2015 IEEE International Conference on
Automation Science and Engineering (CASE)
Aug 24-28, 2015. Gothenburg, Sweden

Standards Landscape and Directions for Smart Manufacturing Systems

Yan Lu, KC Morris, and Simon Frechette

Abstract— **The future of manufacturing lies in being able to optimize the use of resources to produce high quality product and adapt quickly to changing conditions. From smaller lot sizes, to more customization, to sudden changes in supply chain; the variability that manufacturers face is rapidly increasing. A key to enabling adaptive and smart manufacturing systems is the appropriate definition and use of information. Standards are fundamental 1) to facilitate the delivery of the right information at the right time, 2) to enable actions based on that information and 3) to reduce risk of technology adoption and development. This paper provides a review of the standards—a standards landscape—in which future *smart manufacturing systems* will operate. The landscape focuses on standards used to integrate within and across three manufacturing lifecycle dimensions: product, production system, and business. Opportunities and challenges for new standards are discussed. Emerging activities addressing these opportunities are presented. This paper will allow manufacturing practitioners to better understand the standards useful to integrate smart manufacturing technologies within their areas of expertise.**

I. Introduction

A manufacturer's sustainable competitiveness depends on its capabilities with respect to cost, delivery, flexibility, and quality [1]. *Smart Manufacturing Systems* (SMS) attempt to maximize those capabilities by using advanced technologies that promote rapid flow and widespread use of digital information within and between manufacturing systems[2][3][4]. SMS are driving unprecedented production agility, quality, and efficiency across our factories and companies, improving long-term competitiveness. Specifically, SMS use information and communication technologies along with intelligent software applications to

1) Optimize the use of labor, material, and energy to produce customized, high quality products for on-time delivery.
2) Quickly respond to changes in market demands and supply chains.

In 2014 in the United States the President's Council of Advisors on Science and Technology (PCAST) issued a report that identified three top-priority transformative manufacturing technologies: Advanced Sensing, Control, and Platforms for Manufacturing; Visualization, Informatics and Digital Manufacturing Technologies; and Advanced Materials Manufacturing [5]. The first two of the technologies enable the manufacturer's ability to respond to information quickly and efficiently; however, to achieve both effective information flow and system responsiveness, standards are needed. The PCAST acknowledged this when it stated that standards "spur the adoption of new technologies, products and manufacturing methods. Standards allow a more dynamic and competitive marketplace, without hampering the opportunity to differentiate. Development of standards reduces the risks for enterprises developing solutions and for those implementing them, accelerating adoption of new manufactured products and manufacturing methods."

Standards are the building blocks that provide for repeatable processes and the composition of different technological solutions to achieve a robust end result. Standards come in many varieties and forms. Standards.gov [6] and OMB Circular A-119[46] describe in some detail, the variety of forms standards can take. The standards that we will discuss are primarily "voluntary consensus standards." This means they are set by a standards organization based on the consensus of the partners who will be using them. In addition, these types of standards are enforced by voluntary compliance. Such standards are designed to open new market opportunities to their users, particularly SMS users. The standards supporting SMS range from those for information technology and communication through those that govern enterprises and supply chains.

This paper presents an SMS standards' landscape based on a definition of a smart manufacturing ecosystem. The landscape associates standards with product, production system, and business lifecycle dimensions. Section II presents key capabilities and the manufacturing ecosystem as the convergence of the three different lifecycle perspectives in operational manufacturing systems. It also identifies areas where the integration of functions within and across these dimensions will result in more effective systems. Section III describes the landscape in terms of key standards' organizations working in the area, types of standards in each of the three dimensions, and the operational system where the dimensions intersect. Finally, we discuss areas of opportunity for future standards in terms of the smart manufacturing capabilities.

II. Smart Manufacturing Ecosystem

Standards are fundamental for enabling SMS. Different standards contribute in different ways to enabling the

Yan Lu, KC Morris and Simon Frechette are with the National Institute of Standards and Technology, Gaithersburg, MD 20899 USA (corresponding author Yan Lu, 301-975-8228; e-mail: yan.lu@ nist.gov).

capabilities of smart manufacturing systems. To generate an SMS landscape, we identify the standards within scope based on whether a standard contributes to a capability, and analyze where, when and for what purpose the standard is used. This section defines the key capabilities and presents a visualization of a smart manufacturing ecosystem. The following section presents the standards landscape for the ecosystem.

A. Smart Manufacturing Capabilities

Key capabilities of smart manufacturing systems include agility, quality, productivity, and sustainability, which are discussed in more detail in [14]. To analyze the role of existing manufacturing standards, we clarify the definitions of the key capabilities as follows:

<u>Agility</u>: Agility is defined as "the capability of surviving and prospering in a competitive environment of continuous and unpredictable change by reacting quickly and effectively to changing markets, driven by customer-designed products and services" [14]. Critical to the success of agile manufacturing are enabling technologies such as model-based engineering, supply chain integration, and flexible production systems with distributed intelligence. Common metrics to measure agility include *On Time Delivery Percentage*, *Time to Make Changeovers, Number of Engineering Change Order per Year, Cycle Time,* and *Rate of New Product Introduction* [8].

<u>Quality</u>: Traditional quality measures reflect how well finished products meet design specifications. In addition, for SMS, quality also includes measures of product innovation and customization. Traditional quality metrics include *Yield*, *Number of Customer Rejects/Returns per Year*, and *Number of Material Authorizations/Returns per Year*[8]. New quality measurement indicators for innovativeness and personalization are needed.

<u>Productivity</u>: Manufacturing productivity is defined as the ratio of production output to inputs used in the production process. Productivity is a function of manufacturing time and cost, and can be broken down further to labor productivity and material and energy efficiency. As production sizes increase, typically productivity increases; however, for SMS for which customization is a hallmark, productivity measures may need to be adjusted to be more inclusive of responsiveness to customer demand.

<u>Sustainability</u>: While time and cost as measures of productivity have been the traditional drivers for manufacturing, sustainability has taken on more importance. Measurement science for sustainability is not as mature as for time and cost, and is an active area of research[19][18]. As productivity and agility of manufacturing systems increase, the necessity for better understanding and controlling the sustainability-related impacts of those systems increases. Manufacturing sustainability is defined in terms of environmental impact (such as energy and natural resources), safety and well-being of employees and society at large, and economic viability [9].

B. Impacts of Standards

Every manufacturing standard contributes to one or more of these capabilities. For example, by supporting the exchange of product designs amongst engineering systems, ISO 10303 [27] contributes to both agility by streamlining processes, and quality by enabling the integration of different types of analyses. The Quality Information Framework (QIF)[32] similarly enhances both agility and quality.

C. Smart Manufacturing Ecosystem

Figure 1 illustrates three dimensions of concerns that are manifest in SMS. Each dimension—product (green), production system (blue), and business (orange)—is shown within its own lifecycle. The product lifecycle is concerned with the information flows and controls beginning at the early product design stage and continuing through to the end-of-life of the product. The production system lifecycle focuses on the design, deployment, operation and decommissioning of an entire production facility including its systems. The business cycle addresses the functions of supplier and customer interactions. Each of these dimensions comes into play in the vertical integration of machines, plants, and enterprise systems in what we call the Manufacturing Pyramid. The integration of manufacturing software applications along each dimension helps to enable advanced control at the shop floor and optimal decision making at the plant and enterprise. The combination of these perspectives and the systems that support them make up the ecosystem for manufacturing software systems.

Historically, these dimensions have been dealt with as silos of concern. Indeed integration along even one of these dimensions is a non-trivial challenge and is being actively worked. We have observed that organizations that were formed to integrate single dimensions of this ecosystem are expanding in scope to address the digital thread across the dimensions (orange arrows in Figure 1). Paradigms such as continuous process improvement (CPI), flexible manufacturing (FMS), and design for manufacturing and assembly (DFMA) rely on information exchange between the dimensions as indicated on Figure 1. Tighter integration within and across the three dimensions will result in faster product-innovation cycles, more efficient supply chains, and more flexibility in production systems. The combination of these allows for optimal control of the automation and decision-making need to make high-quality, highly-customized goods in tight synchronization with the demand for these goods [10].

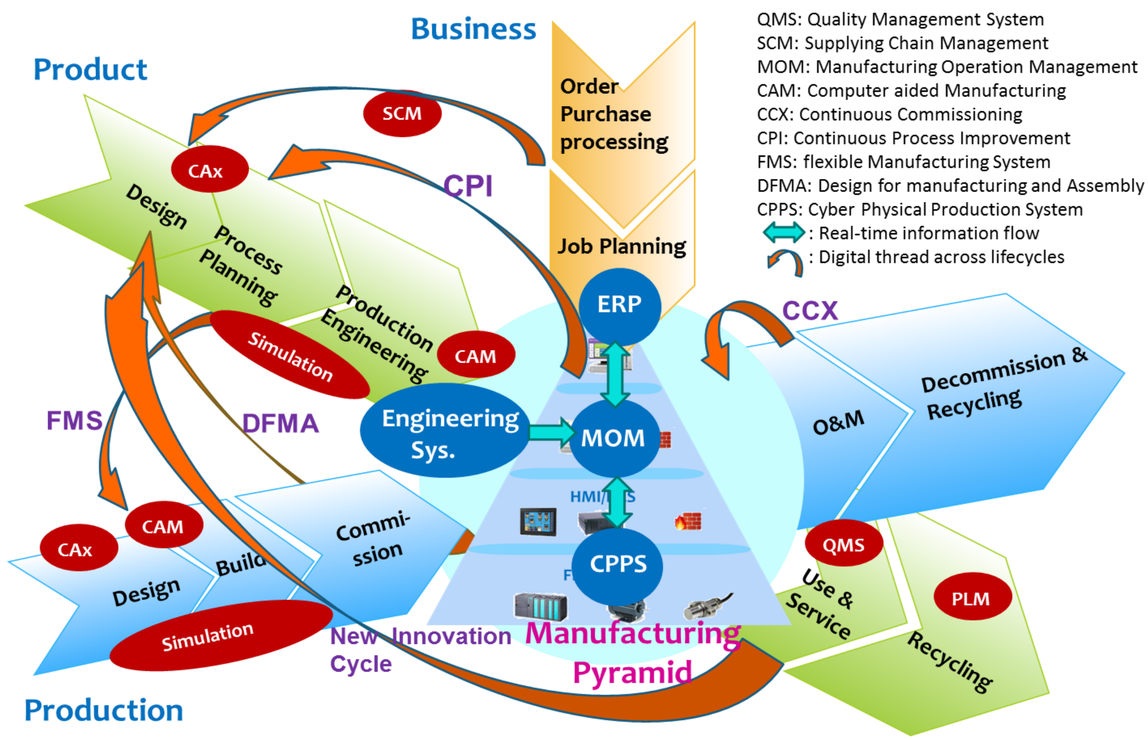

Figure 1 Smart Manufacturing Ecosystem

III. Manufacturing Standards Landscape

Existing manufacturing standards provide "how to" instructions for designers, engineers, builders, operators and decision makers to conduct disciplined activities within their domains, as well as serve as a vehicle of communication for stakeholders across domain borders, borders of the manufacturing system hierarchy, and between life cycle phases. Today, numerous national, regional, and international standard development organizations (SDOs) develop and publish manufacturing industry standards. This section provides a preliminary review of the types of standards for each of the three dimensions. Focusing on those standards that address the manufacturing content is essential for integrating across the three dimensions. While some national or regional standards are considered, more emphasis is placed on international standards. In many cases, local SDOs may have direct liaisons with international SDOs. First we provide an overview of the standards development organizations and then we place the standards in the ecosystem.[1]

A. Standard Organizations

Standards come in several varieties. The more traditional of these are recognized by a formally sanctioned SDO. These organizations facilitate consensus building and ensure that standards are openly available to organizations that wish to use them. In this category are both international standards bodies, such as ISO[20] and IEC[30], and national bodies including professional organizations, which define best practices for their practitioners, such as ASME [21] and ASTM[22]. In the United States, ANSI[23] certifies professional organizations to create standards in their areas of specialization.

The traditional consensus-building process used by these SDOs can be quite time consuming; as a result, other processes have emerged, including *open source*[24]. In this process, the standard can come in the form of a specification describing the standard, a reference implementation of the standard, or both. These standards are often developed within a consortium, maintained collaboratively, and widely available to the public at large. Nonetheless, the ownership of these standards remains a public trust of various sorts and they are open to interested participants. The licensing and governance models for the intellectual property contained in these standards vary greatly) Open source standards sometimes precede more formal sanction by an SDO; and there is often an organization that manages the open source process.

Another approach has been taken by vendor-driven standardization communities whereby a vendor implementation of a proposed standard is selected to define the standard to which other vendors will implement. The chosen implementation becomes the reference to which other vendors implement. This is based on the Microsoft model, where a dominant organization was able to dictate a standard based on their market superiority.

Standards often are defined in suites, which are designed to work together. Examples of this in the Information Technology (IT) world include the collection of standards from groups like WC3 [25] and IETF [26] that have enabled

[1] In the interest of brevity we do not provide references for every standard described. They are easily accessible through an Internet search.

the digital revolution. In the world of manufacturing we find the suite of standards known as STEP, ISO 10303, for product data [27], QIF, and the standards emerging from consortium such as OAGi for enterprise level applications [28]. These standards rely on more fundamental IT standards for syntax, e.g., XML and EXPRESS, and provide the engineering and manufacturing content.

The formal SDOs that are working on standards in the areas needed for smart manufacturing include ISO, IEC [30], and ASTM. Within ISO the technical committee on automation systems and integration (TC184) has two subcommittees (SC) that are of particular interest to our landscape: SC4 and SC5. SC4 focuses on industrial data standards – primarily those related to product data. SC5 focuses on interoperability, integration, and architectures for automation applications. Both SCs have recently become more active with new standards for SMS in development.

IEC, which historically has served the electronics industry, has developed standards that have broader applicability beyond the electronics industry. For example, IEC TC 65 focuses on industrial process control and automation and is active in the integration between product data and production processes. ISO/IEC Joint Technical Committee (JTC) 1 on information technology deals with a large number of standardization topics in IT for manufacturing systems including sensor and device networks and user interfaces. Consequently, these types of standards are included in our landscape.

A number of consortia are developing standards and best practices in the SMS area including OAGi, MTConnect[29], OPC[31], DMSC[32], and MESA[33]. Standards from these organizations sometimes are proposed in ISO and IEC in order to facilitate broader dissemination and adoption. OAGi and MTConnect make standards freely available as open source for download to the public. OPC originally developed standards that allowed device providers to integrate their products into a Microsoft-based platform. OPC has since evolved into an independent standards' organization with its own certification and testing program.

APICS[35], ASTM, MESA, and ISA[34] are industrial professional societies or trade associations working to advance the state-of-the-art in their fields. Their work includes standards, as educational activities, and other benefits to their members. The APICS scope is supply chain and operations management. A part of APICS, known as the Supply Chain Council, produced a series of reference documents, which provide guides on best practices, for the supply chain industry. This rich set of information includes definitions for a wide range of performance metrics for manufacturing operations. ASTM addresses manufacturing and materials, products and processes, and systems and services. MESA is concerned with the production level of Manufacturing Operations Management (MOM) or Manufacturing Executions Systems (MES) and the integration of information systems from the enterprise level into the manufacturing operation. ISA focuses on automation, specifically as applied to "engineering and technology to improve the management, safety, and cybersecurity of modern automation and control systems used across industry and critical infrastructure." While each of these organizations comes from a different perspective, their scopes intersect in our focus areas - product, production system, and business information flows.

Other noteworthy standards come from more academically-oriented professional societies, which typically are ANSI accredited. These include the standards from IEEE[37], ASME, and DMSC. DMSC standards include QIF, which is fundamental for assuring that the entire quality measurement process, consisting of product measurement design, planning, rules, resources, programming, results, and summary statistics, is fully integrated and traceable.

B. Product Development Lifecycle Standards

The product lifecycle in the context of the smart manufacturing ecosystem includes 6 phases as shown in Figure 2: Design, Process Planning, Production Engineering, Manufacturing, Use & Service and End-of-Life & Recycling. The existing standards, particularly during the earlier phases and in the areas of Computer Aided Design (CAD), Computer Aided Manufacturing (CAM), and Computer Aided Technology (CAx) generally have greatly improved engineering efficiency [11]. In addition, these standards enhance modeling accuracy, as well as reduce product innovation cycles, and hence contribute directly to manufacturing system agility and product quality. The culmination of study for this area has resulted in a new product development paradigm known as model-based engineering, or MBE.

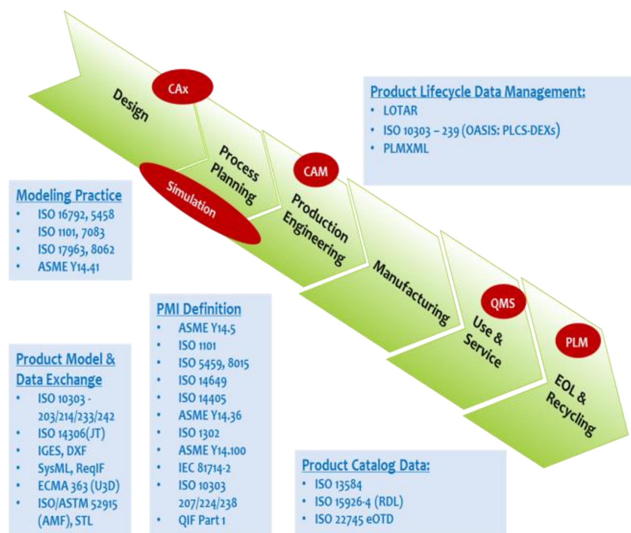

Figure 2 Standards Digitally Threading the Product Lifecycle

Figure 2 also shows a set of select standards related to the product lifecycle phases. These standards are classified into 5 categories: Modeling Practice and Product Manufacturing Information (PMI) Definition, Product Model and Data Exchange, Product Category Data, and Product Lifecycle Data Management.

Modeling-practice standards define digital product-definition data practices for both 2D drawings and 3D models. Product-model and data-exchange standards provide intermediate data exchange formats among CAD software from different vendors. PMI standards define the specifications for making the product including Numerical Control (NC) programming. Product Catalog Data standards specify the principles to be used for defining classes of parts and properties of parts. These standards make it possible to characterize a part independently of any particular supplier-defined identification. Product-lifecycle-data-management standards are designed to enable the exchange of information about a complex product throughout its life; i.e., the information needed and created during the use and maintenance of products.

C. Production System Lifecycle Standards

Most product modeling and design standards are applicable to production system modeling as well. In this subsection, we focus on the standards supporting complex system modeling, automation engineering, and operation and maintenance (O&M) perspectives of production systems.

Typical lifecycle phases for a production system as shown in Figure 3 include Design, Build, Commission, O&M and Decommission. Similarly, the categories of standards supporting production-system lifecycle activities include Production System Model Data and Practice, Production System Engineering, O&M, and Production System Lifecycle Data Management.

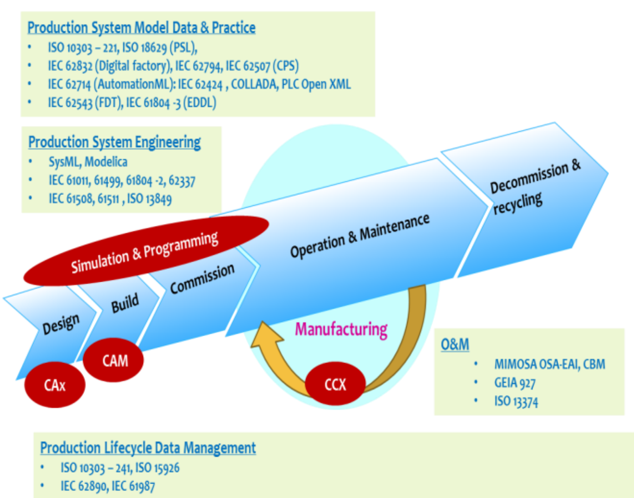

Figure 3 Standards for Production System Lifecycle

Production System Model Data & Practice standards provide guidance for system design, enhance information exchange among stakeholders, and enable virtual commissioning, which can improve manufacturing agility, as well as reduce manufacturing cost. Production System Engineering standards can interconnect engineering tools from different disciplines; e.g., mechanical plant engineering, electrical design, process engineering, process control engineering, Human Machine Interface (HMI) development, Programmable Logic Control (PLC) programming, and robotic programming. Production lifecycle data management standards define the general model of data integration, sharing, exchange, and hand-over for lifecycle support of production facilities. O&M standards define data processing, communication and presentation standards for condition monitoring and diagnostics of machines.

D. Business Cycle and Supply Chain Management

Figure 4 shows enterprise-level interactions for managing the manufacturing supply chain. Standards for these interactions include descriptions of the business objects and corresponding message protocols. These standards are the key to enhancing supply chain efficiency and manufacturing agility. Here, we highlight two sets of critical standards for Business2Business (B2B) and Application2Application (A2A) integration: APICS Supply Chain Operations Reference (SCOR) and Open Applications Group Integration Specification (OAGIS).

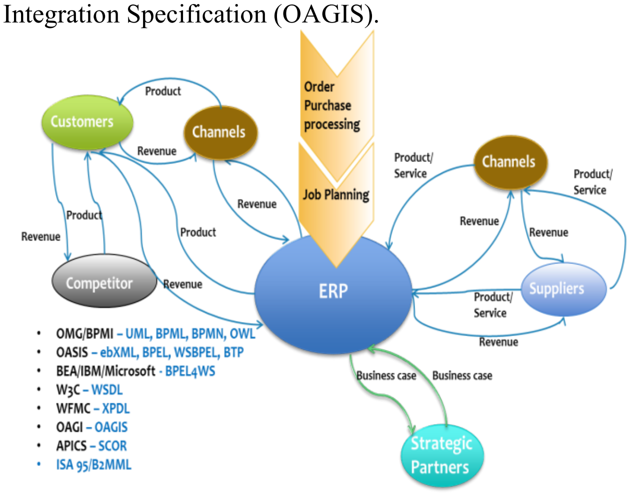

Figure 4: Standards for supply chain management

SCOR is a process-reference model and a de facto standard that identifies and promotes best practices in the management and operation of supply-chain activities across many industries [13]. The model describes the business activities associated with all phases of satisfying a customer's demand. The model uses an approach based on three pillars: process modeling and re-engineering, performance measurements, and best practices. The SCOR model is text based and, therefore, is not directly usable for automation. Nevertheless, SCOR can provide management with a tool that spans the entire supply chain from the supplier's suppliers to the customer's customers.

OAGIS defines a common content model and common messages for communication between business applications. This includes A2A and B2B integration.

E. Manufacturing Pyramid

Product lifecycle, production lifecycle, and the business cycle meet at the Manufacturing Pyramid, which is the core of the SM Ecosystem. Existing standards play critical roles in support of the integration from machine to plant and to enterprise systems. The integration is vital for manufacturers to 1) access field and plant data for making quick decisions and optimizing production throughput and quality, 2) provide accurate measures for energy and material use, and 3) improve shop floor safety and to enhance manufacturing sustainability. In Figure 5, we divide integration standards based on the ISA95[34] hierarchy – sometimes called the manufacturing pyramid, which has also been included within IEC 62264 [30]. ISA95 is a commonly used referenced model for developing automated interfaces between enterprise and control systems. This standard was developed for global manufacturers and designed for applicability to all industries and for batch, discrete, and continuous processes alike.

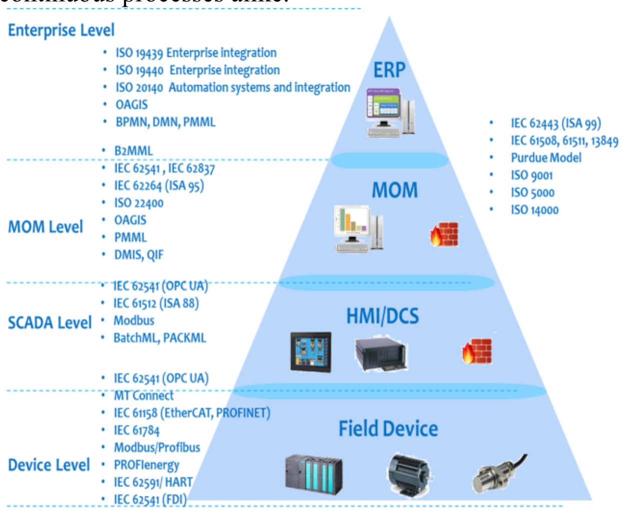

Figure 5: Standards aligned to the ISA95 model

Enterprise-level: The ISO standards listed in Figure 5 define the framework and specify the characteristics of the core constructs necessary for enterprise-level activities. These standards also provide the general principles of a method for assessing environmental impacts of manufacturing systems. The OAGIS standard also defines a common content model for enterprise application integration. Other enterprise-level standards include those for business process modeling practices.

MOM-level: Manufacturing operations management, or MOM, refers to the applications that control plant level operations. The standards in this area include activity models, functional models, and object models of the operations. In addition, there are exchange models published by MESA to support the integration of this level with the enterprise level, e.g., B2MML from ISA 95. OAGIS also defines common messages for communication between some MOM applications. ISO and DMSC define standards at MOM level to manage manufacturing quality and performance. Standards for data analytics could be at this level to support MOM functions.

SCADA-level and Field-level: SCADA-level (supervisory control and data acquisition) and field-level standards in Figure 5 are considered shop floor standards. While these levels were once more distinct, the distinction of interest now is between time and safety critical activities and non-time-critical activities. PLCs are usually connected to HMI based on a non-time-critical communications standard for monitoring and supervisory control. A fieldbus based on real-time communication protocol is necessary to link the PLCs to the field components, such as sensors and actuators. Meanwhile, a series of safety related standards defined by ISO/TC199 and IEC/SC 65A are well adopted at the shop floor to improve machinery functional safety and human safety.

In addition to the communication protocols, there are also important integration standards linking shop floor control to MOM-level and enterprise-level systems. These standards usually define basic information models for field devices, processes, and control and optimization functional capabilities.

Cross-levels: As shown on the right in Figure 5, there are several, cross-level standards for defining manufacturing system security, quality management processes, energy management, and environmental management.

IV. Standards Opportunities for Smart Manufacturing

The standards for manufacturing created in the last 30 years have already achieved a high degree of maturity; however, to enable SMS, further standards development is necessary. We identify several areas in the SM Ecosystem where standards can be extended or new standards should be developed, and identify some new initiatives focused on SMS, which will spur the development of both the technology and standards.

A. Standards Needs

To realize SMS capabilities, the classic manufacturing system architectural paradigm based on a hierarchical control model has to be updated [45]. The paradigm shift is brought on by the introduction of smart devices accessible as services on a network, more embedded intelligence, big data analytics which enables predictive functionality, and cloud technology, which enables virtualization of control and engineering functionalities at all hierarchical levels. With these capabilities in place, wide-spread automation across hierarchical levels using new approaches to control is a realistic possibility.

Table 1 highlights areas where standards can enable greater automation to be realized. Specifically, standards in these areas would improve capabilities associated with agility (A), quality (Q), productivity (P) and sustainability (S). The first column is the area of opportunity for new standards. The second column shows where the standards impact the SM Ecosystem—Product Lifecycle (PL), Production System Lifecycle (PSL), Business Cycle (BC), and Smart Production Pyramid (SPP). The third column shows how the standards map to SMS capabilities. Note, we present this not as a complete list but rather as a starting point for exploration and discussion of the infrastructure of smart manufacturing standards.

As shown in the table a high level reference architecture for SMS, including functional models and architectural definitions, is needed to integrate within and across the extended enterprise including with suppliers and customers.

These models will form the basis for dynamic production capabilities including the customization of end products.

Reference models representing smart devices on the shop floor are also needed and will increase productivity and agility by reconfiguring equipment, as well as allowing for more optimal health maintenance. Smart devices are at the core of the area of technology development that has become known as Cyber Physical Systems, or CPS. In the manufacturing context we are concerned more specifically with CPPS. A reference architecture for CPPS will enable the development of production modules, which incorporate smart devices. As these systems of systems come into place, intelligent machine communication standards along with an architectural framework will allow the automation of system-level controls and transparency of data from the lowest levels of manufacturing to higher control levels as needed.

With this new degree of automation possibilities also comes a need for new types of interfaces for humans to interact with the machines. Much of the performance data for individual machines can be presented to people through dashboards that enable human control. Similarly dashboards for monitoring and controlling system-wide performance are also needed. What these interfaces can, should, and will look like is an area of active research and standards should follow. Already the ISA101 [34] HMI committee was formed to establish standards, recommend practices, and provide technical reports relating to human-machine interfaces (HMIs) in manufacturing and processing applications.

Table 1: Opportunities for Standards for SM Capabilities

Standards Opportunity	**Eco System Dimension**	**Capability**
SMS Reference Model and Reference Architecture	PL, PSL, BC, SPP	A/Q/S/P
CPPS Reference Architecture	SPP	A/Q/S
Smart Devices Reference Model	SPP	P/A
Intelligent Machine Standards	SPP	Q/A/S/P
Human Machine Interface	SPP	Q/P/A
PLM/MES Integration	PL, SPP	A/Q/S/P
Cloud Manufacturing	BC, SPP	P/A
Manufacturing Sustainability	SPP	S

In addition, for production system design, manufacturing operational data is needed to generate new designs and better process plans more quickly. Currently, no standards exist to assess production system capabilities and link the results back to upstream activities in the lifecycle.

For product lifecycle management, a standardized ontology of data and artifacts that capture, store, visualize, search and share both static and dynamic data, both along the product lifecycle and through the supply chain, is recommended by AMP 2.0[5]. The ontology will enable more agility in the supply chain and reuse of products designs for rapid redesign. Product lifecycle data combined with data from the manufacturing processes can enable advanced analyses of the processes themselves including process improvement in terms of productivity, sustainability, and quality.

One vision for SMS is that the products themselves can contain the history of how, when, and where they were manufactured. The MTConnect Institute is starting standards activities that will enable this type of tracability. Technology and standards for big data and cloud manufacturing will allow for many advanced analyses and other functions to be provided on a service basis thereby making them more readily accessible to manufacturers.

Standards related to sustainability evaluation for manufacturing systems are evolving along each of the dimensions described. A barrier to improved sustainability evaluation is the availability of accurate data on resource utilization of individual components of manufacturing systems. How component data is aggregated along each of these dimensions is another technical challenge. Standards are necessary to provide unambiguous, and comparable data to decision-making processes. In 2008 ASTM formed a committee on Sustainability and more recently a subcommittee on Sustainable Manufacturing specifically. While the standards of this subcommittee are not yet complete we expect those to be on the near-term horizon for evaluating how manufacturing systems are impacting sustainability.

B. New Initiatives

Most of the standards areas that we described are being extended to address SMS capabilities. Quite a few new initiatives worldwide have emerged to contribute to the standards and opportunities identified above. The Industrial Internet Consortium (IIC)[36] founded by GE, IBM, CISCO, Intel and AT&T set a goal to "define and develop the reference architecture and frameworks necessary for interoperability." System architecture and reference models are also the main subject areas of Germany's Industry 4.0 Initiative [17]. Industry 4.0 has also developed a standards roadmap for additional communications capabilities and specifications to transform production systems into CPS [17]. Both IEEE and IEC/ISO committees are working on factory floor communications, industrial wireless communication, and device level standards development. The OPC Foundation is actively collaborating with other SDOs to develop companion standards for factory communication based on a manufacturing service oriented architecture.

At the National Institute of Standards and Technology (NIST) several initiatives are addressing SMS needs including a reference architecture for CPS[38]; new standards for Digital Thread [39] and Model-Based Engineering [40];a reference architecture and standards related to big data for SMS.[42]; working with OAGi on standards for cloud-based services for manufacturing; and leading an effort on cyber security for industrial systems, which will have great importance for manufacturers.[43] Additionally, NIST is coordinating the deployment of several advanced manufacturing institutes within the US.[44] These institutes focus on different areas of advanced and smart manufacturing with the goal of transferring research capabilities such as those mentioned into production.

V. Conclusion

The technology for Smart Manufacturing Systems is rapidly evolving. Standards are a fundamental component of SMS and will allow for broad participation in the next generation of the global economy. Standards will allow for systematic, repeatable, and more productive manufacturing systems. Moreover, standards will support the participation of a wide range of organizations from small manufacturers to large multi-national corporations. Perhaps we are on the verge of the next industrial revolution.

Acknowledgments & Disclaimer

Certain commercial systems are identified in this paper. Such identification does not imply recommendation or endorsement by NIST; nor does it imply that the products identified are necessarily the best available for the purpose.

References

[1] Global Agenda Council on the Future of Manufacturing , The Future of Manufacturing: Driving Capabilities, Enabling Investments, URL: http://www.cggc.duke.edu/pdfs/Future_of_Manufacturing_Driving_Capabilities.pdf, Access date March 14, 2015

[2] S. S. Shipp, N. Gupta, B. Lal, J. A. Scott, C. L. Weber, M. S. Finnin, M. Blake, S. Newsome, and S. Thomas, 2012, Emerging global trends in advanced manufacturing, Institute for Defense Analyses, Virginia, US.

[3] J. Davis, T. Edgar, J. Porter, J. Bernaden, M. Sarli, Smart Manufacturing, manufacturing intelligence and demand-dynamics performance. *Computers & Chemical Engineering*, 2012, **47**,145-156.

[4] SMLC, *Implementing 21st Century Smart Manufacturing: Workshop Summary Report*, June 2011, http://www.energetics.com/resourcecenter/products/roadmaps/Documents/SMLC_Smart_Manufacturing.pdf, Access date March 8, 2015.

[5] PCAST AMP Steering Committee Report - Accelerating U.S. Advanced Manufacturing, October 27, 2014.

[6] http://www.nist.gov/standardsgov/definestandards.cfm.

[7] A. Gunasekaran, Agile Manufacturing: The 21st Century Competitive Strategy, Elsevier, 2001

[8] 28 Manufacturing Metrics that Actually Matter, URL: http://blog.lnsresearch.com/blog/bid/188295/28-Manufacturing-Metrics-that-Actually-Matter-The-Ones-We-Rely-On, Accessed on March 14, 2015.

[9] Trade, 2010. How does Commerce define Sustainable Manufacturing? URL: http://www.trade.gov/competitiveness/sustainablemanufacturing/how_doc_defines_SM.asp, Access date March 14, 2015.

[10] PCAST AMP Steering Committee Report - Accelerating U.S. Advanced Manufacturing, Annex 1-10: Transformative Manufacturing Technology, October 27, 2014.

[11] P. Witherell, B. Kulvatunyou, and S. Rachu, Toward the Synthesis of Product Knowledge across the Lifecycle, Proceedings of the ASME 2013 International Mechanical Engineering Congress & Exposition IMECE2013, November 13-21, 2013, San Diego, California, USA

[12] S. Faltinski, O. Niggemann, N. Moriz, A. Mankowski, AutomationML: From Data Exchange to System Planning and Simulation, 2012 IEEE International Conference on Industrial Technology (ICIT), Athens, Greek.

[13] P. Bolstorff, R. Rosenbaum (2003). Supply Chain Excellence: A Handbook for Dramatic Improvement Using the SCOR Model. AMACOM Div American Mgmt Assn. ISBN 0-8144-0730-7.

[14] D. Kibira, KC Morris, Background Study of Methods and Tools for Performance Assurance of Smart Manufacturing Systems, forthcoming NISTIR.

[15] CIMOSA, CIM Open System Architecture. URL: http://www.pera.net/Methodologies/Cimosa/CIMOSA.html, Access date March 8, 2015.

[16] R. Sessions, A Comparison of the Top Four Enterprise-Architecture Methodologies, URL: https://msdn.microsoft.com/en-us/library/bb466232.aspx. Access date March 8, 2015.

[17] German Standardization Roadmap, Industry 4.0. URL: https://www.dke.de/de/std/documents/rz_roadmap%20industrie%204-0_engl_web.pdf, Access date March 14, 2015.

[18] S. Rachuri, KC Morris, U. Roy, D. Dornfeld, S. Kumara, "Sustainable Manufacturing Program Workshop Report," NISTIR 7975, National Institute of Standards and Technology, November 2013.

[19] "Sustainable Manufacturing – A Business Perspective: A Technology Roadmap," University of Kentucky, Institute for Sustainable Manufacturing, Feb. 2015.

[20] International Organization for Standardization (ISO), http://www.iso.org.

[21] American Society for Mechanical Engineers (ASME), https://www.asme.org

[22] ASTM International, http://astm.org

[23] American National Standards Institute (ANSI), http://ansi.org

[24] Open Source Initiative, http://opensource.org/osr-intro

[25] World Wide Web Consortium (W3C), http://www.w3.org

[26] Internet Engineering Task Force (IETF), http://ietf.org

[27] ISO 10303-1:1994, "Industrial automation systems and integration - Product data representation and exchange - Part 1: Overview and fundamental principles," International Organization for Standardization.

[28] Open Applications Group Inc. (OAGi), http://www.oagi.org

[29] MTConnect Institute, http://mtconnect.org

[30] International Electrotechnical Commission (IEC), http://www.iec.ch

[31] OPC, https://opcfoundation.org

[32] Dimensional Metrology Standards Consortium (DMSC), http://www.dmsc-inc.org

[33] Manufacturing Enterprise Solutions Association International (MESA), http://mesa.org

[34] International Society of Automation (ISA), https://www.isa.org

[35] APICS, http://www.apics.org

[36] Industrial Internet Consortium (IIC), http://www.industrialinternetconsortium.org

[37] Institute of Electrical and Electronics Engineers (IEEE), http://www.ieee.org

[38] http://www.nist.gov/cps/

[39] http://www.nist.gov/el/msid/infotest/digital-thread-manufacturing.cfm

[40] http://www.nist.gov/el/msid/mbesummit_2014.cfm

[41] National Institute of Standards and Technology (NIST), http://www.nist.gov

[42] http://bigdatawg.nist.gov/

[43] http://www.nist.gov/cyberframework

[44] www.manufacturing.gov

[45] B. Vogel-Heuser, G. Kegel, K. Bender, and K. Wucherer, Global information architecture for industrial automation. *Automatisierungstechnische Praxis (atp), Oldenbourg-Verlag, Muenchen*, 2009.

[46] https://www.whitehouse.gov/omb/circulars_a119/#3