NIST Advanced Manufacturing Series 100-8

NIST/OAGi Workshop: Drilling down on Smart Manufacturing – Enabling Composable Apps

Nenad Ivezic
Boonserm Kulvatunyou
Dennis Brandl
Hyunbo Cho
Yan Lu
David Noller
Jim Davis
Thorsten Wuest
Farhad Ameri
William Bernstein

This publication is available free of charge from:
https://doi.org/10.6028/NIST.AMS.100-8

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

NIST Advanced Manufacturing Series 100-8

NIST/OAGi Workshop: Drilling down on Smart Manufacturing – Enabling Composable Apps

Nenad Ivezic
Boonserm Kulvatunyou
Yan Lu
William Bernstein
Engineering Laboratory
NIST

Dennis Brandl
BR&L Consulting

Hyunbo Cho
POSTECH University

David Noller
IBM

Jim Davis
UCLA

Thorsten Wuest
West Virginia University

Farhad Ameri
Texas State University

This publication is available free of charge from:
https://doi.org/10.6028/NIST.AMS.100-8

April 2017

U.S. Department of Commerce
Wilbur L. Ross, Jr., Secretary

National Institute of Standards and Technology
Kent Rochford, Acting NIST Director and Under Secretary of Commerce for Standards and Technology

Table of Contents

Abstract

This report summarizes the results from the OAGi/NIST workshop *Drilling down on Smart Manufacturing -- Enabling Composable Apps*, which was held at the National Institute of Standards and Technology campus in Gaithersburg, MD, on April 18-19, 2016. The purpose of the workshop was to identify and discuss challenges in advancing the vision of composable manufacturing systems within the context of open cloud service platforms for Smart Manufacturing systems. The report describes (1) the idea of composable Service-Oriented Manufacturing systems as a basis for achieving easily assembled and re-configured Smart Manufacturing systems, (2) the results of five breakout sessions, and (3) the key findings from the workshop as well as the next steps planned for the workshop series. The breakout session descriptions provide an overview of respective R&D areas, their goals, capability gaps, proposed technology characteristics, and priority working items.

Acknowledgement

Authors would like to thank Simon Frechette, KC Morris, Al Jones, and Mike Brundage for their support in organizing the workshop. Also, special thanks to Chris Peters and Mark Carlisle who reviewed the document and helped with their suggestions to improve it.

Any mention of commercial products is for information only; it does not imply recommendation or endorsement by NIST.

Keywords

Smart Manufacturing, Service Oriented Manufacturing, Standards Development, Digital Manufacturing, Reference Models, Life-Cycle Management, Industrie 4.0, Cyber-Physical Production Systems

Acronyms

API – Application Programming Interface

ASME – American Society of Mechanical Engineers

ASTM – American Society for Testing and Materials

B2B – Business-to-Business

B2C – Business-to-Customer

BPCCS – Business Process Cataloging and Classification System

CAD – Computer-Aided Design

CAE – Computer-Aided Engineering

CC – Cloud Computing

CMK – Crowdsourcing of Manufacturing Knowledge

CPMS – Cyber-Physical Manufacturing Services

CRM – Customer Relationship Management

DDS – Data Distribution Service

DMDII – Digital Manufacturing and Design Innovation Institute

ERP – Enterprise Resource Planning

GUI – Graphical User Interface

IEC – International Electrotechnical Commission

IEEE – Institute of Electrical and Electronics Engineers

IIC – Industrial Internet Consortium

IoT – Internet of Things

IIoT – Industrial Internet of Things

IOF – Industrial Ontologies Foundry

IP – Intellectual Property

ISA – The International Society of Automation

ISO – International Organization for Standardization

IT – Information Technology

JWG – Joint Working Group

KB – Knowledge-Based

KBS – Knowledge-Based Systems

LCM – Life-Cycle Management

LCM SOI – Life-Cycle Management Service-Oriented Integration

MESA – Manufacturing Enterprise Solutions Association

MQTT – Message Queuing Telemetry Transport

MBMSD – Model-Based Messaging Standards Development

MOT-RL – Manufacturing Operations Technology Readiness Level

M/S – Measurements and Standards

MSLCM – Messaging Standards Life-Cycle Management

NIST – National Institute of Standards and Technology

OAGi – Open Applications Group Incorporated

OAGIS – Open Applications Group Integration Specification

OBO – Open Biomedical Ontologies

OEM – Original Equipment Manufacturer

OLE – Object Linking and Embedding

OPC – OLE for Process Control

OPC UA – OPC Unified Architecture

PAI – Priority Action Item

PAT – Priority Action Topic

PLM – Product Lifecycle Management

PLMI-RL – Product Lifecycle Management Integration Readiness Level

PRT – Priority Roadmap Topic

RAMI – Reference Architecture for Industrie 4.0

R&D – Research and Development

RM – Reference Model

RM LCM – Reference Model Life-Cycle Management

ROI – Return-On-Investment

SaaS – Software as a Service

SBIR – Small Business Innovation Research

SCA – Standards Capability Analysis

SCI-RL – Supply Chain Integration Readiness Level

SDO – Standards Development Organization

SKOS – Simple Knowledge Organization System

SM – Smart Manufacturing

SMASM – Smart Manufacturing Apps and Services Marketplaces

SME – Small- to Medium-sized Enterprise

SMRM – Smart Manufacturing Reference Model

SMS – Smart Manufacturing Systems

SMSC – Smart Manufacturing Systems Characterization

SMWG – Smart Manufacturing Working Group

SOA – Service-Oriented Architecture

SOI – Service-Oriented Integration

SOM – Service-Oriented Manufacturing

TC – Technical Committee

W3C – World Wide Web Consortium

Executive Summary

The National Institute of Standards and Technology (NIST) hosted the workshop *Drilling down on Smart Manufacturing -- Enabling Composable Apps* at its Gaithersburg, MD, campus on April 18-19, 2016. Over 60 participants from industry, government, national laboratories, and academia participated. The purpose of the workshop was to identify and discuss challenges in advancing the vision of composable manufacturing systems in the context of open cloud-based service platforms for Smart Manufacturing (SM) systems. The objectives of the workshop were to (1) help in creation of a roadmap for research in this nascent field; (2) inform future technical work; and (3) offer information to government agencies and stakeholders focused on manufacturing systems integration.

The main premise of the workshop is that future Smart Manufacturing systems – enabled by convergence of a number of technological advances applied to manufacturing operations, such as enhanced networking, adaptive automation, cloud services, and data analytics – will be available through on-demand composition of focused apps or services, some of which may be in the form of pay-as-you-go. Such apps or services are cyber-physical applications focused on a single function, as opposed to large, monolithic, multi-functional applications. Manufacturers will access these as on-demand downloadable components or cloud services using a pay-as-you-go model which promises to lower barriers and reduce cost significantly.

However, as the variety of apps, services, and systems available through this new SM development model proliferate, so do the risks associated with using, managing, and integrating them. One way to reduce the risks is to ensure that there is an ecosystem of capable standards and technologies that enable the composition of these apps, services, and systems within a new SM platform.

The workshop participants explored the needed technical foundation for the ecosystem of standards and technologies. The workshop established five working sessions to identify and address issues from different perspectives. The first three working sessions focused on the analysis, methods, and tools for the new platform. The sessions include SM Model-Based Messaging Standards Development, SM Standards Capability Analysis, and SM Systems Characterization. The other two sessions looked into realizing the innovative platform. The sessions included SM Apps and Service Marketplaces and Crowdsourcing of Manufacturing Knowledge. The sessions focused on the following key research ideas:

- **Smart Manufacturing (SM) Model-Based Messaging Standards Development (MBMSD)** focused on enabling efficient development and maintenance of messaging standards, which are key to scalable service-oriented integration.

- **Smart Manufacturing Systems Characterization (SMSC)** focused on technical means and measurement methods to assess manufacturing systems for readiness, capabilities, or maturity levels.

- **Smart Manufacturing Standards Capability Analysis (SMSCA)** focused on gathering context information at lower levels of manufacturing control architectures to support integration from diverse machines and software vendors.

- **Smart Manufacturing Apps and Services Marketplaces (SMASM)** focused on the need for precise vocabularies, technologies, and interface standards for equipment and resources to allow apps and services interoperability and market infrastructure and governance.

- **Crowdsourcing of Manufacturing Knowledge (CMK)** focused on required common ontology and definitions in support of the smart manufacturing marketplace and uniform knowledge representation that supports a variety of crowdsourcing and knowledge management tools.

The main findings from the workshop include the following:

- **Composable SOM Requires Extensive New Technical Capabilities**. Each session was capable of identifying a significant collection of goals, missing capabilities, needed technology & standards, and priority action items, which the participants believe to be essential to their R&D area.
- **R&D Road-mapping is an Important Resource in Developing Composable SOM**. Scientific understanding and technology maturity of workshop topics is initial and should continuously increase, as we are early in our understanding of many complex issues related to achieving the goals. An R&D roadmap is an essential ingredient in planning for outcomes and work in measurement science, standards, and technology to enable the needed capabilities and goals.
- **A Prioritization of Roadmap Topics Will Enable Focused Work in the Community**. A Priority Roadmap Topic (PRT) provides a focus for planned work in the form of a product deemed a key future resource for advancement of state of the art for the session. Next steps should also keep in mind potential impact of the identified priority action items and identify resources and organizations where the work can be housed.
- **Priority Roadmap Topics and NIST Smart Manufacturing Program Are Well-Aligned**. There is a good alignment between NIST Smart Manufacturing activities and the community interests. NIST is addressing a number of identified issues; however, this alignment could increase in the future, resulting in greater synergy across the community. There is a potential for refining common and cross-cutting themes to enable cross-pollination across the workshop sessions.
- **Identification of the Potential Impact of Priority Roadmap Topics (PRT) is important**. The ultimate goal of the workshop series is to enable the community to drive specific R&D projects and transition results into industry. Already, each breakout session identified potential target industry, government, and SDO organizations for their respective PRTs.

1 Introduction

1.1 Background: Composable Service-Oriented Manufacturing (SOM) Systems

We live in the age of *Smart Manufacturing Systems (SMS)* – a new generation of advanced systems on the production floor, in the enterprise, in the supply chain, and enabled by the convergence of information and communication technologies with physical technologies. The exciting vision of providing these SMS capabilities as services within a *Service-Oriented Manufacturing (SOM)* paradigm continues to be of great interest to industry.

For more than a decade, *SOM*, in its many instantiations, has been carrying the promise of bringing greater efficiencies in operating and managing advanced manufacturing technologies and systems. Within its current instantiation, software is available in small "apps" or "services." The software may be a cyber-physical service allowing easy connectivity to and information gathering from physical assets. In addition, some of these apps and services are available on a pay-as-you-go basis (e.g., Software-as-a-Service) lowering the barrier for access to these technologies. Manufacturers access these apps and services from various vendors as downloadable components or cloud-accessible services. The current vision for *SOM* is that these services will be assembled and re-configured easily and economically to execute complex workflow processes. The realization of this goal – *Low-Cost SOM-based SMS* – promises to lower technical and cost barriers for manufacturers significantly.

Because achieving the SOM vision has proven to be far from trivial, this realization has yet to happen. In fact, *Current Implementations of SOM Systems* use *Existing Service-Oriented Integration (SOI) Technologies* only to facilitate the re-engineering of existing monolithic applications into platform-independent services. These approaches have limited ability to integrate across both owned and managed (Software-as-a-Service) service offerings. This makes the goal of reconfiguration very costly and very difficult. Using the *Existing SOI Technologies* has resulted in the *Current Implementations of SOM Systems* that are costly to manage. Adding new capabilities to these SOM systems to meet dynamic and complex workflow-process requirements demands very laborious, manual processes to adapt, extend, or re-configure their component services. We say that these SOM systems can provide only *Limited SOM Life-Cycle Management (LCM) Capabilities* that, in turn, result in *High-Cost, SOM-based SMS*.

Clearly, advances in integration technologies, tools, and methods are needed to reach the SOM vision of *Low-Cost, SOM-based SMS*. That, however, would require extensive new capabilities, including both (1) SOM services life-cycle management and (2) SOM ecosystems life-cycle management. The former includes requirements analysis, design, behavior analysis, provisioning, deployment, discovery, use, and decommissioning of services. The latter includes SOM services composition, configuration management, design of SOM ecosystem operations, and optimization of SOM ecosystem services execution. We refer to this union of the two capabilities as *Extensive SOM LCM Capabilities*.

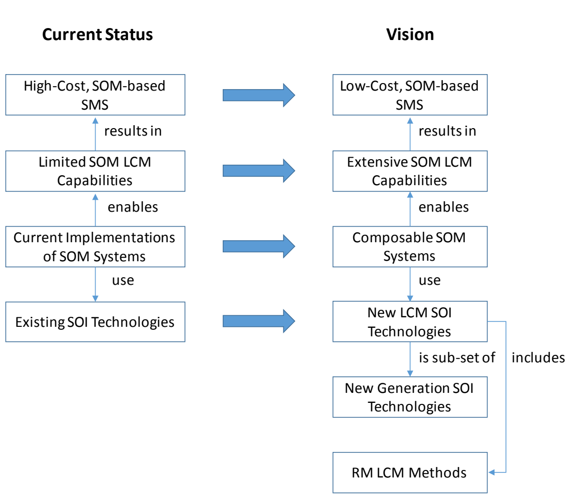

Figure 1.1 – SOM Status and Vision

Manufacturers will be particularly concerned about both time and cost when choosing among vendors who deliver these *Extensive SOM LCM Capabilities.* Time and cost involve three concerns: (1) searching for and discovering relevant manufacturing services, (2) integrating them in interoperable way, and (3) re-configuring them to meet changing requirements.

We refer to systems capable of addressing these concerns and enabling *Extensive SOM LCM Capabilities* as *Composable SOM Systems*. They will be able to provide interoperability orders-of-magnitude more efficiently than currently possible. They will require *New Generation SOI Technologies* to manage precisely the reference semantics of the manufacturing application domain. This drives the need for new research to develop the measurements and standards (M/S) to support both the development and implementation of those technologies. Those M/S will facilitate the communication of information in context-specific ways without failures in interpretation and without costly mediation help, re-interpretation, or manual intervention. The research supporting their development and testing will build on the results of service-oriented architecture (SOA) developments, knowledge-based systems (KBS), Cloud Computing (CC) development, and other technology areas.

However, a glaring gap remains in the current set of *New Generation SOI Technologies:* the lack of *Reference Models Life-Cycle Management (RM LCM) Methods*. Today, and more so tomorrow, these life-cycle management methods for information models, functional models, and process models – among others – will need to efficiently support activities ranging from creation, to adaptation, to usage of these reference models. Techniques used in these LCM methods need to support high-level abstractions, knowledge sharing, separation of concerns, and loose coupling. These techniques include declarative approaches, such as information and knowledge-based models, rule-based systems, and taxonomy- or ontology-based systems. These models, methods, and techniques play essential roles in new methods for (1) achieving precise management of reference semantics for the domain, (2) interpreting reliably the required, context-specific, domain information, and (3) playing a key role in standards allowing for context-specific interpretation. We refer to this needed subset of *New Generation SOI Technologies (*possessing the needed *Reference Models Life-Cycle Management (RM LCM) Methods)* as *New LCM SOI Technologies.*

In our view, to achieve the stated SOM vision, it is imperative to develop the *New LCM SOI Technologies* that provide these *RM LCM Methods*. The benefits of the *New LCM SOI Technologies* are twofold. Firstly, they will facilitate the dynamic creation of *Composable SOM Systems* by providing interoperable, reusable, and re-configurable services. Secondly, they could provide great potential savings, as illustrated in Figure 1.2, where the total costs of fully capable *LCM SOI Technology*-based approaches are compared to other approaches.

As noted above, realizing these benefits will require multi-faceted research into new SOI technologies. Measurement science, including an experimental testbed to support hypothesis testing and experimentation, is needed to support the development of those technologies. Such science may need standard representations for information and knowledge-based patterns as a precursor. Initial formalization of such representations will likely include logic and rule-based knowledge systems; taxonomy/ontology development; knowledge, taxonomy, and ontology management systems and processes; category theory; as well as other advanced frameworks.

Such standards will also be critical to move research results from the testbed into industrial use. Standards will enable the needed interoperability and provide guidelines for conducting development, testing, and implementation of the new technologies. Standards cover a multitude of aspects of the research field, including terminology, definitions, methodologies, metrics, specifications, testing, software, etc.

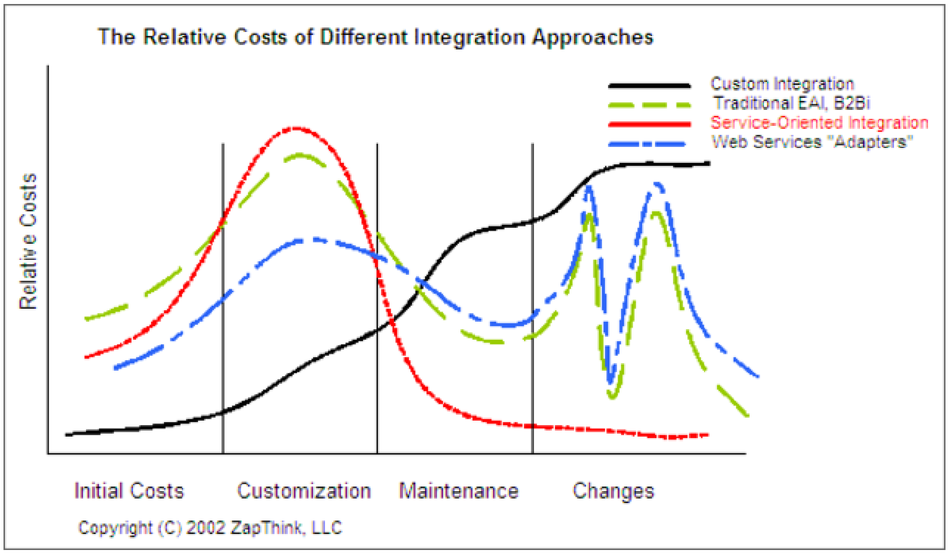

Figure 1.2 – The Relative Cost of Different Integration Approaches (Note: The Web Services "Adapters" refers to the *Existing SOI Technologies*, while Service-Oriented Integration refers to capable *New LCM SOI technologies.)*

In summary, the underlying hypothesis for this new R&D programmatic effort is that measurement science, information standards, and technology advancements for the *New LCM SOI Technologies* will be key enablers of *Composable SOM Systems*, which will move us closer to the vision of *Low-Cost, SOM-based Smart Manufacturing Systems (SMS)*.

1.2 Workshop Motivation and Objectives

The National Institute of Standards and Technology (NIST) hosted the *Drilling down on Smart Manufacturing -- Enabling Composable Apps* workshop at its Gaithersburg, MD, campus on April 18-19, 2016. The event brought together over 60 participants from industry, government, national laboratories, and academia to identify measurement science, standards, and technology challenges, and associated research and development (R&D) needs for advancing the vision of composable manufacturing systems in the context of open cloud service ecosystems for smart manufacturing. The objectives of the workshop were to:

- Serve as a key building block for the creation of a roadmap for research, by developing information on:
  - Goals for Composable SOM systems viewed from a number of different perspectives;
  - Capability gaps preventing the goals of Composable SOM systems;
  - Needed technologies required to address the capability gaps;
  - Future measurement- and standards-related challenges for Composable SOM systems; and
  - Research and development (R&D) needed to address the challenges.
- Inform future NIST technical programs and strategic planning.
- Offer valuable information to other government agencies and stakeholders focused on systems integration within manufacturing environments.

1.3 Workshop Technical Sessions

1.3.1 How were session topics selected?

Figure 1.3 illustrates the previously identified standards and technology R&D issues[1] that hinder both the creation of the ecosystem and the adoption of the new platform. This workshop addressed the top five R&D issues through various working sessions, as shown in the figure. These sessions, their objectives, and key outcomes are the subject of this report.

Workshop Breakout Session	Potentially Impacts	R&D Issue	R&D Issue Category
SM Systems Model-based Messaging Standards Development		Inadequate standards development processes	Standards Adoption
SM Systems Characterization		Difficult to use standards	
SM Standards Capability Analysis		Overlapping and unclear standards capabilities	
SM Apps & Service Marketplaces		Additional standards needed	Standards Development
Crowdsourcing of Manufacturing Knowledge		New architecture needed	Architecture

Figure 1.3 – Issues hindering new open-cloud platform for Smart Manufacturing and the sessions addressing the issues

1.3.2 Session descriptions

This report is based on workshop discussions within five technical sessions, each taking a separate perspective on developing RM LCM methods to achieve Composable SOM Systems. Common to their differing perspectives is that they are focused on developing knowledge-based modeling approaches to achieve RM LCM methods. The knowledge-based modeling allows capture and sharing of descriptions and specifications of manufacturing systems, processes, and products in computer-processable forms. The computer-processable models capture information, know-how, guidance, and standards that enable Composable SOM systems.

- **Smart Manufacturing (SM) Model-Based Messaging Standards Development (MBMSD) Methods** provides knowledge-model-based specification for conveying context and usage information for manufacturing services within SOM Systems. This novel approach to specification will be used to support messaging standards life-cycle-management (MSLCM) capabilities.
- **Smart Manufacturing Systems Characterization (SMSC) Methods** develops knowledge-model-based characterizations of both the manufacturers' requirements and the technologies' capabilities. These novel methods will be utilized to support reasoning about the composability of these technologies within an SMS based on their interface designs.
- **Smart Manufacturing (SM) Standards Capability Analysis (SCA)** provides knowledge-model-based specifications for conveying information about data interchange, systems integration, and data

[1] Nenad Ivezic, Boonserm Kulvatunyou, Yan Lu, Yunsu Lee, Jaehun Lee, Albert W. Jones, Simon P. Frechette. OAGi/NIST Workshop on Open Cloud Architecture for Smart Manufacturing. Available at https://dx.doi.org/10.6028/NIST.IR.8124.

fusion. These novel methods will be utilized to support the development of (1) a Smart Manufacturing Reference Architecture and (2) information standards and system interfaces based on that architecture. Both are needed to allow disparate services/systems to exchange, understand, and exploit information flows – especially across product, production, and business lifecycles.

- **Smart Manufacturing Apps and Services Marketplaces (SMASM)** explores knowledge-model-based definitions of multiple aspects of SOM systems, apps, and marketplaces. These novel models will be utilized to support the identification and analysis of current technological and other challenges as well as requirements from the stakeholders for Composable SOM Systems.

- **Crowdsourcing of Manufacturing Knowledge (CMK)** investigates new knowledge-model-based approaches for capturing manufacturing knowledge from "the crowd." These new models will be used to build new methods and tools that play key roles in gathering and managing the new types of manufacturing knowledge that is becoming available using distributed SOM architectures.

1.3.3 Sessions charge

The workshop participants were given charge to discuss and report on the topics in their respective breakout sessions in such a way as to support structured presentation of roadmap material (for details of the workshop roadmapping methodology, see Appendix B):

- Develop succinct descriptions of the session, business or market motivations, missing product or service capabilities, and proposed technologies that can deliver the needed capabilities in support of the business or market motivations.

- Collect priority action items that reflect belief there is a priority to advance state of knowledge on a specific topic.

- Propose Priority Roadmap Topics (PRTs), where possible, to provide ideas how the identified priority action items can be refined into potential products that have measurements science, standards, or testing aspect to them.

1.4 Workshop Report Organization

The ideas presented in this report are a reflection of the different perspectives given by the workshop attendees. As such, they can, at best, be viewed as a representative sampling of the entire industry. We envision a follow-on workshop to refine the research roadmap material for Composable SOM Systems presented in this report. The organization of the report is as follows. Sections 2-6 represent the main content of the report and describe the results of each breakout session by providing an overview of the R&D area, followed by the session participants' identified goals, capability gaps, technology characteristics, priority working items, and next steps that discuss priority roadmap topics. Section 7 offers conclusion and next steps for the workshop series.

Appendices are provided to help the reader understand the adopted framework to create and interpret this workshop report. Appendix A provides definitions of key terms describing Composable SOM Systems. Appendix B provides definitions of key terms, description of the process used to synthesize the report, and questions guiding the content of the report's technical sections. Appendix C provides resources to advance the state of maturity for Priority Roadmap Topics identified in the breakout sessions.

2 Breakout 1 - Smart Manufacturing Model-Based Messaging Standards Development Methods

2.1 Overview

The first breakout session focused on developing advanced reference model life-cycle management (RM LCM) methods for a new generation of messaging standards. The research discussions centered on Model-Based Messaging Standards Development (MBMSD) methods, which the group believes will advance the RM LCM methods, and their encompassing SOI technologies. These MBMSD methods will do so by providing knowledge-model-based specifications for conveying both the context and the usage of the available manufacturing services. This is in line with the expectation to communicate and act on information in context-specific ways without failures in interpretation and without costly mediation help, re-interpretation, or manual intervention.

These RM LCM Methods are then utilized for advancing messaging standards life-cycle management (MSLCM) capabilities. In this way, the MBMSD methods focus on improving messaging standards and their deployment by exploiting the usage information for the standard. This improvement in standards and their deployment enhances the composability (configuration and re-configuration) of messaging-intensive SOM systems and enables more-interoperable services, and better search and discovery of relevant manufacturing services.

2.2 Goals

The goals defined in this session are summarized in Table 2.1. The MBMSD methods support these goals by focusing on improving integration of and the performance of MSLCM processes. This makes these processes more shareable, supportive of learning, well-documented, convenient, traceable, collaborative, repeatable, consistent, and agile. The improvements result in two major change goals for the business and market processes. One change goal is that they enable consistent integration methodologies, resulting in efficient integration processes. The other is that they enable commonly accepted standards-based service-oriented integration processes. These changes are needed because (1) service-oriented integration approaches are needed for cloud-enabled services and (2) such standards-based service-oriented integration is being embraced by industry.

Table 2.1. Goals for Model-Based Messaging Standards Development (MBMSD) Methods
Business/market performance objectives • To make messaging standards life-cycle management (MSLCM) processes more supportive of learning and reuse, well-documented, convenient, traceable, collaborative, repeatable, consistent, and agile. • To make the process of deploying messaging standards more efficient.
Business/market processes change goals • To enable consistent integration methodologies, resulting in efficient integration processes. • To enable commonly accepted standards-based service-oriented integration processes.
Business/market performances non-technical goals • To help obtain business buy-in to the value proposition of standards-based integration. • To help change the culture of systems integration.
Results of business/market processes • To enable greater agility of integrated systems by removing duplication of services and enabling common services.

• To enable vendor-neutral integration solutions

In addition to the technical issues associated with improving integration approaches, there are two additional, non-technical goals that will impact how the stakeholders go about addressing business or market objectives. The first concern, within the enterprise, is to help obtain the business buy-in to the value proposition of standards-based integration. Second concern, also within the enterprise, is to help change the culture of systems integration.

Two results of the business/market processes are ranked high. First one is to enable greater agility of the systems by removing duplication of (within enterprise) and enabling common services. Second one is that manufacturers like "to keep their options open", which translates into using only vendor-neutral, open-standards-based integration solutions.

2.3 Capability Gaps

The participants identified the following capability gaps standing in the way of addressing the above business and market goals. The gaps are summarized in Table 2.2.

The functional quality of messaging standards and application programming interfaces (APIs) is of particular concern in this area of work. Two capability gaps have been identified to address the functional concern. First, there is no MSLCM capability to manage canonical standards. Second, the capability to generate computer interpretable, precise APIs by the MSLCM system is lacking.

To enable the goals identified in the previous section, a number of capability gaps related to methods and tools need to be addressed. Basically, a suite of tools is needed to support each phase of MSLCM from requirement, design, development, and test to deployment. First, methods and tools are needed to support collaborative, traceable message specification development. Second, there is a need for common tools to enable knowledge sharing, particularly with regard to deployment experiences. Third, adequate meta-data repositories and tools to manage the meta-data, tag message specifications, and search based on such meta-data are needed. Fourth, deployment tools should support large messaging standards. Finally, the tools and methods should support management of semantics of standards.

Table 2.2. Capability Gaps for MBMSD Methods
Function properties: • Canonical standards. • Usable, precise APIs.
Methods and tools: • Methods and tools to support collaborative, traceable MSLCM. • Common tools and shared knowledge in support of MSLCM. • Adequate meta-data repositories and tools in support of MSLCM. • MSLCM deployment tools supporting large messaging standards. • MSLCM supporting management of semantics of standards.

2.4 Technology Characteristics

The following technological characteristics are necessary for the capability gaps to be removed. These characteristics are summarized in Table 2.3.

MSLCM methods should use a business-process-first design approach to yield efficient and effective integrations. In contrast, interfaces that are based on data-first messaging specification development can result in hard-to-reuse services, and chatty and difficult-to-reconfigure integrations.

An MSLCM system should support middle-out, top-down, and bottom-up integration processes. The decision for the varied-process support follows from variations in standards development, usage, and maintenance approaches across different industries and use cases.

An MSLCM system should support integration processes that fit the needs and constraints of both small and large enterprises. The assumption is that small enterprises use standards for integration in fundamentally different ways than large companies.

For a number of years, researchers and academics have been proposing to include the business-context description in the governing structures of the MSLCM methods. Despite the recognized challenges, there is agreement among industry practitioners that this is necessary for MSLCM to be successful.

Regarding the MSLCM tooling, there is a perceived, significant, benefit in using a cloud-based infrastructure to facilitate knowledge sharing. Hence, an MSLCM system should be supported by an accessible (e.g., Software-as-a-Service- (SaaS-) based) repository of messaging standards and implementation guides.

A number of architectural decisions (related to the methods) for MSLCM approaches have been suggested. First, component-level MSLCM approaches should be used, allowing increased precision and effectiveness of standard specifications. Second, MSLCM should be supported by consistent and common integration requirements and feedback, enabling up-to-date understanding of the changing standard specifications and greater synchronization in their usage.

Table 2.3. Technology Characteristics for MBMSD Methods
Method decisions: • MSLCM should use business-process-first design to support integration process efficiency. • MSLCM should support middle-out, top-down, and bottom-up processes to achieve universal integration processes usability. • MSLCM should support processes that fit small and large enterprise needs and constraints. • MSLCM should be based on business context. • MSLCM should be based on context-classification scheme.
Tool decisions: • MSLCM should be supported by an accessible (e.g., SaaS-based) repository of messaging standards and implementation guides.
Method architecture decisions: • Component-level MSLCM. • MSLCM should be supported by consistent and common integration requirements and feedback.

2.5 Priority Action Topics

The identified priority action topics were focused on making progress in understanding the requirements for, and the design of, MSLCM methods and tools, with the desire to start addressing the capability gaps.

The needs analysis for MSLCM methods resulted in three major topics. The first involves formalizing MSLCM processes for both as-is (manual) and to-be (tool-supported) states. The second involves capturing use cases for tools in support of the MSLCM processes. The third involves agreeing on a sharable meta-model for MSLCM processes.

The needs analysis for MSLCM tools resulted in two major topics. The first involves designing a front-end user interface for an MSLCM tool (enabling exploration of wizard-like capabilities) to engage and support advanced functionalities. The second involves capturing requirements for tools in support of the MSLCM process.

Table 2.4. Priority Action Topics
Methods Requirements Analysis • Formalize the MSLCM process for both as-is (manual) and to-be (tool-supported) states. • Capture use cases for the MSLCM. • Develop, prototype, and validate the MSLCM meta-model.
Tools Requirements & Design • Design front-end user-interface tool for the MSLCM. • Capture requirements for tools in support of the MSLCM process.

2.6 Conclusion and Next Steps

The major conclusion of this breakout session was that a Business Process Cataloging and Classification System (BPCCS) was needed in addition to the Semantic Refinement Tool (SRT) that has been under development. The SRT supports the design, development, test, and deployment phases of the MSLCM, while the BPCCS supports the integration requirements gathering and meta-data management phases.

This conclusion came about because all the participants revealed an interest in exploring the possibility of using business-process models as a basis for specifying context (meta-data) and using it to drive requirements and discover reuse of integration and messaging standards artifacts. In addition, BPCSS appears to be a tool that can deliver impact necessary for the future measurements and standards.

NIST, in collaboration with the Smart Manufacturing Working Group (SMWG) within the OAGi consortium, has been developing such a BPCSS for some time. At this point, that BPCSS is a primary Priority Roadmap Topic (PRT), and it is well aligned with the specified Priority Action Items identified in the session. The maturity level of the BPCCS PRT is high; it includes an initial prototype and the verification/validation of the BPCCS deliverable for the industry requirements that is on-going in the SMWG.

The next steps involve continued execution of the BPCCS PRT within the OAGi where continued development of the prototype, validation in industrial use cases, and integration with the SRT are planned.

3 Breakout 2 – Smart Manufacturing Systems Characterization (SMSC) Methods

3.1 Overview

With the introduction of the Smart Manufacturing (SM) concept, manufacturers are faced with many technologies and ways to improve their manufacturing systems. Smart Manufacturing Systems Characterization (SMSC) will enable unbiased tools or guidelines, allowing manufacturers to better understand systems they use and environments in which they operate, and to prioritize their investments in the new technologies. This, in turn, will help increase efficiency and effectiveness of architecting/designing new SMS.

SMSC methods provide an indicator and measurement process to characterize a manufacturing system for its readiness to deploy SM technologies or be part of an SM network.

As mentioned in the introduction, Smart Manufacturing Systems Characterization (SMSC) Methods advance RM LCM (Reference Model Lifecycle Management) Capabilities for LCM SOI Technologies by providing knowledge-model-based characterization of both the manufacturers' requirements and the technologies' capabilities for manufacturing services used within SOM Systems. This is in line with the expectation to communicate and act on information in context-specific ways without failures in interpretation and without costly mediation help, re-interpretation, or manual intervention.

These RM LCM Capabilities are then utilized to allow reasoning about composability of these systems and components within a manufacturing system and with respect to their interface designs, developing Smart Manufacturing Systems Characterization. This enables Composable SOM Systems for messaging-intensive manufacturing systems by supporting interoperable integration, search for and discovery of relevant manufacturing services, and configuration and re-configuration of these services.

3.2 Goals

The following market- and business-related goals have been identified (summarized in Table 3.1):

The focus goal of the SMSC Methods area of work is to enable a meaningful and usable Smart Manufacturing Systems Characterization approach. However, to accomplish that goal, a clear definition and common understanding of what constitutes Smart Manufacturing Systems needs to be established. Only with well-defined, shared definitions of SMS, can reliable characterization methods be developed. Related goals are to define a quantifiable Return-On-Investment measure to drive adoption of SM or as a proof of business value, and to identify the steps required to be ready for SM.

Application of an appropriate pattern for implementation of SM relies on a means of characterizing different manufacturing systems (V-Model [assembly], A Model [disassembly], X model [assembly and disassembly], batch, continuous, and discrete). The requirements for each of these different models means that there may be different ways to determine the producer's capability in implementing SM, and the steps that can be taken to implement SM.

Table 3.1. Goals for Manufacturing Systems Characterization (SMSC) Methods
Business/market performance objectives • To enable a meaningful and usable approach to Smart Manufacturing Systems Characterization.
Business/market processes change goals

• To increase efficiency and effectiveness of justifying, architecting/designing of Smart Manufacturing systems. • To identify the series of steps required to be ready for implementing SM by determining the readiness level, or capability maturity level of the business.
Resources needed for the market/business performance objectives • To obtain a clear definition and common understanding of the elements that make up a Smart Manufacturing (SM) system. • To obtain a quantifiable definition for Return-On-Investment (ROI) for investment in SM.
Business/market performances non-technical goals • To raise the comfort level of SMEs in the SM solutions and issues they are addressing, including security.
Results of business/market processes • To obtain well-defined architectures and solution types for Smart Manufacturing developments. • To increase efficiency of Standards Life-Cycle Management (SLCM) processes. • To develop description models and methods for SM solutions that will be meaningful to SMEs. • To define readiness-level metrics usable in characterization approaches.

3.3 Capability Gaps

Successful implementation of SMSC methods require multiple steps. The most important, and one that needs to be quickly addressed, is the alignment of the different industry standards that are struggling to address SM. This includes standards committees for IEC, ISO, W3C, and IEEE, as well as national efforts in the USA, Germany, France, Japan, China, South Korea, India, and other countries. Without a single target – or a set of non-overlapping standards – for addressing SMSC, there will be significant duplication and wasted effort. Some of the key issues because of this gap are: the lack of a clear definition and common understanding of what constitutes a Smart Manufacturing system, no quantifiable ROI or proof of business value to drive adoption of SM, and the lack of a direction to move forward.

There was a common feeling that (1) everything is moving so fast and it is hard for standards to keep up, (2) it is hard for SMEs to relate to the abstract models that are being used in standards, (3) it is equally hard to know how a company relates to others in moving to SM, (4) it is difficult to understand what the first steps should be, and (5) a great concern exists about the security implications of moving to SM.

Table 3.2. Capability Gaps for SMSC Methods
Non-functional properties: • Align standards from different industries for their effective use in the characterization methods (e.g., MT Connect, OPC UA, data historian standards).
Tools: • Technical means to capture state of a manufacturing organization in regards to Smart Manufacturing solution types and/or reference models. • Systems to collect data relevant to Smart Manufacturing solutions and provide the data to customers. • Educational and training systems to develop needed skill sets for Smart Manufacturing solutions (e.g., controls, automation, IT). • Cost-efficient, available data analytics methods.

• Readiness-level metrics.

3.4 Technology Characteristics

Some technical method to capture the current state of a manufacturing organization in regards to SM and/or reference models is needed. The concern is that SMEs do not have systems in place to collect SM data and provide it to their customers. The skill sets needed to implement SM are currently not widely available. They include expertise in a combination of IT, controls, automation, security, and process knowledge. Equally limiting is the shortage of subject matter experts in SMEs. The situation is further complicated due to different standards in different industries (MT Connect, OPC UA, data historians, AutomationML, PLCOpen, etc.). Each of these standards, mostly for communication to devices and across field networks, has arisen because of an industry-segment-specific need. Hence, implementing SM requires at least some knowledge of multiple industry-segment-specific standards.

Table 3.3. Technology Characteristics for SMSC Methods
Resource definition decisions: • Product definitions and manufacturing process (Bill of Process) definitions should be standardized • Smart (Cyber-Physical) Manufacturing Asset definitions and Equipment Capabilities definitions (Bill of Capabilities) should be standardized • Smart (Cyber-Physical) Manufacturing Asset Security Management
Readiness Level (or Capability Level or Maturity Level) Decisions: • Manufacturing Operations Technology Readiness Level (MOT-RL) (e.g., Infrastructure in place, security zones in place, patch management system in place, incident response management system in place, etc.) • Supply Chain Integration Readiness Level (SCI-RL) • Product Lifecycle Management Integration Readiness Level (PLMI-RL), possible equivalent of Recipe models in ISA 88 • Manufacturing Operations Management Capability Maturity Model Level

3.5 Priority Action Topics

Table 3.4 summarizes the identified Priority Action Topics during the discussions.

Table 3.4. Priority Action Topics
Develop, standardize concept definitions • Develop a concise and succinct definition of SM. • Develop an ROI model that can be applied to SM. • Determine if the Readiness Level method is the correct one to use. • Start standardization of Resource Definitions. • Develop SM Readiness Level metrics.
Deploy, maintain standard definitions

- Develop testing tools (or certification) to ensure standards are correctly applied or readiness level correctly assessed.
- Guidelines for using the readiness metrics.
- Process to evolve and improve the readiness level definitions and metrics.

3.6 Conclusion and Next Steps

The candidate Priority Roadmap Topics (PRT) for SMSC are driven by the following immediate needs:

- Develop a concise and succinct definition of SM (For example, in Industrie 4.0, definition implies ‘Mass production of single units’, or ‘Mass customization’)
- Develop an ROI model that can be applied to SM regardless of the specific industry segment or production method.
- Determine which Readiness Level, Capability Level, or Maturity Level method is the correct one to use.
- Start standards for Product Definitions, standard ways to define the manufacturing processes (Bill of Process) and of Smart (Cyber-Physical) Manufacturing Asset definitions, and standard ways to describe the equipment capabilities (Bill of Capabilities).

4 Breakout 3 – Smart Manufacturing (SM) Standards Capability Analysis

4.1 Overview

Effective and efficient use of information and services is a key to successful adoption of Smart Manufacturing Technology in a service-oriented integration (SOI) paradigm. Manufacturing standards not only provide specifications and guidelines for product, production, and enterprise system engineering, but also facilitate proper information flow during manufacturing system operations. This session focused on the need and directions for Smart Manufacturing Standards Capability Analysis. In order to conduct gap and capability analysis of existing standards, a conceptual model (the Smart Manufacturing Reference Model) is necessary to divide the complex target systems into subdomains and identify their boundaries and needs for standards. Mapping current coverage of available standards based on the conceptual model naturally leads to identification of gaps, conflicts, and overlap of smart manufacturing standards. The Smart Manufacturing Reference Model (SMRM) provides an organizing framework that facilitates coordinated development of standards, platform/component, and implementation. Development of the SMRM is one of the deliverables for this working area and has the goal of enabling efficient development of the SM systems artifacts.

As mentioned in the introduction, Smart Manufacturing Standards Capability Analysis (SMSCA) advances RM LCM Capabilities for LCM SOI Technologies by providing knowledge-model-based specification of data interchange, and systems integration and fusion. This is in line with the expectation to communicate and act on information in context-specific ways, without failures in interpretation and without costly mediation help, re-interpretation, or manual intervention.

These RM LCM Capabilities are then utilized to allow development of the Smart Manufacturing Reference Architecture and corresponding information standards and system interfaces based on that reference architecture. The reference model enables reasoning about disparate services/systems to exchange, understand, and exploit information flows – especially across product, production, and business lifecycles. This enables composable SOM systems for smart manufacturing systems by supporting interoperable integration, search for and discovery of relevant manufacturing services, and configuration and re-configuration of these services.

4.2 Goals

Existing standards development organizations (SDOs) are continuing to diversify in order to accommodate increasing needs of applying new technology and business models into manufacturing industry. Although traditional SDOs such as IEC, ISO, ASTM, and ASME continue to work on standards of significant importance to smart manufacturing, special-interest groups such as some newly formed consortia are taking opportunities to create specialized standards in a more open way, faster and with wider adoption potential. Thus, today's manufacturers, OEMs, and software and device providers find it more difficult to navigate through a plethora of conflicting, overlapping, and redundant standards and to identify the ones applicable to their processes and systems. In addition, both SDOs and special-interest consortia are facing the challenge of developing standards without seeing the "Big Picture" in parallel, yet disjoint paths. The goal of conducting systematic smart manufacturing standard capability analysis is to address the above challenges faced by both standards users and developers and to help the greater manufacturing standards community define appropriate roadmaps to achieve its business goals.

Table 4.1 summarizes the identified market- and business-related goals.

Table 4.1. Goals for Smart Manufacturing Standards Capability Analysis (SMSCA) Methods
Business/market performance objectives • To enable SDOs to define appropriate roadmaps for smart manufacturing standards development and improve the adoption rates of resulting standards. • To enable manufacturers, OEMs, manufacturing software, and device vendors and service providers to identify the most-applicable standards for their system/product/service design, development, operations, and management in order to achieve market competitiveness.
Business/market processes change goals • To enable Smart Manufacturing (SM) systems lifecycle performance advancements (e.g., vertical and horizontal systems integration, flexible manufacturing, shorter time to market, better asset utilization) by building on existing system solutions (not rip-and-replace). • To enable a systematic standards development process, from requirements collection to development and maintenance.
Results of business/market processes • Agile product development to support increased consumer demand for greater product variation, shorter model durations, and the need for improved quality and lower costs. • Better use of the large amounts of data that exist in historian and other systems (ERP, PLM, CRM, etc.), as the data are currently hard to use for decision making. • Lean/coordinated standards development process, improved standards coverage, and less conflict and overlap.

4.3 Capability Gaps

While we all agreed that the first smart manufacturing standards capability gap is a lack of smart manufacturing reference models (SMRM) and reference architecture (SMRA specifically for SOM), all session members recognized that there is a need to define key SM terms and definitions across different manufacturers. Use scenarios should be collected about the service-oriented architecture style for smart manufacturing. Specifically, mass customization and "Lot Size 1" must be considered. Common information models and service models needed to cover various manufacturing domains are missing.

Another SM standards gap is the need for an extensive survey of existing manufacturing standards and, following that, continuous maintenance of the list, even though there are some preliminary works already done by ISO and IEC. With the first two gaps filled, an improved standards landscape based on the NIST SM standards landscape has to be developed to group and classify the exiting standards. A software tool is needed for standards users to navigate the SM standards landscape, search for, and identify applicable standards for their applications.

For SM standards developers, development of a standards meta-model could help improve standards lifecycle management, by establishing traceability to requirements and enabling design for reuse. Tools similar to the OAGi Business Process Cataloging and Classification System can help contextualize the use of SM standards.

Lastly, common platforms will definitely improve smart manufacturing system integration efficiency.

Table 4.2. Capability Gaps for SMSCA Methods
Methods:

• Common Smart Manufacturing Reference Models (SMRM) to define needs and to map manufacturing standards. • An inventory of existing manufacturing standards. • Use scenarios for service-oriented manufacturing to realize smart manufacturing visions. • Smart Manufacturing Reference architecture (SMRA) to define the smart manufacturing function structure and interaction models. • Common information models for smart manufacturing covering lifecycles and value chains. • Methods for description of context for effective usage of data at levels 1 and 2. • Methods for easy fusion of data/information from diverse sources, domains, and lifecycle activities. • Methods for integration of systems from different vendors. • Definition of standard device interfaces (cyber-physical) that allow easy plug-in.
Tools: • Smart manufacturing standards map to navigate, search and identify applicable standards for manufacturers, OEMs and software/device/service providers. • Common SM standards meta-model and lifecycle management tools.
Definitions: • Key SM terms and definitions across different manufacturers.

4.4 Technology Characteristics

It has been discovered through the session discussions that many SDOs or consortia have already started to investigate the smart manufacturing standards gaps listed in the previous section. The results from those individual efforts will provide a solid foundation for the coordinated effort to be taken by all of the SDOs and consortia. Table 4.3 shows some related technology achievements to be incorporated by the joint effort.

Table 4.3. Technology Characteristics for SMSCA Methods
General technology decisions: • SMRM should rely on/reuse RAMI model, NIST Smart Manufacturing ecosystems. • SMRM should include Process Models and Information Models. • SMRA should include communication layer and assess IIC, DMDII, MT Connect, OPC UA, MQTT, DDS, and other alternatives. • SMRA could be developed in collaboration with IIC, IEC, DMDII, MESA, and others. • SMRA should include Service Layer (service models, use cases). • SMRA should also include a reference implementation. • SMRA should allow reuse of IoT solutions (including analytics) from commercial world (economy of scale), but SMRA shouldn't depend on the IoT technology. • SM standards landscape should be built on top of the NIST, IEC, and IEO works. • SM standards map can be developed through joint working group between IEC TC 65 and ISO TC 184, and reuse IEC Smart Grid Standards Map technology. • SM standards meta-model and lifecycle management tools can be developed based on two previous NIST SBIR efforts.

4.5 Priority Action Topics

The identified priority action topics were focused on smart manufacturing reference model and reference architecture development and the tools for smart manufacturing standards map. Table 4.4 shows several top prioritized tasks.

Table 4.4. Priority Action Topics for SMSCA Methods
Review & Analyze Related Work • Survey existing manufacturing reference models (ISA 95/RAMI/NIST/Japan/China). • Survey standards landscape work from IEC, ISO, and NIST. • Develop SM standards Map.
Define Terms and Concepts • Clarify/position the levels in ISA 95's terminology. • Clarify SDO terminology discrepancy (reference model, architecture, framework, etc.), mapping working groups of ISO TC 184 and IEC TC 65, JTC1. • Define semantic models for SOM for easy service integration.
Organizational Items • ISO and IEC will pursue collaborative arrangements to create joint working group (IEC/ISO JWG21) to define SM reference model.

4.6 Conclusion and Next Steps

Many joint efforts are emerging to work on the Priority Action Topics listed above. Specifically, IEC and ISO are forming a joint working group, JWG 21, to develop SM reference models. Terms and definitions are now in development under IEC TC 65, as are the SM use cases. IEC is also developing a better standards classification system and improving the SM standards landscape by incorporating prior research results from different countries (France, Japan, etc.) and consortia (AutomationML, OPC-UA, and MTConnect).

At this point, we are working on semantic service models at both the enterprise- (Section 2) and shop floor-levels (cyber-physical manufacturing services - CPMS). This PRT is well aligned with the Industrie 4.0 RAMI model, where the I4.0 component is defined with service interfaces. The service models should consider Properties and Classes that describe products according to the concept of ISO 13584.

5 Breakout 4 – Smart Manufacturing Apps and Services Marketplaces (SMASM)

5.1 Overview

In this session, new concepts and methods for design and analysis of Smart Manufacturing Apps and Services Marketplaces (SMASM) were investigated. The SMASM working area considered plans to enable (1) shared, secure, open-access infrastructure rich in data and integration functionality for easier system integration and composability, (2) a marketplace that can drive technological capability beyond just products taking advantage of market visibility and market-driven intelligence, and (3) integrating services on standards, uncertainty quantification, benchmarking, performance-use metrics, systems modeling, and many more. The marketplace is viewed as a rich clearinghouse of application resources, tools, capabilities, and information.

As mentioned in Introduction, Smart Manufacturing (SM) Apps and Services Marketplaces (SMASM) advances RM LCM Capabilities for LCM SOI Technologies by providing knowledge-based-models and definitions for a multitude of operational aspects of SOM systems/apps and marketplaces. This is in line with the expectation to communicate and act on information in context-specific ways without failures in interpretation and without costly mediation help, re-interpretation, or manual intervention.

These RM LCM Capabilities are then utilized to allow identification and analysis of current technological and other challenges as well as requirements on SMASM placed by stakeholders. This enables composable SOM systems for messaging-intensive manufacturing systems by supporting interoperable integration, search for and discovery of relevant manufacturing services, and the configuration and re-configuration of these services.

5.2 Goals

The concept and scope of today's Smart Manufacturing Apps and Service Marketplace(s) is an open question and is not jointly agreed upon by stakeholders. Table 5.1 summarizes the primary goals outlined by this workshop session panel.

Table 5.1. Goals for Smart Manufacturing Apps and Service Marketplaces (SMASM)
Business/market performance objectives • To enable (1) ready access to data, analytical, modeling, and optimization resources for manufacturing, supply chain-wide; (2) methods for identification, evaluation, and testing of a broad range of commercial, open-source, and experimental software and digitized hardware, (3) a vehicle for contribution towards new solution innovations, and (4) a clearinghouse for data, service certifications, requirements, and applications experiences from the stakeholder (e.g., designers, providers, and users) perspective
Business/market processes change goals • To enable (1) shared, secure, open-access infrastructure, rich in functionality for easier system integration and composability, (2) a marketplace that supports rapid engineering development, testing, implementation, and deployment by a variety of providers (including developers, professional service providers, and users themselves)who can support infrastructure integration, product interoperability, and systems changes, and (3) allow integrating services on standards, uncertainty quantification, benchmarking, performance-use metrics, systems modeling, and many more.
Business/market performances non-technical goals

• Marketplace needs a value proposition, critical mass, and diversity of services and customers to be attractive to users and providers, as well as to overcome a market tendency for vendor-specific marketplaces.
Results of business/market processes: • To enable rich source of validated and certified services and products (apps/software). • To enable a collaboration (testing, evaluating) environment for new and emerging services and products. • To support the ability to rapidly architect and execute complex platforms and socio-technical systems. • To enable accessible solutions to integrate and empower workers (including involving them in service and app design process). • To enable bringing tools to workers, not scale workers to tools. • To support integration of (possibly different) competences and cultures. • To help align solutions to the needs of the user. • To enable a true market with associated functions (including making use of market forces). • To enable a wide spectrum of discoverable services. • To enable a marketplace ecosystem - factory floor, supply chain, design, etc. • To enable more efficient- and effective-to-test-with-realistic-data software products. • To enable marketplace investment in, and incorporation of, know-how (not to replace workers). • To help companies to successfully reorganize corporate and operational functions; identify who is responsible. • To enable adoption of new, changing business models for providers and users; enable identification of well-defined long-term and short-term business cases. • To help manage people, readiness, culture, and expectations. • To help establish trusted relationships between (platform and services/apps) providers and users. • To allow participation of small, medium, and large companies, each of which tends to think differently and to have different scales, expectations, and marketplace objectives. • To allow identification and existence of multiple solutions/approaches to the same problem.

5.3 Capability Gaps

From an overarching viewpoint, there are competing philosophies that include a universal marketplace and multiple, targeted marketplaces. Arguments span domain-specific requirements, security/certification needs, innovation potential, interoperability, access barriers, and scalability, to name a few. The desire for the highest security possible or a less-strict governance structure translates into ranges of management, mediation, and entry requirements, and tradeoffs with access and leveraging market forces. Key aspects are trusted ownership of data produced by the marketplace and neutrality with the products and services.

The participants identified the following capability gaps standing in the way of addressing the above business and market goals.

Table 5.2. Capability Gaps for CMK Methods
• Function properties: o Assured data quality and trust validation process. o Security and confidence critical. o Need to address space, synchronization, and legacy. o Aim governance toward certification, but not too much.

o Verification and validation levels depend on scale. • Other challenges and barriers: o Total cost (or uncertainty regarding it) is a major barrier for SMEs and multi-national enterprises alike. o Trust issues between developer and user. o Manufacturers giving away (some) control to application developer. o How can the data/analysis based in data be trusted (finger pointing in case of problems)? o Injustice in ROI and business value. o Safety/security concerns. o Identifying the value of adding a service. o Verification in itself is not trivial. o Level of configuration needed (too high and it might defy purpose of marketplace).

5.4 Technology Characteristics

The following technology characteristics (relating to decisions on architectures, approaches, technologies, or methods) have been identified as necessary for resolving the capability gaps:

Table 5.3. Technology Characteristics for Smart Manufacturing Apps and Services Marketplaces (SMASM)
Methods decisions: • Do not use "mobile phone apps" analogy; it might indicate a level of maturity that neglects needed critical discussion on a fundamental level and might furthermore be perceived degrading at shop-floor level. • Distinguish marketplace connects vs. apps subsets; marketplace needs to be a true market; B2B not B2C. • Do not attempt to solve the standard problems; instead it should empower people to solve the problems; useful cloud standards for containerization; machine standards, such as MT Connect; need interface standards to achieve interoperability. • High degree of interoperability among marketplace products; ability to plug into infrastructure; cloud standards opportunity for interoperability; interoperability needs to evolve; big distinction between run-time data and analysis data. • Terminology important but not defined; terminology needed to get to a framework; need to define interoperability; different levels (ISA 95) will need different standards; standards needed for different lifecycles. • Accept company standards but wrap or translate for interoperability; governance of marketplace important; shared infrastructure is important; support for manufacturing competence is needed. • Big distinction between run-time data and analysis data. • Cloud standards in good shape; there is indication that marketplace can help resolve various machine shop, spectrum bands, and data formats issues.

5.5 Priority Action Topics

The following are priority action topics proposed by the session participants:

Table 5.4. Priority Action Topics
Conceptualization

- Need for more precise vocabulary that does not alienate
- Draw know-how from other domains – e.g., gaming and medical
- Security and confidence critical
- Avoid artificial duplication
- Develop industry use cases

5.6 Conclusion and Next Steps

A rich marketplace of services is seen as key to Smart Manufacturing taking full advantage of IT technologies that now make it possible to deploy software as services. There was a consensus among the diverse group of experts from academia and industry (users and service providers) that because marketplaces can expedite access to essential applications and services, they are a desired path to accelerate exploitation of Smart Manufacturing benefits. It was further agreed upon that a legacy approach of large monolithic software solutions is aligned with increasing dynamics and complexity and substantially greater integration efforts. Successful use cases in which Marketplace function, access, and impact can be prototyped, and the real value to users be demonstrated, are necessary and essential. These use cases need to be focused on real industrial problems, work with real data, and need to be communicated clearly and transparently (including their limitations and challenges). There is additional need to demonstrate that the Marketplace can support a different market dynamic associated with much more extensive implementation of application systems across small, medium, and large manufacturers. These application systems comprise multiple vendor products and involve data from heterogeneous sources and environments. System-component technologies readily grow and change and vendor products are more readily investigated, tested, and changed as new technologies and methodologies are developed. In order to create an environment where a Marketplace can survive, there are key questions to address. A high degree of interoperability is needed for applications within a marketplace ecosystem. The marketplaces need to support integration with existing manufacturing infrastructure. Operational, data, and IT standards, standards-based wrappers that are independent of software operating systems, and translators for company-specific standards are needed to effectively interoperate. There is a key need to address the business model of the Marketplace and converge on how trusted responsibilities will be dealt with and ultimately monetized. Cyber-attack security, data-source security, and data verification and validity are critical. Data ownership, company privacy, regulated data, and IP security all need to be managed. Trust, real and perceived risks, workforce skill gaps, and organizational integration get in the way of the collaborative opportunity potential of Smart Manufacturing and the role of the Marketplace.

6 Breakout 5 - Crowdsourcing of Manufacturing Knowledge (CMK)

6.1 Overview

This session focused on the need and directions for development of Crowdsourcing of Manufacturing Knowledge for Smart Manufacturing Systems. Formal knowledge models are necessary components of smart manufacturing systems. One of the main challenges in developing formal knowledge models is to efficiently elicit knowledge from distributed resources and form a coherent body of knowledge that can be validated and extended by user communities. Most of the existing knowledge models in the manufacturing domain were developed in a centralized and top-down fashion. This working area is exploring the requirements, challenges, and opportunities regarding capturing manufacturing knowledge from “the crowd.” Ultimately, the objective is to develop a community-centric crowdsourcing method, process, and tool that allow for the growth of a reference model and knowledge base for manufacturing system design and analysis.

As mentioned in the introduction, Crowdsourcing of Manufacturing Knowledge (CMK) advances RM LCM Capabilities for LCM SOI Technologies by developing knowledge-model-based approaches for capturing manufacturing knowledge from “the crowd.” This is in line with the expectation to communicate and act on information in context-specific ways without failures in interpretation and without costly mediation help, re-interpretation, or manual intervention.

These RM LCM Capabilities allow new knowledge-based models, methods, and tools to play a key role in gathering and managing manufacturing knowledge that is more palatable/feasible in the new distributed-manufacturing SOA architectures. This enables composable SOM systems for manufacturing systems by supporting interoperable integration, search for and discovery of relevant manufacturing services, and configuration and reconfiguration of these services.

This section included four topic areas related to crowdsourcing techniques, wherein participants discussed issues, challenges, and opportunities with respect to (1) requirements, (2) approaches, (3) standards, and (4) stakeholders. Each discussion topic was preceded by a perspective from an invited speaker. Below, we review the questions and primary talking points from each area.

6.1.1 Requirements for knowledge capture in smart manufacturing

For this topic, the focus was on understanding the types of knowledge that would be captured and formalized in a Smart Manufacturing knowledge base. What types of knowledge should be captured? What kinds of questions could be explored? The consensus was that not all types of manufacturing knowledge could be crowdsourced. Therefore, one of the goals of any early research in this field should be to identify the knowledge types that can be elicited and formalized using a crowdsourcing approach. The discussion topics also covered

- existing efforts related to the development of manufacturing knowledge models,
- the desired level of formality for manufacturing knowledge models,
- support structures that would enable success.

6.1.2 Approaches for knowledge capture: top-down vs. bottom-up

This topic focused on knowledge capture and elicitation approaches for Smart Manufacturing. What are the motivations for adopting a crowdsourcing approach? Can crowdsourcing capabilities be successfully applied to capturing manufacturing knowledge? How can one validate the captured knowledge and maintain its consistency over time?

6.1.3 Tools, methods and standards for knowledge capture for smart manufacturing

This portion focused on tools, methods, and standards that are currently available for development, representation, and validation of knowledge models for smart manufacturing. What standards are already available and what standards need to be developed? The panel discussed if the existing standards landscape is suitable for a crowdsourcing environment.

6.1.4 Stakeholders of knowledge models for smart manufacturing

The objective of this session was to develop an understanding of various parties that would benefit from the existence of open-source knowledge models for smart manufacturing. In particular, the following questions were addressed: How to create and incentivize communities of knowledge users? Is there a need and role for a neutral party in the creation of a SMS knowledgebase? Is there an opportunity to combine the more-focused efforts of different groups to leverage infrastructure and expand the breadth of coverage? What incentives and governance models would be needed? How to find synergies among developers and users?

6.2 Goals

Based on the attendees' discussion including the identification of business problems, the following market- and business-related goals were identified:

Table 6.1 summarizes the goals for CMK methods identified by the workshop participants. Key points of the discussion centered around the elicitation, retainment, and maintenance of tacit knowledge. There was common agreement that too often when an organization loses experts, knowledge retention is a major challenge. Regardless of whether the community requires a CMK solution to capture such knowledge, the importance of during so is significant.

In any crowdsourcing scenario, one of the primary challenges is incentivizing contributions from the crowd. Existing efforts have demonstrated varying degrees of success. The session participants spent considerable time identifying attributes and features of successful crowdsourcing efforts. GrabCAD (grabcad.com), initially founded in 2009 as a web-based platform for engineers to share CAD models, was a primary focus of conversation. GrabCAD quickly grew and today boasts more than 2 million users and about 700,000 open source models. The fundamental point of the discussion was on the reasons for GrabCAD's success. The discussions' salient points were mostly centered around incentivization. GrabCAD offers several direct benefits for their users to continue participating as active users. These include engineering spotlights, user profiles, design competitions, etc. GrabCAD also began with a common currency among designers, i.e. solid geometric models. What would be valuable in manufacturing like CAD models are to engineering designers?

For any crowdsourcing effort to be successful, it is imperative (1) to promote a culture of sharing through various channels, such as professional manufacturing societies and trade groups (2) to incentivize participation through gamification, leaderboards, credits, etc. and (3) to reach critical mass of users and sharable information.

Table 6.1. Goals for Crowdsourcing of Manufacturing Knowledge (CMK) Methods
Business/market performance objectives • To enable retainment of tacit knowledge within an organization. • To enable elicitation of tacit knowledge. • To enable cost-efficient, extensible re-usability of knowledge models.

• To allow IP-issue-free crowdsourcing processes.
Business/market processes change goals • To allow usability and accessibility of the crowdsourced knowledge.
Business/market performances non-technical goals • To allow clear value proposition for participation in crowdsourcing through incentives. • To identify role for a neutral party. • To enable participation of resource-constrained SMEs. • To enable greater understanding of the culture of sharing. • To enable equal access and benefits to all users in creating respective competitive advantage. • To enable visibility of the crowdsourcing effort through increased awareness, attracting and engaging the audience, marketing, on-ramping, viral marketing, etc. • To enable resolution of conflicts of interest among multiple types of organizations from academia, government, industry.
Results of business/market processes • To allow resolution of data issues that are not organized, too aggregated, or not applicable to domain-specific problems.

6.3 Capability Gaps

The participants identified the following capability gaps standing in the way of addressing the above business and market goals.

This breakout session was more academic than the others. As a result, participants proposed a number of open research questions that would benefit the community if answered or, at minimum, explored. Questions included but were not limited to the following:

- How to properly capture manufacturing models in mathematical, machine-readable formalisms?
- How to represent manufacturing knowledge in a general, standardized way, considering the various abstraction levels of analysis and domain-specific challenges in knowledge reuse?
- What are the appropriate governance models to handle or extract proprietary knowledge?
- How to measure the completeness of a manufacturing knowledge base when using the crowd to populate it?
- How to validate the captured knowledge?

Table 6.2 reflects the capabilities lacking to ensure success for CMK-related efforts. Some of these are still research questions.

Table 6.2. Capability Gaps for Crowdsourcing of Manufacturing Knowledge (CMK) Methods
Non-Functional properties: • Crowd-related: identification, recruitment, validation, engagement.
Methods: • Methods to enable use of a wide variety/diversity of existing tools (languages, abstraction levels). • Methods to address gap between existing levels of users' expertise and the required expertise for using the tools.

• Methods and tools to manage variety of models which will be acquired. • Methods to allow model reusability. • Methods and tools to deal with knowledge instantiation. • Methods and tools to allow quick gathering of digital information. • Specialization from contributors (internal vs. external). • Reaching critical mass of knowledge. • Methods to measure completeness of knowledge in a repository. • Methods and tools for maintenance of crowdsourced knowledge base. • Reasoning and problem-solving methods and tools. • Mechanism to harness existing information. • Methods and tools for gamification of crowdsourcing activities.
Standards: • Definitions (What are we crowdsourcing? And how?). • A common ontology and definitions for the marketplace. • Protocol for testing expertise levels. • Validation mechanism for crowdsourced models. • Uniform knowledge representation that supports a variety of tools.

6.4 Technology Characteristics

To help remove some of the capability gaps mentioned above, the session participants identified a number of technology characteristics. Since the CMK session was heavily research-oriented, these characteristics are still academic issues.

One of the primary areas of discussion throughout the session was centered around leveraging an "expert-based" or local crowd specifically for the elicitation of manufacturing knowledge. An example of this would be a library of ontologies related to manufacturing enterprises. In order to build such a resource, several standards development efforts would be required. For example, to agree on terms, definitions, and usage, a controlled English lexicon would be required (e.g., the functional basis from Oregon State University). One solution would be to use Knowledge Organization Systems models such as formal thesauri. A formal thesaurus (based on a Simple Knowledge Organization System, for example) lends itself better to a crowdsourcing scenario due to its simpler semantics. Strict validation procedures and guidelines, through either a peer-review system or automated techniques, or a combination of them, would be required to verify appropriate contributions to the knowledge base. A common library of manufacturing knowledge would require a specified curator, a central administrator who is responsible for maintenance as well. Additionally, there would be development requirements for such a system, including graphical user interfaces (GUIs), acquisition of physical disk space, application programming interfaces (APIs), and possibly plug-ins into existing computer-aided engineering (CAE) systems.

Table 6.3 lists high-level goals specifically for technology-related needs for CMK methods.

Table 6.3. Technology Characteristics for CMK Methods
Standards Decisions: • Standards representations should be consistent across analysis tools. • Standard mathematical descriptions of models. • Controlled English lexicon, such as functional basis from Oregon State. • Guidelines on hierarchical construction, extension, reuse, and analysis of performance models for manufacturing processes. • Validation procedures/guidelines for KB contributions.

• Crowdsourcing knowledge elicitation procedures. • Guidelines for transforming knowledge elicitation to acquisition. • Guidelines for use (with use cases and examples).
Tool Decisions: • Library of ontologies that are modular and complementary. • Middle-ontology to support cohesion of the library of ontologies. • Central curator (administrator). • Prototypes, user studies, and refinement – GUI, interfaces, translators, etc.

6.5 Priority Action Topics

While discussing these technology characteristics to aid CMK, session participants quickly realized that such an undertaking would require significant "buy-in" from the research community. Driving consensus around this area is a challenge and requires in-person meetings to make significant progress. For example, one of the key action items is coming to a consensus on a core abstract ontology for the manufacturing community. Considering the number of proposed manufacturing-related ontologies in literature, this task seems daunting. One challenge would be to properly scope such an ontology. Should product-based concepts be included? What about supply chain-specific concepts? Session participants agreed to focus on existing successes of similar efforts. In other words, any CMK efforts should borrow models and practices from successful web-based communities, such as GrabCAD, and research communities that have developed their own agreed-upon corpus of terms and concepts, such as the biomedical research community. This recommendation is explained in more detail in Section 6.6.

The following are priority action topics, shown in Table 6.4, proposed by the session participants:

Table 6.4. Priority Action Topics
Conceptualization: • Define an initial terminology set. • Nail down core abstract ontology (e.g. process, product, manufacturing resource).
Analyze best practices & methods: • Conduct literature review (crowdsourcing techniques, existing KBs, model representation). • Review existing commercial tools (what's out there?). • Understand GrabCAD's success (and that of other engineering-related crowdsourcing efforts that have shown success). • Identify best practices for crowdsourcing. • Understand crowdsourcing task design. • Identify community crowds.
Design methods: ▪ Create manufacturing models and test their use.

6.6 Conclusion and Next Steps

This section presented key takeaways from the breakout session, entitled Crowdsourcing for Manufacturing Knowledge (CMK). Early in the session discussion, it became evident that this area requires significant research before risks of implementation are mitigated. Issues related to incentivization, crowd engagement, knowledgebase maintenance, and proper knowledge representation and validations were consistently raised.

Based on the above priority action items, it is evident that many issues related to CMK require a larger, more representative consensus from the manufacturing research community. This session has helped motivate a new effort for the convergence of existing knowledge acquisition research in the manufacturing domain, coined the Industrial Ontologies Foundry (IOF)[2]. Analogous to the Open Biomedical Ontologies (OBO) Foundry[3], the primary purpose of the IOF is to assist in obtaining curated, high-quality ontologies for the manufacturing domain. Not only would this aid in CMK efforts, but the IOF itself can be considered a CMK-based activity in its own right.

According to session participants, risks for crowdsourcing manufacturing knowledge include: gaining a critical mass of people, gaining a critical mass of knowledge, commitment of the leadership, commitment of the crowd, staying power of the used technologies, quality of the content, livelihood of the content, breadth of KB, and discipline of the contributors. Risks to success in the IOF echo similar challenges.

[2] http://blog.mesa.org/2017/03/working-towards-industrial-ontology.html

[3] http://www.obofoundry.org/

7 Summary

This document reports on the 2016 workshop *Drilling down on Smart Manufacturing -- Enabling Composable Apps*, which is second in a new series of workshops begun in 2015 to foster a shared vision of a new Smart Manufacturing (SM) platform that will support Composable Service-Oriented Manufacturing (SOM) systems. The workshop explored the needed technical foundation for achieving the vision. The following are main findings from the workshop and next steps planned for the workshop series.

7.1 Key Findings

7.1.1 Extensive New Technical Capabilities Are Needed for Composable SOM

Realizing the vision of Composable Service-Oriented Manufacturing (SOM) requires many advances in underlying technologies to build more capable systems-integration technologies. The focus of the workshop and the community has been described in this report as (1) providing new reference models life-cycle management (RM LCM) capabilities and (2) using those capabilities to build new life-cycle management service-oriented integration (LCM SOI) technologies.

Each breakout session, within its respective area of interest, discussed advances in RM LCM capabilities for LCM SOI technologies. Common to the sessions' differing perspectives is that all sessions focused on developing knowledge-based modeling approaches to achieve RM LCM methods. This focus is in line with developing needed capabilities to communicate and act on information in context-specific ways without failures in interpretation and without costly mediation help, re-interpretation, or manual intervention. These RM LCM capabilities are then utilized to allow new models, methods, and tools to play a key role in enabling composable SOM systems by supporting interoperable integration, search for and discovery of relevant manufacturing services, and configuration and reconfiguration of these services. In summary, the following is how the five breakout sessions develop knowledge-model-based RM LCM capabilities to enable advances towards composable SOM:

- **Smart Manufacturing (SM) Model-Based Messaging Standards Development (MBMSD) Methods** provides knowledge-model-based specification for conveying context and usage information for manufacturing services within SOM Systems, and which will be used to support efficient messaging standards life-cycle-management (MSLCM) capabilities.

- **Smart Manufacturing Systems Characterization (SMSC) Methods** develops knowledge-model-based characterizations of both the manufacturers' requirements and the technologies' capabilities, which will be used to support reasoning about the composability of these technologies within an SMS based on their interface designs.

- **Smart Manufacturing Standards Capability Analysis (SMSCA)** provides knowledge-model-based specifications for conveying information about data interchange, systems integration, and data fusion, enabling development of (1) a Smart Manufacturing Reference Architecture and (2) information standards and system interfaces, which are needed to allow disparate services/systems to exchange, understand, and exploit information flows.

- **Smart Manufacturing (SM) Apps and Services Marketplaces (SMASM)** explores knowledge-model-based definitions of multitude aspects of SOM systems, apps, and marketplaces, which will be used to support the identification and analysis of current technological and other challenges as well as requirements from the stakeholders for Composable SOM Systems.

- **Crowdsourcing of Manufacturing Knowledge** investigates new knowledge-model-based approaches for capturing manufacturing knowledge from "the crowd," which will be used to build new methods, and tools that play key roles in gathering and managing the new types of manufacturing knowledge that is becoming available using distributed SOM architectures.

7.1.2 R&D Road-mapping is an Important Resource in Developing Composable SOM

This workshop report provides descriptions of the goals, missing capabilities, proposed technology characteristics, and priority action items in five working areas, based on the participants' discussions in the corresponding breakout sessions. This material is presented in a common, structured, format in order to enable an R&D road-mapping effort. Future workshops will review progress and refresh the road-mapping material as needed.

The road-mapping material can be used by the stakeholder community to plan and direct development of new technologies and by SDOs to develop the standards needed to integrate those technologies into Composable Service Oriented Manufacturing systems. NIST will be carefully reviewing this and future workshop findings to update its program in Smart Manufacturing Systems Design and Analysis (SMSDA) to further align it with industry's needs and priorities.

The following are some of the research topics representative of the workshop sessions:

- **Smart Manufacturing Model-Based Messaging Standards Development (MBMSD) Methods** discussed (1) Common processes for developing and maintaining standards-based, service-oriented integration; (2) Tools for developing collaborative and traceable integration standards; and (3) Methods for discovering, documenting, and sharing context-dependent standards-usage experiences.
- **Smart Manufacturing Systems Characterization (SMSC) Methods** discussed (1) Technical means, which may include a reference model, to capture the current state of a manufacturing organization in regards to SM; (2) Standards for product definitions and manufacturing processes, SM asset definitions and equipment capabilities, and SM asset security management; and (3) Measurement methods to assess a manufacturing system in the form of readiness, capabilities, or maturity levels.

- **Smart Manufacturing Standards Capability Analysis (SCA)** discussed (1) Specification and means for gathering context information at levels 1 and 2 of the ISA-95 manufacturing control architecture; (2) High-level SM reference architecture, including communication, process, data, and service models to support integration of data from diverse machines and software vendors; and (3) Mechanisms for fusing data from diverse sources across domains, lifecycle activities, and vendors.

- **Smart Manufacturing Apps and Services Marketplaces (SMASM)** discussed (1) Need for precise vocabularies accessible through multiple viewpoints; (2) Technologies for assisting people in manufacturing tasks and workflows; (3) Interface standards for equipment and resources to allow app interoperability; and (4) Market infrastructure and governance (e.g. certification of apps and services) to provide scaled security and confidence.
- **Crowdsourcing of Manufacturing Knowledge** discussed (1) Common ontology and definitions in support of the SM marketplace; (2) Validation mechanisms for the crowdsourced knowledge models; and (3) Uniform knowledge-representation that supports a variety of crowdsourcing and knowledge-management tools.

7.1.3 Prioritization of Roadmap Topics is Needed to Enable Focused Work in the Community

For each of the workshop breakout sessions, a target Roadmap Priority Topic (PRT) was identified. A PRT provides a focus for planned work in the form of a product deemed key or as a critical future resource for advancement of state of the art for the session. PRT allows planning of needed resources to achieve tangible outcomes and desired impacts on measurement science, enabling the technology, standards, new capabilities, and goals. The following are potential PRTs identified for each session:

- **Model-Based Messaging Standards Development (MBMSD):** Business Process Cataloging and Classification System (BPCCS)
- **Smart Manufacturing Systems Characterization (SMSC):** Classification Model of SM Systems Requirements and Capabilities
- **Smart Manufacturing Standards Capability Analysis (SMSCA):** Smart Manufacturing Reference Architecture
- **Smart Manufacturing Apps and Service Marketplaces (SMASM):** SM Service Marketplace Requirements Engineering Method
- **Crowdsourcing Manufacturing Knowledge (CMK):** Repository of CMK resources.

The PRTs in all sessions but the first are in the earliest identification/conceptualization stage and they provide a starting point for further analysis of scale of interest, target scope, needed and available resources, and feasibility of the idea. Nevertheless, the identified PRTs provide a needed focus for future discussions, and they may continue to be refined. They may also serve to refocus interest on other areas and PRTs in the future. An initial set of PRT maturity-assessment criteria was identified to guide future evolution of the workshop sessions and PRT development, with the aim of ultimately leading to PRT executions in focused R&D projects.

7.1.4 Workshop Roadmap Priority Topics and NIST Smart Manufacturing Program Are Well-Aligned

The NIST SMSDA program plans to continue to work with the stakeholder community in all five initial workshop working areas to further the state of knowledge and capabilities needed for the platform for Composable SOM apps and systems. The table shows that current projects within the NIST SMSDA program are well aligned with more than half of the identified Priority Roadmap Topics (PRTs). Future alignment is expected to be even greater.

Table 7.1. Alignment of Priority Roadmap Topics (PRTs) &NIST Smart Manufacturing Systems Analysis and Design (SMSDA) Program

	NIST SMSDA Program Projects:	
	Service Oriented Architectures for Smart Manufacturing (SOA4SM) Project	Performance Assurance for Smart Manufacturing Systems (PASMS) Project
Model-Based Messaging Standards Development (MBMSD)		
Business Process Cataloging and Classification System (BPCCS)	+	
Smart Manufacturing Systems Characterization (SMSC)		
Classification Model of SM Systems Requirements and Capabilities		+
Smart Manufacturing Standards Capability Analysis (SMSCA)		
Smart Manufacturing Reference Architecture	+	
Smart Manufacturing Apps and Service Marketplaces (SMASM)		
SM Service Marketplace Requirements Engineering Methods	*	

Crowdsourcing Manufacturing Knowledge (CMK)		
Industrial Ontology Foundry	*	*

(Legend: **+** NIST program is actively working in the R&D area; ***** NIST program is following the R&D area)

7.2 Next Steps: R&D Projects to Enable Industrial Impacts

The ultimate goal of the workshop series is to enable the community to drive specific R&D projects to contribute to the vision of composable SOM apps/services and systems. The community has expressed interest in continuing to meet on annual basis to work together and explore the state of the art in composable SOM apps/services and systems. The goal for the future is to assure that identified and new Priority Roadmap Topics (PRTs) are used to initiate new activities not only in NIST R&D programs but also in other industry, academia, and government R&D programs. In addition, the goal is to enhance the maturity of the PRTs and enable their execution in a collaborative R&D setting with high probability of success. The maturity-assessment criteria for the PRTs, some of which are identified in this report, will be further refined and used to drive the stakeholders' activities towards PRT execution. Along with the R&D focus, future workshops will pay close attention to potential impact of the R&D efforts executing the PRTs. The following table showcases potential places for impact of the current and candidate PRTs in industry, SDOs, and government.

Table 7.2. Potential impact of session PRTs on Industry, SDO, and government agencies

Working Session / PRT Name	**Potential impact**
Model-Based Messaging Standards Development (MBMSD)	
Business Process Cataloging and Classification System (BPCCS)	Enabling new generation of model-based OAGIS standard at the OAGi and other SDOs
Smart Manufacturing Systems Characterization (SMSC)	
Classification Model of SM Systems Requirements and Capabilities	Enabling Smart Manufacturing Systems Characterization Methods at MESA and other SDOs
Smart Manufacturing Standards Capability Analysis (SMSCA)	
Smart Manufacturing Reference Architecture (SMRA)	Enabling Inter-SDO (ISO, IEC, etc.) alignment on SMRA
Smart Manufacturing Apps and Service Marketplaces (SMASM)	
SM Service Marketplace Requirements Engineering Methods	Enabling Industry & Government (Corning, General Mills, DoE, etc.) move to create Smart Manufacturing marketplaces
Crowdsourcing Manufacturing Knowledge (CMK)	
Industrial Ontologies Foundry	Enabling Multi-Industry & Government (AutoCAD, USAF, Dassault, etc.) technology advancements

Appendix A – Key Terms

Smart Manufacturing Systems (SMS) – New generation of advanced manufacturing systems enabled by the convergence of information and communication technologies with emerging physical technologies to influence more efficient, automated, programmable, and flexible forms of manufacturing to meet changing consumer demands, market conditions, and supply chain capacities.

Service-Oriented Manufacturing (SOM) Systems – Manufacturing systems paradigm influenced by the service-oriented views of computing and information systems where manufacturing capabilities and resources are provided as services within a distributed, open ecosystem of service providers and consumers who use these services in assembling their systems.

SOM Life-Cycle Management (LCM) Capabilities – Capabilities of SOM Systems that include both (1) the SOM services life-cycle management (including requirements analysis, design, analysis, provisioning, deployment, discovery, use. and decommissioning of services) and (2) the SOM ecosystems life-cycle management (including SOM services composition, design of SOM ecosystems operations, and, optimization of SOM ecosystem services execution).

Composable Service-Oriented Manufacturing (SOM) – High-value SOM approaches with the core capability to search for and discover relevant manufacturing services, effectively integrate them in interoperable ways, and allow configuration and re-configuration of these services to meet changing requirements.

Service-Oriented Integration (SOI) Technologies – Systems-integration technologies using only service interactions in a service-oriented architecture.

Next Generation Service-Oriented Integration (SOI) Technologies – SOI Technologies emerging to address the complexities of engineering and managing the SOM systems and their ecosystems. The SOI Technologies combine and build on the results from service-oriented architecture (SOA) developments, knowledge-based systems research, Cloud Computing development, and other advanced technology areas. A key concern is the potential of SOI technologies to affect all facets of life-cycle management (LCM) of both the SOM services and the SOM ecosystems.

New Lifecycle Management Service-Oriented Integration (LCM SOI) Technologies – Subset of the Next Generation SOI Technologies that enable RM LCM Capabilities (see below), which in turn are needed to enable Composable SOM systems, and efficient LCM of both the SOM services and the SOM ecosystems.

Reference Models Life-Cycle Management (RM LCM) Methods – The LCM SOI Technologies methods that rely on information, functional, process, and other models, as well as LCM methods for these models. The methods address the activities ranging from creation, to adaptation, to use of the reference models. Techniques used in the LCM methods need to support high-level abstractions, separation of concerns, and loose coupling. Hence, they use declarative approaches, including information- and knowledge-based models, rule-based systems, and taxonomy- or ontology-based systems. These models and methods play essential roles in achieving precise management of reference semantics for the domain and reliable interpretation of context-specific domain information required by Composable SOM Systems.

Appendix B – Workshop Report: Terms, Development Process, and Content Framework

In this section, we provide definitions of key terms, description of the process used to synthesize the report, and questions guiding the content of the report's technical sections. We start with a statement of intent for this report and a summary of the basic concepts used in this report (Section B.1). Then, we describe steps used to synthesize content of sessions' outputs (Section B.2). Finally, we present questions governing the content of each section reporting on the respective workshop technical session (Section B.3). Our intent is to provide the reader a framework with which to better understand the session findings detailed in Sections 2-6.

B.1 Intent and Basic Concepts

The intent for this report is to provide an interpretation of 2016 workshop results in support of a development and future management of a roadmap that will assist the growing R&D community in starting new efforts on Composable Service-Oriented Manufacturing (SOM) Systems.

The following are the key concepts used in the report:

- *Goals, Capabilities, and Technologies* represent the Why, the What, and the How dimensions of work proposed in each of the working sessions.
- *Priority Action Items* (*PAI*) and *Priority Action Topics* (*PAT*) represent individual and aggregated action items proposed in each of the working sessions.
- *Priority Roadmap Topics* (*PRT*) represent refinements or specializations of Priority Action Topics (PATs) into measurement science- and standards-focused activities.

B.2 Report Development Process

The following were steps used to synthesize content of sessions' outputs:

- *Develop Vision Statement for the new research area* (see Introduction). In this step, we describe overall motivation for the research area (i.e., Composable SOM systems), planned capabilities of target manufacturing systems to enable the vision, and properties of technology solutions proposed to deliver the capabilities.
    - The envisioned capabilities of target manufacturing systems should be refineable at the next, more specific level of systems description (corresponding to the areas in workshop sessions), enabling more precise capability specification.
    - Similarly, proposed technology properties should allow their refinement at the next more specific level of systems description (also at a workshop session level), enabling more precise technology specification.
- *Develop Sessions' Overviews, Goals, Capability Gaps, and Technology Characteristics*. For each workshop session we capture succinct descriptions (Overviews), business or market motivations (Goals), missing product or service capabilities (Capability Gaps), and proposed technologies (Technology Characteristics) that can deliver the needed capabilities.

- *Session Overview* should capture the intent behind the session and provide statements of technology focus and planned capability development. These statements should be in alignment with the overall vision statement of envisioned capabilities and proposed technology properties, as stated in Introduction.
- *Goals* should capture key aspects of target business and market performances and related aspects.
- C*apability Gaps* should capture functional, non-functional, resource, and other key aspects of the capabilities that must be added to reach the goals.
- *Technology Characteristics* should capture proposed approaches (implying technology decisions or constraints) for any of the methods, standards, tools, and resources presumed to be used for filling in the Capability Gaps.

* *Collect Priority Action Items*. For each workshop session, we collect Priority Action Items (PAIs) proposed during the sessions.
    - *Priority Action Items (PAIs)* reflect perceived shortfalls requiring advancement with respect to the session's state of knowledge on a specific topic.
* *Aggregate Priority Action Items into Priority Action Topics*. We aggregate each session's PAIs into Priority Action Topics (PATs) that are associated with an envisioned deliverable type (e.g., product, method, tool, standard).
    - *Priority Action Topics (PATs)* reflect perceived needed deliverables that aggregate needed advancements (as captured in PAIs) within the session.
* *Specialize the Priority Action Topics into Priority Roadmap Topics*. Refine the PATs into measurement-science-focused Priority Roadmap Topics (PRTs) and provide additional information, including milestones and metrics.
    - Goal is to define focused and coherent work items that follow the Priority Action Items, while taking into account available resources and restrictions on the resources, to achieve tangible outcomes and desired impacts on measurement science and standards enabling target capabilities and goals.
    - The candidate Priority Roadmap Topics (PRTs) should be judged on PRT maturity assessment criteria, including: (1) alignment with Priority Action Items; (2) relevancy of measurement science and standards to the PRT; (3) coherency and prioritization of the action items (with respect to lifecycle issues) that lead to meaningful milestones; (4) expression of the target capabilities in a meaningful and verifiable manner; (5) identification of potential approaches that are known and can be readily applied; (6) potential impact; and (7) sufficiency of resources to proceed with execution of the PRT.

B.3 Workshop Sessions' Content

Each workshop session's outcomes were reported by answering the following sets of questions:

B.3.1 Overview

The Overview sub-section provides answers to high-level questions about the working session:

- What problem or opportunity motivated the topic of the working session?
- How is the session aligned with the envisioned advancement in target technology area – the reference model life-cycle management (RM LCM) for service-oriented integration?
- Is the planned advancement in line with the expectation to communicate and act on information in context-specific ways without failures in interpretation and without costly mediation help, re-interpretation, or manual intervention.
- What is the plan for the technology advancement to achieve advancement of Smart Manufacturing capabilities?
- Does that planned SM capability support composable SOM systems by enabling interoperable integration, search for and discovery of relevant manufacturing services, or configuration and re-configuration of these services?

B.3.2 Goals

In the Goals sub-section, we were governed by the following questions:

- What are essential business/market performances?
- What essential processes are sought to be changed by way of the business/market performances?
- What concerns inform selection and ultimate validation and potential impact of reaching the business/market performances?
- What are essential results/outcomes of the business/market process enabled by this focus area?
- What are essential resources needed for achievement of goals?

B.3.3 Capability Gaps

In the Capability Gaps sub-section, we were governed by the following questions:

- What essential functions, capabilities, or activities are missing to achieve Goals?
- What properties, and factors of these functions, capabilities, or activities are essential (such as tools, standards, guidelines, shared knowledge, repositories, etc.)

B.3.4 Technology Characteristics

In the Technology Characteristics sub-section, we answered the following questions:

- What are technology decisions suggested to address the capabilities in the Capability Gap section?

B.3.5 Priority Action Topics

In the Priority Action Topics sub-section, we consider the following questions:

- What are Priority Action Items that make up the Priority Action Topics?

B.3.6 Conclusion and Next Steps

In the Conclusion and Next Steps sub-section, we are getting ready to identify Priority Roadmap Topics (PRTs) that would drive the future roadmapping activities towards tangible R&D outcomes by starting specific R&D projects. The questions we are answering include:

- What PRTs are envisioned to be subject of interest in this technical session and why?
- Are PRTs well-aligned with identified Priority Action Items during the workshop session?
- What is the maturity level of the PRTs?
- What are the next steps to increase maturity of and/or execute the PRTs?

Appendix C – Driving R&D Outcomes with Priority Roadmap Topics

As described in Appendix B, the purpose of Priority Roadmap Topics (PRTs) is to drive the future roadmapping activities towards tangible R&D outcomes with desired impacts on measurement science and standards that enable the target technology, capabilities, and goals. In other words, PRTs are intended to be a bridge between (1) high-level planning dealt with in roadmaps and (2) specific R&D projects concerned with creating deliverables that provide needed technology and address capability gaps.

In the following sections, we provide PRT resources to help in future roadmapping activities. Section C.1 contains a template to use for PRTs. Section C.2 provides an example PRT for the MBMSD workshop session – the BPCCS PRT. Section 3 provides an individual example and summary PRT maturity assessment tables, based on the PRT evaluation criteria in Section B.2.

C.1 Priority Roadmap Topic Template

Table C.1 shows a proposed template for PRTs.

C.1. Priority Roadmap Topic: <PRT Label>			
Technology Specification			
<Technology Descriptions driving the PRT>			
Years	**Roadmap Item**	**Milestone**	**Target Capability**
1-3	• <Roadmap Item 1> • …	• <Item 1: Milestone 1> • …	• <Item 1 Milestone 1: Target Capability 1> • …
3-5	• <Roadmap Item 1> • …	• <Item 1: Milestone 1> • …	• <Item 1 Milestone 1: Target Capability 1> • …
5+	• <Roadmap Item 1> • …	• <Item 1: Milestone 1> • …	• <Item 1 Milestone 1: Target Capability 1> • …

Table C.1 – PRT Template

C.2 Priority Roadmap Topic Example

Table C.2 shows an example PRT for the MBMSD Working Session: the Business Process Catalog and Classification System (BPCCS).

Table C.2. PRT for BPCCS

Priority Roadmap Topic: Business Process Cataloging and Classification System (BPCCS)			
Technology Specification			
Business process SLCM system that: (1) uses business-process-first design; (2) supports middle-out, top-down, & bottom-up processes; (3) supports processes that fit small and large enterprise needs and constraints; (4) Enables component-level standards management; (5) Supports consistent and common integration requirements and feedback; (6) Enables Context-classification scheme; (7) Enables Business context; (8) Uses accessible (e.g., SaaS-based) repository of messaging standards and implementation guides			
Years	Roadmap Item	Milestone	Target Capability
1-2	• Capture use cases for SLCM • Formalize SLCM process for both as-is (manual) and to-be (tool-supported) states • Model SDO SM scenarios as BP models • Develop BPCCS meta-model and prototype BPCCS • Validate BPCCS in cooperation with SDO	• SM use cases analysis completed • BP standard development & usage process proposed • OAGIS mfg. scenarios standardized as business process models • Catalog of SM business process prototyped • OAGIS-validated BPCCS	• 2+ Mfg. use cases analyzed for requirements • The process validation against the Mfg. use cases • 80%+ OAGIS Mfg. Scenarios • 80%+ priority requirements met • Validated on 2+ Mfg. use cases and using OAGIS Mfg. BPMs
3-5	• Capture requirements for tools in support of SLCM process • Design front-end, user-interface tool for SLCM • Train an SDO membership for BPCSS use and adoption • Organize for BPCCS collaborative development and use • Re-design and prototype BPCCS as a cloud-enabled solution • Develop collaborative processes for top-down and bottom-up business process modeling	• Catalog of SM Business Processes Populated • BPCCS adopted at SDO for collaborative development	• 80% of OAGIS BP models populated in the BPCCS • At least 1 SM standard business process developed at SDO
5+	• Design and deploy BPCCS for use at SDO	• BPCCS implementation deployed at SDO	• 1+ SDO deployment

C.3 Priority Roadmap Topic Maturity Assessment

Table C.3 shows an individual example of a PRT maturity assessment table – for the candidate BPCCS PRT identified in Section 2.6 – based on the PRT criteria in Section B.2.

Table C.3 Example Maturity Assessment of the BPCCS Priority Roadmap Topic (PRT)
Is PRT well-aligned with priority action items? • The PRT is well-aligned with priority action items. It includes all PAIs identified in the session and includes additional complementary action items.
Does the PRT involve or contribute to measurement science and/or standards? • The BPCCS contributes to the measurement science and/or standards by way of formalizing and making operational business process models and their classifications, which represents a key aspect of context in which messaging among collaborating systems take place. Such context needs to be shared and to allow comparisons, making it obviously supporting measurement science and/or standards.
Are activities coherent and properly prioritized (with respect to lifecycle issues) to lead to meaningful/verifiable milestones? • At the present level of abstraction, the activities seem to be properly captured to lead to captured milestones
Are the target capabilities expressed in a meaningful and verifiable manner? • Target capabilities have been verified with industry stakeholders and seem to be meaningful.
Are potential approaches known and can they be readily applied?

• Potential approaches are partially known but require additional development, which has been completed. Presently at least one such extended approach is being applied.
Is potential impact significant and verifiable? • NIST has been supporting an industry effort to develop a BPCCS within the OAGi Smart Manufacturing Working Group (SMWG). In this WG, the potential impact of this work has been verified with industry stakeholders.
Are sufficient resources identified to proceed? • Within the OAGi SM WG, there is a mix of government and industry participants allowing for the work to be done on the PRT.

Table C.4 shows a template for PRT evaluation that may be used in the future as a summary of all planned PRTs. One or more Priority Roadmap Topics (PRTs) would be identified in a corresponding working session. The PRTs would be assessed with respect to a number of maturity criteria. The table summarizes the assessment results, showing the results for the BPCCS PRT in the top row. A plus sign is used to indicate positive maturity assessment of the PRT with respect to the corresponding criterion, while a negative sign is used to indicate a negative assessment for the criterion. For a new working area, it would be normal to expect negative signs populating most, if not all, of the fields for the PRT, indicating where the R&D activities are only starting to be initiated and coordinated.

Table C.4. Summary Priority Roadmap Topics (PRTs) Maturity Assessment							
C1: Is the PRT well-aligned with priority action items? C2: Does the PRT involve or contribute to measurement science and/or standards? C3: Are activities coherent and properly prioritized (with respect to lifecycle issues) to lead to meaningful/verifiable milestones? C4: Are the target capabilities expressed in a meaningful and verifiable manner? C5: Are potential approaches known and can they be readily applied? C6: Is potential impact significant and verifiable? C7: Are sufficient resources identified to proceed?							
	C1	C2	C3	C4	C5	C6	C7
Model-Based Messaging Standards Development (MBMSD)							
Business Process Cataloging and Classification System (BPCCS)	+	+	+	+	+	+	+
Smart Manufacturing Systems Characterization (SMSC)							
<PRT Title>	<+/->	<+/->	<+/->	<+/->	<+/->	<+/->	<+/->
Smart Manufacturing Standards Capability Analysis (SMSCA)							
<PRT Title>	<+/->	<+/->	<+/->	<+/->	<+/->	<+/->	<+/->
Smart Manufacturing Apps and Service Marketplaces (SMASM)							
<PRT Title>	<+/->	<+/->	<+/->	<+/->	<+/->	<+/->	<+/->
Crowdsourcing Manufacturing Knowledge (CMK)							
<PRT Title>	<+/->	<+/->	<+/->	<+/->	<+/->	<+/->	<+/->