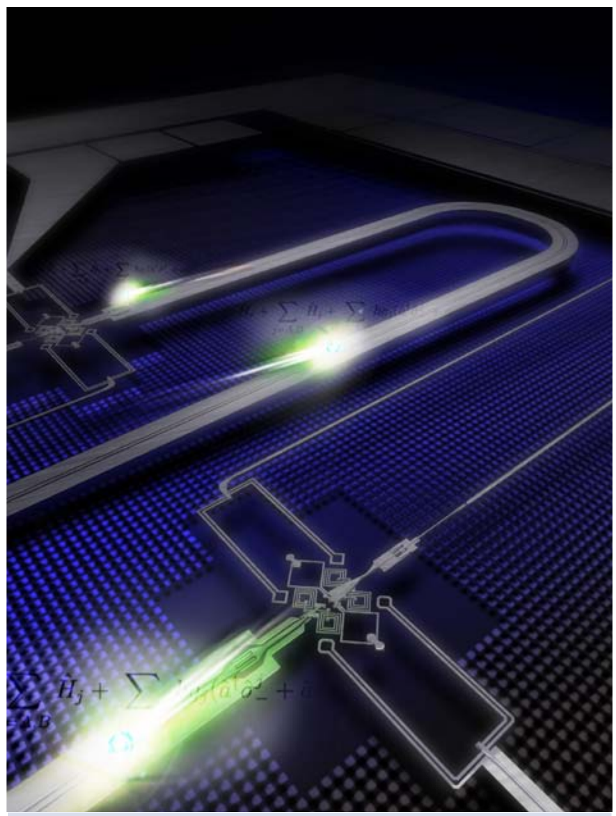
As shown in Figure 1-3, technologies at the core of smart manufacturing collectively enable effective integration of the increasingly complex components that make up modern manufacturing systems. Continued advances in these technologies are needed to enable a substantially greater segment of industrial plants to take advantage of smart manufacturing concepts.

Workshop Objectives and Outcomes

The workshop on Implementing 21st Century Smart Manufacturing was held in Washington, D.C., on September 14-15, 2010, to identify and prioritize the actions needed to overcome some of the challenges to smart manufacturing and foster widespread implementation. The workshop tapped the expertise and insights of 75 experts from a diverse cross-section of industry, government, academia, and the national laboratories.

The workshop built upon critical technology areas that had been identified in a 2009 report, S*mart Process Manufacturing: An Operations and Technology Roadmap* (https://smart-process-manufacturing.ucla.edu/). Using that document as a foundation, participants worked to identify and further describe a set of 10 discrete, priority actions.

During the workshop, separate breakout groups discussed priority actions to promote SM in each of the three manufacturing structures as described in Figure 1-4: batch, continuous, and discrete. Each of these structures has distinct operating characteristics, and most industries are dominated by one of the three. In some industries, however, two or more operating structures may be present, particularly when there are thousands of different products. Food processing, for example, uses batch and continuous processing as well as discrete, with the potential to significantly facilitate use of SM across the industrial sector.



Artist's rendition of superconducting quantum cable, which could enable future quantum computers to break codes, search databases, and perform other tasks at exponentially higher speeds than today's most powerful computers

Source: National Institute of Standards and Technology. Illustration by: Michael Kemper

Most of the priorities identified were found to be cross-cutting in nature—i.e., they are important to all types of manufacturing regardless of operating structure. Ideally, the outcomes of these actions will achieve progress toward an affordable computational environment that can be implemented by a wide range of enterprises, from small to large. In that environment, manufacturing intelligence (i.e., data, and information gathered on all aspects of manufacturing) could be applied to achieve optimized, sustainable, agile, and demand-driven industrial plants and supply chains.

This summary report outlines the 10 priority actions and the relevant pathways for implementation. Mechanisms for industry-academia-government collaborations are also suggested to catalyze breakthroughs and encourage technology transfer to a wide segment of industry.

Figure 1-4. Breakout Groups for Manufacturing Operations

- **Batch operations** manufacture products from a few material inputs in single lots or batches; start-up, shut down, set-up, and clean-out costs impact performance; industries include pharmaceuticals, specialty glass, chemicals, semiconductors, and engineered materials.
- **Continuous operations** manufacture a wide range of products from few material inputs; capacity utilization and final product inventories impact performance; industries in this category include chemicals, petroleum refining, steel making, pulp and paper, and aluminum.
- **Discrete operations** assemble products from a large number of components; control of component inventories and responsiveness to orders impact performance (e.g., assembly, packaging, and fabrication); industries include consumer electronics, automotive, and equipment and machinery manufacture.

Automated production line in modern dairy factory
Photo Credit: iStock/8159592

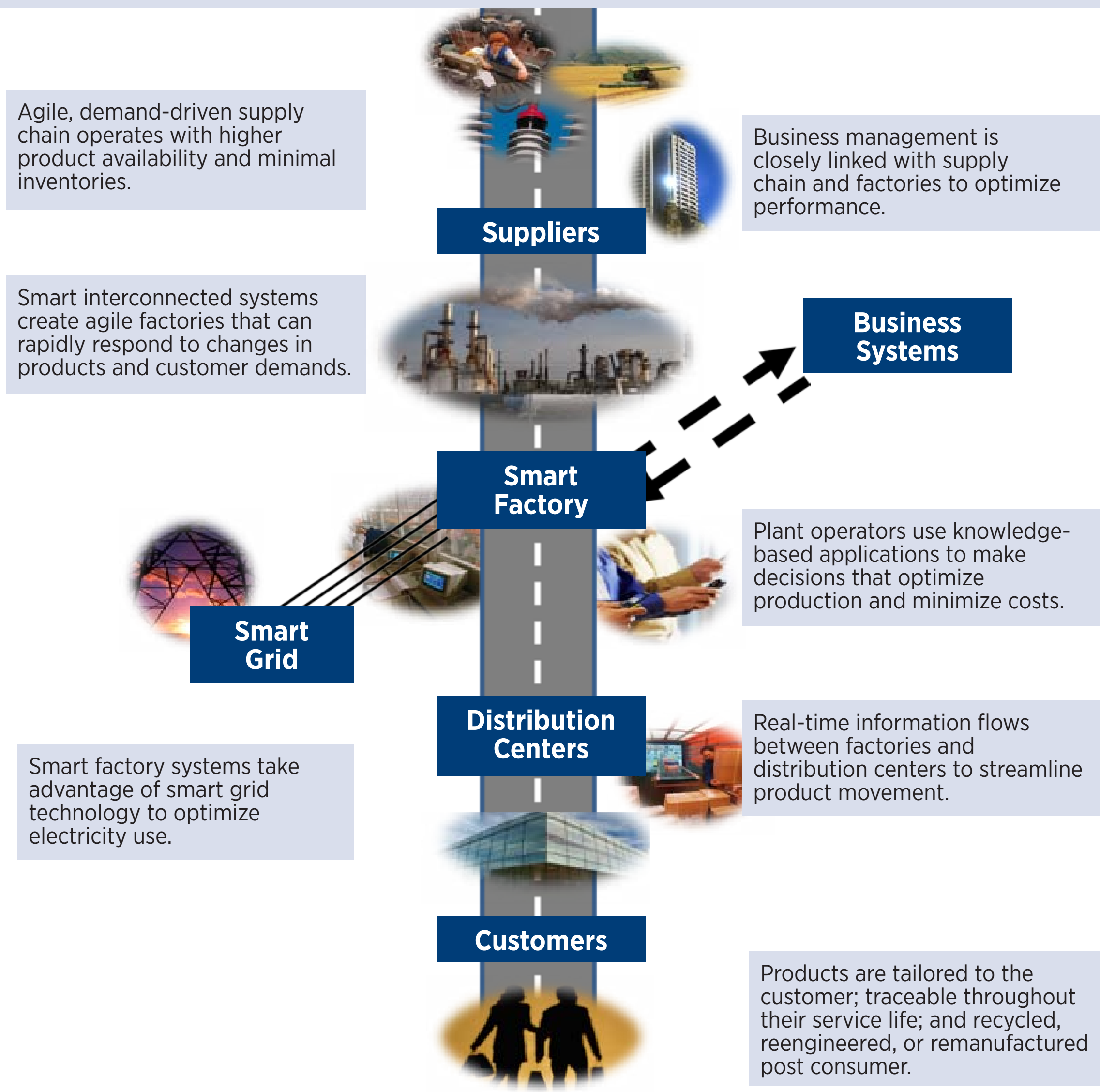
2. Vision and Goals for the Smart Manufacturing Enterprise

Vision for the Future

The ideal smart manufacturing enterprise would comprise all aspects of manufacturing, from plant operations to the supply chain, and enable virtual tracking of capital assets, processes, and resources throughout the entire product life cycle. The end result would be flexible, agile, and innovative manufacturing environments in which performance and efficiency are optimized and business and manufacturing operations work efficiently in tandem. A proposed vision for this smart manufacturing enterprise is illustrated in Figure 2-1. A number of companies are already embracing portions of the coordinated, smart enterprise approach.

Figure 2-1. Concept of the Smart Manufacturing Enterprise

Smart, modern factories are interconnected with suppliers, distributors, customers, and business systems via information technology (data, voice, mobile, etc.) to create a highly optimized and competitive business enterprise.



Goals and Performance Metrics

A number of manufacturing goals could be achieved through advances in smart manufacturing and the implementation of key concepts. These goals will lead to overarching outcomes, as outlined below.

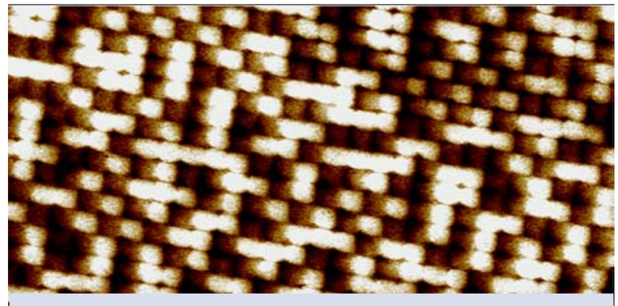
2020 Goals

Achievement of the following goals will be instrumental in attaining the overarching outcomes described above.

- Lower the cost for applying advanced data analysis, modeling, and simulation in core manufacturing processes.
- Lower the cost of pre-competitive infrastructure, including data and information networks, interoperable hardware and software, and shared business data.
- Establish an industry-shared, community-source platform that provides access to customizable open-access software, serves as an applications or "apps" store and clearinghouse and facilitates innovation.
- Create and provide broad access to next-generation sensing technologies and the digital infrastructure for the enterprise application of manufacturing intelligence, (e.g., disposable sensors, data fusion, wired and wireless networks which combine data from different sources to achieve greater measurement accuracy and more intelligence).
- Establish national test beds or accessible user facilities for smart manufacturing concepts and make them available to companies of all sizes.
- Develop virtual factory and supply chain tools (e.g., real-time simulation and visualization, virtual test beds, dynamic risk analysis, dynamic supplier involvement) for real-time planning and point-in-time tracking/traceability of materials and products.

Automated sorting of solar cells at BP Solar Facility in Frederick, MD

Photo Credit: DOE/NREL



Nanodot arrays that respond to magnetic fields with record levels of uniformity will enhance prospects for commercially viable nanodot computer drives, which will provide at least 100 times the capacity of today's hard disk drives

Photo Credit: National Institute of Standards and Technology. Justin Shaw

- Apply dashboard performance tools (e.g., key performance indicators, dynamic monitoring, dynamic visualization of critical data, like a car dashboard) across the enterprise to manage dynamic production, use, and storage of essential resources (energy, water, air) sustainability and EH&S.

Overarching Outcomes

Technology innovation and economic health. Highly integrated smart systems will enable the development of innovative pathways to competitively manufacture existing and novel materials and products in response to growing domestic and global markets.

Agility. Agile processes in highly optimized manufacturing plants and supply networks will enable rapid response to fluctuations or new trends in customer demands.

Resource efficiency. Ready access to usable manufacturing intelligence on operational inputs (energy, water, materials, labor, and time) will allow factories to run more efficiently and minimize the use of precious resources.

Safety and confidence. Products and processes will be guaranteed safe and reliable through comprehensive tracking of the sustainable production and real-time handling of all material inputs throughout the factory and supply networks.

Sustainability. Smart U.S. manufacturing processes will minimize impacts on the environment and climate and improve the sustainability of critical U.S. industries, such as clean energy, defense, biotechnology, medicine, and homeland security.

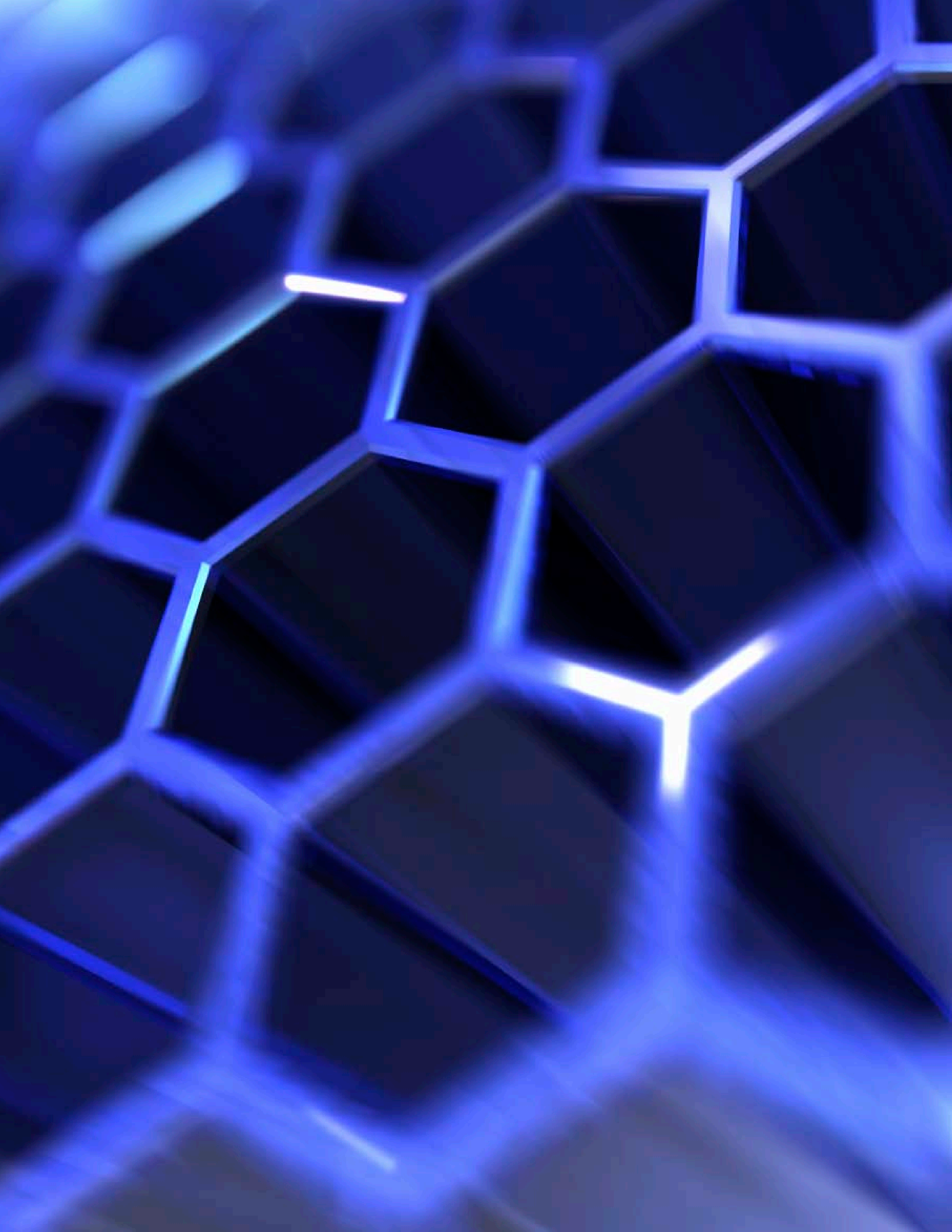
Next-generation workforce. A manufacturing workforce with advanced skills and talent will be able to more fully take advantage of manufacturing intelligence.

Measures of Performance

Table 1 identifies the metrics for evaluating progress toward overarching outcomes and goals. While interim progress can be achieved in the near- and mid-term, most of these metrics assume a 2020 timeframe for goal attainment.

Table 1. Metrics for Assessing Progress Toward Goals

Reduced product cycles	Achieve a 10-fold acceleration in commercialization cycles (from idea to market). This would provide a competitive edge in global markets and drive a significant increase in exports.
Reduced costs associated with SM models and tools	Reduce the implementation cost of smart software and systems by 80-90% from current benchmarks, with substantial reductions achieved by 2015. More affordable models and computing platforms will drive wider adoption of SM in all types of operations.
Enterprise-wide implementation of SM concepts	Drive toward modeling 90% of plant assets (equipment, systems) in 75% of plant operations across the manufacturing enterprise. Routine and widespread use of SM in manufacturing and business operations will revolutionize and optimize the way business is transacted across companies and supply chains.
Demand-driven, efficient use of resources in highly optimized, safe industrial plants	Enable lasting and significant impacts on manufacturing performance, including • A 20% increase in operating efficiency, leading to a 30% reduction in operating costs • A 25% reduction in safety incidents • A 25% improvement in energy efficiency • Up to a 40% reduction in cycle times • A 40% reduction in water use • Product tracking and traceability throughout the supply chain
Create common understanding of product sustainability	Achieve data and modeling frameworks to enable transparent understanding of product sustainability from cradle to grave and create pathways to incentives for supply chain sustainability.
Maintain and grow the existing U.S. industrial base	Create an environment conducive to innovation and achieve integration of engineering and business systems across companies, industries, and supply chains. Measures of progress include the following: • Revenue increase of 25% by expansion of suppliers into adjacent or entirely new industries • Revenue increase of 25% from new products and services • Double the capacity of small and medium enterprises in the total market space • Commensurate increases in highly skilled, sustainable jobs



3. Proposed Action Plan

Ten priority actions were identified on the basis of their potential to substantially increase the penetration of SM into a broader spectrum of the industrial sector, and to enable the use of SM in a range of plant sizes and companies, from small to large. The priority actions are organized into the following four categories:

- Industrial Community Modeling and Simulation Platforms for Smart Manufacturing
- Affordable Industrial Data Collection and Management Systems
- Enterprise-wide Integration: Business Systems, Manufacturing Plants, and Suppliers
- Education and Training in Smart Manufacturing

Proposed implementation plans for each of the priority actions are described below and in Figures 3-1 to 3-10.

Industrial Community Modeling and Simulation Platforms for Smart Manufacturing

Greater use of SM will require models and computing platforms that are easily accessible and available to a wide range of users yet protect intellectual property. Computational tools will also need advanced functionality to support more sophisticated analysis and decision making in the plant environment and enable integration with business systems across the manufacturing enterprise. This functionality includes integration of all key performance indicators and enterprise-wide data, encompassing raw materials, equipment, utilities, facilities, products, and logistics. Human factors must also be incorporated into decision tools and automated systems to enable the integration of "machine" knowledge with human behavior and actions.

Robotic, computer-controlled automotive assembly line
Photo by Rainer Plendl, provided by iStock/9919705

The priority actions needed to achieve community platforms are outlined below; detailed priority action plans are provided in Figures 3-1 to 3-4.

Priority Action 1: **Create Community Modeling and Simulation Platforms for the Virtual Plant Enterprise**

Standardized, community-accessible, open-source computing platforms (customizable, open-access software, data networks) with plug-and-play capability are needed to successfully apply smart manufacturing systems across a broad segment of industrial users, from small to large. These platforms would utilize generic application modules than can be internally customized by individual companies to simulate specific plant configurations without exposing intellectual property to external software developers. Standards and protocols will also be needed to support mixing and matching of generic modules and effective data exchange.

Priority Action 2: **Develop Next-Generation Toolbox of Software and Computing Architectures for Manufacturing Decision Making**

Next-generation software and computing architectures are needed to effectively mine data and use it to solve complex problems and enable decision making based on a wide range of technical and business parameters. Advanced software would incorporate risk assessment into plant management; deliver energy management and optimization techniques; and provide faster, more efficient operational management tools.

Priority Action 3: **Integrate Human Factors and Decisions into Plant Optimization Software and User Interfaces**

Tools and techniques are needed to better integrate human factors and decisions into smart software tools. This integration would enable faster, more disciplined decision making on the plant floor and allow operators to become “knowledge” workers. Integration of human decisions would also enable operators to see the more immediate impacts of their actions and foster an environment of continuous improvement. Plant-operator user-friendly interfaces will also be needed to enable ready application of software tools.

Priority Action 4: **Expand Availability of Energy Decision Tools for Multiple Industries and Diverse Skill Levels**

Tools (e.g., energy dashboards, automated data feedback systems, energy “apps”for mobile devices, energy optimization software) are needed to improve real-time decision making about energy use and options across the manufacturing plant. Collecting and interpreting energy data at the level required to make effective decisions can be challenging and time consuming. In some cases, plant personnel lack the knowledge to correctly interpret such data. Integration of plant energy data with external information, such as the current cost of energy at the local utility, weather conditions, and other factors, could provide new insights and enable comparison of diverse energy options.

Figure 3-1.

Priority Action: Create Community Modeling and Simulation Platforms for the Virtual Plant Enterprise

Standardized, community-accessible, open-source computing platforms (customizable, open-access software, data networks) with plug-and-play capability are needed to successfully apply smart manufacturing systems across a broad segment of industrial users, from small to large. These platforms would utilize generic application modules than can be internally customized by individual companies to simulate specific plant configurations without exposing intellectual property to external software developers. Standards and protocols will also be needed to support mixing and matching of generic modules and effective data exchange.

Barriers

- High cost of software and customizing tools for individual plants
- Lack of platforms/software that can easily be applied across sectors
- Inadequate accessibility/feasibility of SM tools for small/medium enterprises (SMEs)

Benefits

- Enables manufacturers (from small to large) to adopt and customize software
- Standardizes models to enable consistent use and results
- Makes software development faster, easier, and cheaper
- Supports improvements in operating efficiency, safety, health, energy use, and the environment
- Improves usability in diverse environments
- Engages entrepreneurs to develop new software modules

Action Plan

2012

Develop cross-industry plan to attack problem; define the scale and relative difficulty of each element

- Focus initially on energy management as phase one
- Benchmark current competencies
- Develop/define key performance indicators (KPIs)—process and products
- Define data and architecture needs

Develop data federation infrastructure to enable transfer and testing of beta systems

Establish standards and architecture for plug-and-play, modular, modeling platform and infrastructure

2015

Conduct multi-industry demonstration of robust software with key characteristics

- Open source, able to solve certain classes of problems, adaptable, plug and play

Validate model scalability through pilot projects across sectors

Create program to facilitate deployment

- Pilot sites
- Business models and incentives
- Auditing and documentation of improvements
- Program to assist SMEs in implementing new models/tools

2020

Incorporate visualization and advanced algorithms

Technology Targets

- Computing platforms for plant environments
- Generic, smart function blocks that work across multiple industries and processes
- Interoperable software (common database, language, etc.)
- Technology with high usability assurance and accessibility
- Architecture standards to enable mix/match of function blocks; data exchange standards
- Plug and play capability
- Both business and technical key performance indicators (KPIs)
- Modern visualization techniques

Performance Targets

- Reduce total cost to implement models; cost drops 80-90% in five years
- Increase plant operating efficiency by 10% (loss/unit product)
- 25% reduction in safety incidents

Potential Roles

Industry: Benchmarking, planning, standards, architectures for plug and play, visualization, assisting SMEs

National Laboratories: Algorithms, benchmarking, planning, standards, architectures for plug and play, visualization

Universities: Benchmarking, planning, visualization, algorithms

Standards Organizations: Standards, architectures for plug and play, standard model platforms

Figure 3-2.

Priority Action: Develop Next-Generation Toolbox of Software and Computing Architectures for Manufacturing Decision Making

Next-generation software and computing architectures are needed to effectively mine data and use it to solve complex problems and enable decision making based on a wide range of technical and business parameters. Advanced software would incorporate risk assessment into plant management; deliver energy management and optimization techniques; and provide faster, more efficient operational management tools.

Barriers

- Complexity of risk factors in decision making
- Weaknesses in current models
- Model scalability
- Limited self-healing capabilities
- Variable data quality
- High cost of software development

Benefits

- Creates fast, agile tools to improve all metrics, from energy to emissions, productivity, and safety
- Enables rapid engineering evaluation and better understanding of implications of shifts in processes, energy sources, and products
- Improves decision making at operator level
- Increases flexibility (increased sales, product competitiveness, reduced time to market)
- Allows life-cycle analysis of assets and tracking of key parameters
- Identifies inflection point in metrics, leading to lower costs

Action Plan

2011

Conduct inventory of software and tools across industries

- Current state and future needs
- Functionality required (design, cost, uncertainty, risk, energy management, critical processes)
- Other requirements (usability, interface, speed, interoperability)

Understand gaps in existing tools; create plan for development to fill gaps

Begin to build repository of software and tools

2015

Define operational framework via collaborative forums; create next-generation software-building tools

Build global database of physical, chemical, and thermal properties

Improve multivariate analysis techniques for large numbers of process variables

Develop algorithms applicable across industries (large scale, self-healing, self-regulating)

Integrate decision making with software platforms; create learning/adaptive tools

2020

Conduct demonstrations at multiple plants (self regulating, self healing models)

Develop accelerated software approaches (better graphical user interfaces)

Establish base of shared learning

Automate software and tool maintenance life cycle

Technology Targets

- Advanced tool box of inferential, predictive software and architectures
- Standardized process flow sheets with multiple layers of parameters
- Simplified model-building tools
- Decision making in risky environments
- Techniques to extract knowledge (forensic, multivariate analysis)
- Learning and adaptive models (self regulating, self healing, easily sustainable)
- Software warehouse (virtual repository with source of record, to enable tool certification)

Performance Targets

- 30% reduction in capital intensity
- Up to 40% reduction in cycle time
- Positive, measurable impact on energy, emissions, throughput, yield, waste, productivity, incidents, and risk factors

Potential Roles

Industry: Processors: Input on needs, problems, and current state; case studies, pilots. Vendors: tool solutions, software, interoperability, software prototyping

National Laboratories: Computational repository, algorithm development; cyber infrastructure

Universities: Software, algorithms, learning/adaptive frameworks, data analysis, testing

Standards Organizations: Software standards, certification processes, International Organization for Standardization (ISO)

Figure 3-3.

Priority Action: Integrate Human Factors and Decisions into Plant Optimization Software and User Interfaces

Tools and techniques are needed to better integrate human factors and decisions into smart software tools. This integration would enable faster, more disciplined decision making on the plant floor and allow operators to become "knowledge" workers. Integration of human decisions would also enable operators to see the more immediate impacts of their actions and foster an environment of continuous improvement. Plant-operator friendly user interfaces will also be needed to enable ready application of software tools.

Barriers

- Modeling uncertain human behavior
- Lack of usable tools that do not require higher skills levels
- Complexity of learning/adaptive software frameworks
- High cost of software development

Benefits

- Increases productivity through knowledge-empowered workers
- Creates self-organized workers and greater job satisfaction
- Promotes continuous process improvements
- Enhances ability to improve all KPIs at the operator level with potential reductions in cost
- Improves usability and effectiveness of software and tools

Action Plan

2015

Incorporate human decisions and factors into tools; evaluate how users interact with systems

Develop software that can be used by non-engineering or higher level plant personnel for "what if" analyses

Develop prototype software and conduct pilot demonstrations in multiple industries; focus on positive improvements in key performance indicators

Develop user-friendly interfaces for plant operations

2020

Continue to incorporate human-centered design and quantitative human factors into software systems

Expand integrated modeling capabilities to include energy, carbon, productivity, and quality

- Create integrated methodology
- Validate results; show impacts on key performance indicators

2030

Incorporate adaptive feedback from factory "knowledge" workers into models

Conduct pilot demonstration of advanced software across industries

Technology Targets

- Learning and adaptive software with human decisions factored in
- Faster (possibly real-time), more disciplined decision-making on the manufacturing floor
- Ability to see positive and negative impacts of decision making
- Capability for modeling all KPIs
- Intuitive controls and worker interfaces
- Operator- and role-based automation

Performance Targets

- Measurable improvements in key metrics (energy use, operating costs, product costs)
- Increased labor productivity
- Reduced turnover (workforce and material)

Potential Roles

National Laboratories: Definition of requirements for integrated software and adaptive methodology in collaboration with industry

Universities/Industry: Collaborations on simulation and software methodology and tools

Standards Organizations: Definition of interfaces for factory integrated systems (data definitions)

Figure 3-4.

Priority Action: Expand Availability of Energy Decision Tools for Multiple Industries and Diverse Skill Levels

Tools (e.g., energy dashboards, automated data feedback systems, energy "apps" for mobile devices, optimization software) are needed to enable better decision making about energy use across the manufacturing plant in real time. Collecting and interpreting energy data at the level required to make effective decisions can be challenging and time consuming, and knowledge about how to correctly interpret data is often lacking. Integration of factory energy data with external information, such as current cost of energy at the local utility, weather conditions, and other factors, could provide new insights and enable comparison of different energy options.

Barriers

- Difficulty and time involved in collecting and interpreting energy data
- Lack of energy data with which to make comparisons or optimize systems

Benefits

- Makes energy data readily available, enabling decisions that reduce energy use and costs
- Achieves near-term energy savings (significant when aggregated across industry)
- Serves dual purpose of training new engineers in smart systems and energy management

Action Plan

Year	Actions
2012	Develop data-based tools that go to the plant operator level and incorporate "useful" data (e.g., do not require an engineer to interpret) Document successes from large companies to demonstrate viability to SMEs Engage universities to help deploy data and tools Leverage existing programs (e.g., NIST/MEP) to promote tools
2013	Connect data-based tools to deployment strategies for technology and practices to encourage energy savings
2014	Establish methods for data maintenance Establish outreach programs to reach diverse industry segments of all sizes

Technology Targets

- Operator-usable decision tools with capability to interpret plant energy data and select efficient choices
- Comparison of energy options based on process, product, and energy source
- Integration of all plant functions from a total energy perspective

Performance Targets

- Reduction in energy use of 25%
- New energy decision tools are used in 90% of plant assets in 75% of plant operations across the manufacturing enterprise
- Large increase in number of engineers/ technicians capable of making efficient energy decisions

Potential Roles

Industry: Screened data and validation, data collection

Government: Information dissemination, outreach programs

Universities: Tool implementation, data aggregation, and development

Affordable Industrial Data Collection and Management Systems

Large amounts of data will be needed to support enterprise-wide smart manufacturing systems. Data will need to be collected, stored, analyzed, and transmitted using highly efficient, standardized methods. Managing and using data effectively and affordably is a major challenge for smart manufacturing. Addressing current data system limitations will require development of consistent data methods and new collection frameworks that use comprehensive sensor networks and simplify data transfer. Data systems will also need to be interoperable and exchangeable across diverse platforms and uses. The two priority actions needed to create affordable data systems are outlined below; detailed priority action plans are provided in Figures 3-5 and 3-6.

Priority Action 5: **Establish Consistent, Efficient Data Methods for all Industries**

Effectively collecting, storing, reconciling, and using data across the manufacturing enterprise is a key aspect of smart manufacturing systems and successful deployment of operational models. Collection and use of engineering data in manufacturing facilities today is relatively inefficient due to the lack of standardized, easily usable data systems. Significant improvements are needed in today's data management systems and methods for mining intelligence from manufacturing data. This includes better data protocols and interfaces, and communication standards.

Priority Action 6: **Develop Robust Data Collection Frameworks (Sensors, Data Fusion, Knowledge Capture, User Interfaces) across the Manufacturing Enterprise**

An information technology (IT) framework is needed to collect more robust and complete information; maintain data fidelity; and provide simplified, effective knowledge transfer related to manufacturing equipment, facilities, and systems. The framework would ideally apply sophisticated software to deliver manufacturing intelligence, provide simplified IT user interfaces, and readily capture human knowledge in a proactive way. Advanced, rapid, low-cost sensors would expand the volume and variety of data, enabling more comprehensive analysis and optimization of plant operations. Data fusion technologies could be applied to combine sensor data from different sources and achieve greater measurement accuracy.

Figure 3-5.

Priority Action: Establish Consistent Data Methods for all Industries

Effectively collecting, storing, reconciling, and using data across the manufacturing enterprise is a key aspect of smart manufacturing systems and successful deployment of operational models. Collection and use of engineering data in manufacturing facilities today is relatively inefficient due to the lack of standardized, easily usable data systems. Significant improvements are needed in today's data management systems and methods for mining intelligence from manufacturing data. This includes better data protocols and interfaces, and communication standards.

Barriers

- Low efficiency of engineering personnel in data collection and use
- Lack of consensus on data, software, and interfaces required to develop scalable methods for energy-intensive process prototypes

Benefits

- Provides consistent basis for data collection and use that can be applied across industries
- Facilitates dramatic increases in SM deployment
- Removes barriers to penetration of more complex, high-level manufacturing intelligence gathering
- Facilitates cost-effective integration of cross-enterprise systems

Action Plan

Year	Actions
2012	Define requirements for consistent data methods (data protocols and interfaces, communication standards) and the value proposition Conduct gap analysis; create development plan Benchmark current inefficiencies (time spent looking for data, using data) across industries Determine data and interfaces required for reducing energy use and carbon in energy-intensive process prototypes
2013	Develop licensing strategy for IP of data methods (open source) Develop new data methods, protocols, and standards Conduct competition (Grand Challenge similar to the X Prize) to commercialize technology
2014	Conduct high-level beta testing of data methods Facilitate product integration via incentives for vendors/users, toolsets, other means Explore incentives for SMEs to participate Explore incentives for suppliers to adopt common data methods

Technology Targets

- Fundamental data quality management systems embedded in business models and software
- Communication standards and consistent data methods
- Repository of valuable knowledge on demand, with protocols for interpretation
- Metadata (e.g., self-diagnosing data), including data history, to enable an object-oriented virtual enterprise
- Architecture to support tunable data and learning software systems

Performance Targets

- Two-fold increase in productivity: dramatic reduction in time wasted on data collection/manipulation
- Work toward zero wasted time for collecting, binning, cleaning, reconciling data

Potential Roles

Industry: Input on consistent method requirements

National Laboratories: Data methods and analysis, validation

Universities: Data and analysis

Standards Organizations: Standards development

Figure 3-6.

Priority Action: Develop Robust Data Collection Frameworks (Sensors, Data Fusion, Knowledge Capture, User Interfaces) Across the Manufacturing Enterprise

An information technology (IT) framework is needed to collect more robust and complete information; maintain data fidelity; and provide simplified, effective knowledge transfer related to manufacturing equipment, facilities, and systems. The framework would ideally apply sophisticated software to deliver manufacturing intelligence, provide simplified IT user interfaces, and readily capture human knowledge in a proactive way. Advanced, rapid, low-cost sensors would expand the volume and variety of data, enabling more comprehensive analysis and optimization of plant operations. Data fusion technologies could be applied to combine sensor data from different sources and achieve greater measurement accuracy.

Barriers

- Inefficiency of existing knowledge-capture systems and problem-solving capabilities
- Complexity of knowledge capture and transfer
- High cost of sensors
- Lack of effective real-time sensors for biological systems

Benefits

- Reduces “thinking” time and frees up time for management
- Increases innovation and “just-in-time” use of ideas
- Improves organizational and manufacturing productivity
- Accelerates product manufacturing and commercialization cycles
- Increases speed of data collection
- Lowers cost and difficulty of data collection and interpretation

Action Plan

2015

Develop enhanced sensors for massive, affordable data capture

- Lower cost while increasing resolution
- Develop soft sensors for product quality monitoring in food/pharma/biotechnology
- Develop multi-environment “lick and stick” sensors

Develop IT framework (processes, technology, infrastructure, people) for recording and retrieval of knowledge during information generation, capture, and use; design appropriate user interfaces

Develop pedagogic tools based on generational and cultural profiles

Develop adaptable methods for transitioning to a knowledge-based organization

Identify data best practices to support process model simplification

2020

Conduct data pilots in different industries; devise approaches for broad deployment

Actively engage in re-education of workforce

Identify knowledge management curriculum

Technology Targets

- Fast, cheap sensors adaptable to many different environments
- Soft and virtual low-cost sensors (real-time release of data)
- Non-redundant systems that capture human knowledge
- Maintenance of data fidelity
- Proactive real-time information retrieval
- Simplified IT user interfaces
- Software systems as knowledge management vehicles (time-stamped data retrieval ability)
- Effective data taxonomy

Performance Targets

- Detailed knowledge capture and management systems support 70% of industrial processes
- Two-fold increase in speed of problem resolution

Potential Roles

National Laboratories: Structure of knowledge management systems; sensor development

Universities: Education on knowledge management systems

Industry: Implementation/use of knowledge management systems; sensor development and testing

Standards Organizations: Data/system standards

Other: Link consultants and think tanks that are already working in this area

Enterprise-wide Integration: Business Systems, Manufacturing Plants, and Suppliers

The manufacturing enterprise is much larger than the manufacturing process and the products it generates. It includes a large business and management function that spans manufacturing plants, companies, and industries. The integration of manufacturing operations and business functions across the supply chain is a central and advantageous aspect of a future smart manufacturing enterprise. Successfully integrating business planning and manufacturing decisions could profoundly increase productivity and efficiency in the use of all types of resources, from materials to energy, water, and labor. Integration across supply chains, without loss of intellectual property, could open new doors to improving supplier performance and pave the way for suppliers to capture new or adjacent markets. The priority actions needed to achieve enterprise-wide integration are outlined below; detailed priority action plans are provided in Figures 3-7 to 3-9.

Priority Action 7: **Optimize Supply Chain Performance through Common Reporting and Rating Methods**

Proactive, sense-and-response methods are needed to enable real-time assessment of supplier performance. Proactive computing systems continuously sense and respond. They acquire data from multiple sources, analyze the data, and draw conclusions or determine actions. A public repository and computer-enabled sense and response reporting method would provide dashboards of performance by industry and across supply chains, creating a consistent means to reward participating suppliers for exemplary performance in key areas.

Priority Action 8: **Develop Open Platform Software and Hardware to Integrate and Transfer Data Between Small/Medium Enterprises (Supplier Companies) and Original Equipment Manufacturers**

An affordable, open, standard platform of software and hardware is needed to integrate small/medium suppliers with Original Equipment Manufacturers (OEMs). This would enable the rapid, effective transfer of data between companies while ensuring protection for intellectual property (IP). Achieving this integration will require common languages and architectures that can be applied across diverse supply chains. The benefits would be supply chain optimization, lower barriers to entry for SMEs in new industries, and easier, less costly supply chain integration.

Priority Action 9: **Integrate Product and Manufacturing Process Models**

Product and manufacturing process models need stronger interfaces to reduce time to market, improve product quality, and enhance the ability of plants to adapt or transition to new products. The objective is to develop a suite of validated, open-source software and standardized approaches (networks, virtual and real-time simulation, data transfer systems) that can be applied and customized for individual industries. A suite of integrated product and process models would facilitate successful integration of enterprise and plant-level planning, thus enabling multi-objective optimization of key performance indicators.

Figure 3-7.

Priority Action: Optimize Supply Chain Performance through Common Reporting and Rating Methods

Proactive, sense-and-response methods are needed to enable real-time assessment of supplier performance. Proactive computing systems continuously sense and respond. They acquire data from multiple sources, analyze the data, and draw conclusions or determine actions. A public repository and computer-enabled sense and response reporting method would provide dashboards of performance by industry and across supply chains, creating a consistent means to reward participating suppliers for exemplary performance in key areas.

Barriers

- Defining data ownership and transferability
- Concerns over protection of IP
- Cost of participation
- Lack of incentives for suppliers to participate

Benefits

- Drives suppliers to optimize performance
- Provides supplier assurance and standards
- Increases visibility of supplier performance
- Integrates demand, planning, and operational improvements
- Enables analysis of U.S. competitive gaps via industry dashboards
- Recognizes companies for performance

Action Plan

2012

Develop common language/vocabulary for reporting; create supporting data architectures

Conduct forum on methods to define and measure common metrics

Develop genealogy and public reporting requirements

Identify and develop needed infrastructure

- Cloud-based, value chain software
- Simple, scalable, secure, and reliable platforms and networks

2013

Construct dashboard capability that is role-based in supply chain

Leverage access to create and scale results in Nielsen-like rating systems based on core competencies

Develop impact analysis and reporting protocols to “make public” key events about production schedules (as allowable)

2015

Develop energy and carbon footprint processes and require members to report by product SKU

Define the role of each supplier in the supply network and their reporting capability

Technology Targets

- Nielsen-like rating system that provides insights on core supplier competencies and performance
- Accessible database of select, public data on supplier processes and products
- Performance data available by product stock keeping unit (SKU)
- Dashboard-type results to compare performance across companies and industries
- Common data architecture, language, and vocabulary

Performance Targets

- Service-level agreements that can be used by suppliers to increase visibility
- High percentage of suppliers participating in service-level agreements and response mechanisms

Potential Roles

National Laboratories: Central repository of reusable software and best practices

Universities: Training programs and tools to help deliver this priority action; develop new models/theory to educate/train

Industry: Validation of software and practices

Standards Organizations: Validation and creation of software; consolidated reporting requirements

Figure 3-8.

Priority Action: Develop Open Platform Software and Hardware to Integrate and Transfer Data Between Small/Medium Enterprises (Supplier Companies) and Original Equipment Manufacturers

An affordable, open, standard platform of software and hardware is needed to integrate small/medium suppliers with Original Equipment Manufacturers (OEMs). This would enable the rapid, effective transfer of data between companies while ensuring protection for intellectual property (IP). Achieving this integration will require common languages and architectures that can be applied across diverse supply chains. The benefits would be supply chain optimization, lower barriers to entry for SMEs in new industries, and easier, less costly supply chain integration.

Barriers

- Concerns over protection of intellectual property
- Lack of standardization in current data systems
- Lack of platforms that can accommodate diverse data requirements across industries

Benefits

- Makes integration across value chains easier and less costly
- Increases speed of information transfer across supply chains
- Enhances global competitiveness of SMEs
- Potentially attracts OEMs to manufacture in the United States
- Enables OEMs to optimize the enterprise-wide supply chain
- Aligns OEM supply chains
- Lowers entry barriers to diversification of SMEs into new industries

Action Plan

2012

Establish a Common Semantic Library (common language and vocabulary)

Develop and define KPIs for products, processes, supply chain, and sustainability

Define reference architecture and data requirements

- Data elements
- Technical, business elements
- Processes and products

2015

Develop prototype reporting systems (e.g., reference architecture, sub-language)

Conduct proof-of-concept studies to validate system(s)

Update and refine software to validate scalability

Conduct pilot demonstrations across sectors

Define patterns for service-oriented architecture

2020

Explore programs and incentives to encourage wide-spread adoption

Promote standardization through industry and trade organizations

Technology Targets

- Simple, scalable, secure, reliable, and affordable infrastructure
- Common language and vocabulary applied across supply chains and OEMs
- Effective sub-languages and reference architectures
- Data sharing systems that maintain protection of IP

Performance Targets

- Across-the-board reduction in operating costs (operations and maintenance, labor, transportation, energy)
- Increase in percentage of on-time deliveries and shipments
- Participation includes up to 60% of SMEs

Potential Roles

National Laboratories: Platforms, common language, standardization

Universities: Engineering, business schools, computer science: platforms, common language, sub-languages, reference architecture

Industry: SMEs, application providers, large manufacturers: prototypes and testing, demonstrations

Other: Industry associations: promoting use of platforms

Figure 3-9.

Priority Action: Integrate Product and Manufacturing Process Models

Product and manufacturing process models need stronger interfaces to reduce time to market, improve product quality, and enhance the ability of plants to adapt or transition to new products. The objective is to develop a suite of validated, open-source software and standardized approaches (networks, virtual and real-time simulation, data transfer systems) that can be applied and customized for individual industries. A suite of integrated product and process models would facilitate successful integration of enterprise and plant-level planning, thus enabling multi-objective optimization of key performance indicators.

Barriers

- Concerns about protection of intellectual property
- Complexity of developing common interfaces that work across equipment and product computing platforms
- Lack of tools for effectively integrating virtual and real-time data

Benefits

- Increases the speed of problem solving
- Potentially improves all key metrics
- Reduces time to market for new products
- Leads to improvements in product quality
- Increases plant flexibility to accommodate changes in product slate

Action Plan

2012	Develop the standards and tools for interfacing product and process models; capture best practices by industry Leverage high-performance computing facilities and centers of expertise for modeling as “shared services”
2013	Develop the capability to capture IP for models Identify models that lead to repeat business decisions and build the business case for such models Develop an open source approach for model creation, validation, and reuse (e.g., centers for validating model prototypes)
2014	Create a national repository of validated models Publish standard approaches for use

Technology Targets

- Integration of virtual and real-time models
- Ability to use the model as a control system
- Adjustment of models without feedback mechanisms
- Affordable, with capabilities available to all plants, regardless of size
- Closed-loop chain between products and processes
- Sufficient business case for investment in integrated modeling

Performance Targets

- Significant reduction in time to market
- Measurable improvements in product quality
- Industry-wide ability to implement and validate tracking and tracing capability

Potential Roles

National Laboratories: Models and standards; develop model libraries

Universities: Validation and test centers

Industry: Sharing of models and best practices

Education and Training in Smart Manufacturing

A skilled workforce is needed to continue developing technology and other components of smart manufacturing and to enable its efficient adoption and widespread use at the plant level. While there are many pathways for educating the workforce, it is essential that university and college curricula incorporate SM concepts. Inclusion of these concepts in higher education will ensure a cadre of engineers and scientists trained in the needed disciplines. In-plant or industrial training programs are also needed to train operators in the use of new tools and to ensure that human factors are continuously incorporated into computational and automated plant systems. Operators who can see the impacts of their decisions on plant operations and learn from those decisions become highly efficient assets. The priority action for developing a skilled workforce in this field is outlined below; a detailed priority action plan is provided in Figure 3-10.

Priority Action 10: **Enhance Education and Training to Build Workforce for Smart Manufacturing**

Training modules, new educational curricula, smart design standards, and effective learner interfaces will all contribute to creating a workforce skilled in SM techniques and provide pathways for continuous learning.

Education at higher levels (e.g., junior colleges, high schools, universities) should be better aligned with the skills needed to create better smart industries. Collaboration between industry and educational facilities will help to establish curricula that are dynamic and relevant to current industry needs. Training provided by industry should be structured for all levels of employees and build knowledge of all the KPIs. Skilled workers would be able to rapidly adapt to new smart technology. In turn, SM technology would incorporate operational feedback to provide continuous learning for workers.

Figure 3-10.

Priority Action: Enhance Education and Training to Build Workforce for Smart Manufacturing

Training modules, new educational curricula, smart design standards, and effective learner interfaces will all contribute to creating a workforce skilled in SM techniques and provide pathways for continuous learning

Barriers

- Disconnect between higher education curricula and industry needs
- Lack of workers trained to ensure rapid and successful implementation, acceptance, and maintainability of new technologies, modeling environments, and modules
- Lack of operational/use feedback to improve SM platforms

Benefits

- Empowers workforce with operating information and real-time feedback on productivity
- Attracts next-generation manufacturing workers
- Ensures availability of trained workforce; provides mechanism for college and university-based training
- Increases productivity through employee knowledge
- Leads to higher worker buy-in and retention

Action Plan

Year	Actions
2012	Define scope of the training program; consider all elements of deployment: module developers, users, installation and maintenance Partner with colleges and universities on curriculum Define information needs to empower the workforce; include operational parameters plus sustainability Create design standards and intuitive worker interfaces that enable continuous learning Incorporate industry experience and requirements in teaching methods Develop problem solving approaches that include user feedback and verification
2015	Execute and refine training programs as new technologies are developed Expand training programs into new industries, universities, and colleges
2020	Continue to execute and refine training programs as new technologies are developed

Technology Targets

- Dynamic, modern teaching methods
- Technical training and maintenance modules
- Training packages for all employee levels, from data to plant assets
- Job task analysis and industry experience incorporated into life-long learning curricula
- National availability of curricula at undergraduate and graduate levels

Performance Targets

- Train sufficient engineering candidates to deploy and use new technologies in target markets (number of people trained)
- Percent of companies/industries that adopt new technologies and teaching methods
- Reduced industry training costs

Potential Roles

National Laboratories: Manufacturing extension partnerships

Universities: Trainers and content

Industry: Experts (e.g., SMEs, OEMs, software developers)—content and input on specific needs

Other: Coordination and program management by government (e.g., DOL, NSF, Department of Education)

4. Infrastructure Needs

A systemic infrastructure is needed to support the implementation and use of smart manufacturing throughout industry. To be effective and reach a wide number of users, this infrastructure needs to be simple, scalable, secure, reliable, and affordable. A number of core technologies and systems are essential to establish an SM infrastructure with the needed characteristics. These are outlined below.

Data Systems

- Semantic ontology (i.e., structural frameworks for organizing information)
- Standards and protocols
- Advanced data collection and storage capabilities
- Low-cost, easy-to-use wireless infrastructures

Usability

- Effective user interfaces (e.g., effective visualization, intuitive systems)
- New and complete interoperability between all systems, both internal and external to the industrial plant
- Knowledge management functions that remove barriers to information management and use

Automated robot picking up bricks on a conveyor in an automated brick making plant
Photo from iStock/8422996

Workforce

- Body of competent, knowledgeable experts in the field; training systems (e.g., modules like flight simulators) and skills development (interdisciplinary, including both business and technical)

Computational Platforms

- Cloud-based, value chain methods
- Generic algorithms
- Accessible products database to support sustainable products
- Open interface computing for programming, minimizing the need to protect intellectual property
- Expanded and secure cyber infrastructure

A high speed telecommunications transmitter
Photo from iStock/11589070

5. Potential Models for Collaboration

Collaborative efforts have been instrumental in accelerating the development and deployment of some notable advanced technologies. A number of historical models were identified that could potentially be applied to future public-private collaborations in smart manufacturing. These models and some factors that would be conducive to the success of future collaborations are described below.

Potential Collaborative Models

Hub Model: A knowledge and research hub could support open-source, functional blocks and platform development. Participants might have a vested interest in common threads but could also form consortia to solve particular problems quickly and at relatively low cost. The U.S. DOE Energy Innovation Hubs, for example, are modeled after the centralized management characteristics of the Manhattan Project and similar efforts. Each hub brings together leading scientists to focus on a high-priority technology.

Industry Consortia Model: In this model, work would be coordinated through an industry-led, member organization, similar to FIATECH or SEMATECH. This model includes a Board of Directors with representation from industry, academia, and technology providers. FIATECH is a not-for-profit industry consortium that focuses on fast-track development and deployment of technologies to improve design, engineering, build, and maintenance cycles in the construction of large assets. FIATECH members, who include not just industry but universities and research institutes, work collectively on projects to discover, develop, and deploy high-value technologies. The group also serves as a clearinghouse for new ideas. SEMATECH is similar in nature. It was originally funded through government subsidies and is now a private-sector organization with international divisions.

Success Factors for Collaboration

The success factors identified for future collaborative activities in smart manufacturing are listed below. A key underlying factor for success is direct participation by industry. Active industry participation from inception will help to ensure end user buy-in and acceptance of new technologies.

- Flexible methods of partnering
- Meaningful timeline for results
- Intellectual property protection
- Mapping of actions to enterprise outcomes
- Open to all companies at some co-investment level (including SMEs)
- Testing and demonstration, not just theory and science
- Multidisciplinary nature
- Direct industry/owner involvement
- Multi-year program
- Accommodation of work-in-kind
- Representation by all stakeholders

Appendix A: Abbreviations

ACEEE	American Council for an Energy-Efficient Economy
DOE	Department of Energy
DOL	Department of Labor
EERE	DOE Office of Energy Efficiency and Renewable Energy
EHS	Environmental, health, and safety
IP	Intellectual property
ISO	International Organization for Standardization
IT	Information technology
ITP	DOE Industrial Technologies Program
KPI	Key performance indicators
MEP	Manufacturing Extension Partnership
NIST	National Institute of Standards and Technology
NSF	National Science Foundation
OEMs	Original Equipment Manufacturers
SKU	Stock keeping unit
SM	Smart manufacturing
SMEs	Small and medium enterprises
SMLC	Smart Manufacturing Leadership Coalition
USDA	U.S. Department of Agriculture

Appendix B: Glossary of Selected Terms

Adjacent market or industry: Adjacent market segments share common characteristics in application requirements and community relationships (e.g., automotive components is an adjacent market to tractor-trailer components). Adjacent markets are not far from a company's core business in terms of technology, channels, and brands.

Architecture: Computer architecture or digital computer organization is the conceptual design and fundamental operational structure of a computer system; in software, architecture comprises the structural elements, subsystems, sub-assemblies, and parts that work together to deliver the desired computational result.

Cloud computing: In a cloud computing environment, any computer connected to the Internet is connected to the same pool of computing power, applications, and files. It allows users to have secure access to applications and data from any type of network device. Users can store and access any number of files on a remote server rather than physically using a storage medium. Most users of the Internet today are likely using a form of cloud computing.

Semantic ontology: In information technology, ontology is a formal representation of knowledge as a set of concepts and the relationships between them. Semantics refers to the data structures specifically designed and used for representing information content.

Cyber security: The protection of information (on computers and networks) against unauthorized disclosure, transfer, modification, or destruction.

Dashboards: Dashboard reports are used by businesses to visually present critical data graphically in a comprehensive form so that you can make quick and effective decisions, in much the same way that a car dashboard works.

Data fusion: Combines sensor data from different sources to achieve greater measurement accuracy

Interoperability: Ability of diverse systems and organizations to work together (inter-operate); ability of two or more systems or components to exchange information and to use the information that has been exchanged (IEEE); ability to accomplish end-user applications and use models and simulations using different types of computer systems, operating systems, and application software, interconnected by different types of local and wide area networks.

Key performance indicators: These are quantifiable measurements used to assess the critical success factors of an organization. They will differ depending on the organization and there are thousands in use today. Examples include elements of cost, productivity, quality, energy, environment, sustainability, or other factors.

Manufacturing intelligence: Information gathered from a diverse spectrum of manufacturing processes, equipment, facilities, and business systems that can be analyzed to optimize process performance and product quality, make business decisions, and for a host of other purposes.

Manufacturing enterprise: This encompasses all elements of manufacturing and the interactions needed to deliver products to the market – suppliers, factories, business functions, and distribution centers.

Metadata: Data which provides further details about the characteristics of a data point or operation. For example, in photography, metadata might include the copyright and contact information, what camera created the file, along with exposure information and other camera settings.

Open source: In software development, open source generally refers to software that is openly accessible and is produced through bartering and collaboration, with the end-product, source-material, and documentation available at no cost to the public.

Test bed: Often referred to as a platform for experimentation and demonstration of technology is in the later stages of research and development. Test beds are one way to provide rigorous and reproducible testing of scientific theories, computational tools, and new technologies.

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