NIST Advanced Manufacturing Series 100-15

2017 NIST/OAGi Workshop: Enabling Composable Service-Oriented Manufacturing Systems

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

This report summarizes the results from the 2017 NIST/OAGi Workshop: Enabling Composable Service-Oriented Manufacturing Systems, which was held at the National Institute of Standards and Technology campus in Gaithersburg, MD, on April 10-11, 2017. This was the third in a new series of workshops begun in 2015 to foster a shared vision of a new Smart Manufacturing (SM) platform to support Composable Service-Oriented Manufacturing (SOM) systems. The purpose of the workshop series is to identify and discuss challenges in advancing the vision of open cloud service platforms for Smart Manufacturing systems. As in the previous workshop reports, the document describes (1) the vision of Composable Service-Oriented Manufacturing systems as a basis for achieving easily assembled and re-configurable Smart Manufacturing systems, (2) the five breakout sessions, each addressing the vision from a unique perspective, 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 research and development areas, their goals, capability gaps, proposed technology characteristics, and priority working items.

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Keywords

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

Acronyms

API – Application Programming Interface

ASME – American Society of Mechanical Engineers

ASTM – ASTM International

B2B – Business-to-Business

B2C – Business-to-Customer

BFO – Basic Formal Ontology

BPCCS – Business Process Cataloging and Classification System

BPMN – Business Process Model and Notation

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

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

MSSRT – Message Standards Semantic Refinement Tool

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

URL – Uniform Resource Locator

W3C – World Wide Web Consortium

Executive Summary

The National Institute of Standards and Technology (NIST) hosted *2017 NIST/OAGi Workshop: Enabling Composable Service-Oriented Manufacturing Systems* at its Gaithersburg, MD, campus on April 10-11, 2017. Over 100 participants from industry, government, national laboratories, and academia participated. This was the third 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, including what is now called microservices. As in previous workshops, the purpose was to identify and discuss challenges in advancing the vision of Composable Service-Oriented 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 industry, government agencies, and other stakeholders focused on manufacturing systems integration.

The main premise of the workshop is that future Smart Manufacturing systems will be enabled by revolutionary convergence of several technological advances applied to manufacturing operations, such as enhanced networking, adaptive automation, cloud services, and data analytics. Significantly, the systems of the future will be available through on-demand composition of focused apps or services. 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 to adoption and reduce cost significantly.

However, as the apps, services, and systems available through this new SM development model diversify and 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 continued to explore the needed technical foundation for the ecosystem of standards and technologies as well as the SM platform. As in the previous year, the workshop had five working sessions to identify and address issues from different perspectives. Three of the sessions maintained the same topics as the previous year, while two sessions adapted their topics of exploration. Nevertheless, the first three sessions continue to focus on the analysis, methods, and tools for the new platform. The sessions include SM Model-Based Message Standards Development, SM Systems Characterization, and SM Reference Models & Architecture (previously SM Standards Capability Analysis). The other two sessions considered realizing the innovative platform. The sessions included SM Apps and Service Marketplaces and Industrial Ontology Foundry (previously Crowdsourcing of Manufacturing Knowledge). The sessions focused on the following key research ideas:

- **Smart Manufacturing (SM) Model-Based Message Standards Development (MBMSD)** focused on innovative modeling methods and tools for efficient development and maintenance of message standards, which are key to scalable service-oriented integration.

- **Smart Manufacturing Systems Characterization (SMSC)** focused on technical means and measurement methods that can be used to assess an organization’s manufacturing systems for readiness, capabilities, and maturity level in their plans to implement smart manufacturing.

- **Smart Manufacturing Models and Architecture (SMMA)** focused on developing reference models and architecture to support integration of diverse machines and software vendors’ applications. More specifically, the session explored how service-oriented-architecture can help integrate Internet of Things (IoT), digital factory, and cloud computing technologies into modern manufacturing environments and

enable the manufacturing systems to respond in real time to meet changing demands and conditions in the factory, in the supply network, in customer needs, while learning from past experience to enable continuous improvement.

- **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.

- **Industrial Ontology Foundry (IOF)** focused on exploring the value and feasibility of standardization of concepts and relations describing the intended meanings within the industrial domain in a manner that enables computer reasoning and improves reasoning across data sources.

The main findings from the workshop include the following:

- **Composable SOM Requires Extensive New Technical Capabilities**. Each session identified a significant collection of goals, missing capabilities, needed technology & standards, and priority action items, which the participants believe to be essential to their respective R&D areas. The shared focus across the sessions provides new and relevant reference models life-cycle management (RM LCM) capabilities and knowledge-based modeling approaches to achieve the capabilities. The hallmark of the relevant RM LCM capabilities is their ability to communicate and act on information in context-specific ways without failures in interpretation and without costly mediation help, re-interpretation, or manual intervention.
- **R&D Road-mapping is an Important Resource in Developing Composable SOM**. The state of scientific and technological maturity of the workshop topics is in very initial stages 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 the work in measurement science, standards, and technology to enable the needed capabilities and goals. The measurements science, standards, and technology to be developed include manufacturing message standards, collaborative development tools, context specification methods, smart manufacturing capability reference models, systems readiness measurement methods, context specification methods, reference architectures, vocabularies, workflow technologies, common ontologies, and validation mechanisms.
- **A Prioritization of Roadmap Topics Will Enable Focused Work in the Community**. A Priority Roadmap Topic (PRT) provides a focus for planned work deemed to be key for advancement of the state of the art for the session. PRTs contain measurement science-relevant aspects in addition to other standards and technology concerns. Next steps should also keep in mind potential impact of the identified prioritized action items and identify resources and organizations where the work can be housed. PRTs include standards life-cycle management tools, classification models, reference architectures, requirements engineering methods, repositories, and ontology development methods.
- **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 and with other organizations. 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. Most breakout sessions identified potential target industry, government, and SDO organizations for their respective PRTs. The potential impacts include new generation of standards, novel smart manufacturing systems characterization methods, enabling inter-SDO alignments, creation of novel smart manufacturing marketplaces, and enabling cross-industry technology advancements.

The major changes from the previous year workshop include increased focus of the two newly titled sessions that reflect a more precise area of interest for the community. The overall directions for the workshop and the sessions remain on course from the previous year.

1 Introduction

This report documents the third workshop in a new workshop series on the topic of Composable Service-Oriented Manufacturing (SOM) systems. We start by summarizing the previous introduction and motivation for Composable SOM systems[1], followed by a description of the workshop and the report itself.

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

The industry pursuit of Smart Manufacturing (SM) by improving the nascent state of Service-Oriented Manufacturing (SOM) continues. Existing approaches produce SOM systems that are costly to manage; changes to these systems to meet dynamic and complex workflow-process requirements demand laborious manual processes to adapt or re-configure their component services. The vision for SOM is that future cyber-physical systems will be available in small apps or services and assembled or re-configured economically to execute complex workflow processes. These small apps have alternately been called "microservices" and perform very specific business, technical, or operational services, and are linked together by other applications or workflows.

Advances in integration approaches are needed for the vision of SOM-based SM to materialize. That, however, requires new capabilities, including (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 services composition, design of service ecosystem operations, and optimization of service ecosystem execution.

Manufacturers are concerned about the time and cost of adopting these new capabilities. That includes efficiencies of (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 efficiently addressing these concerns as Composable SOM Systems.

Achieving such Composable SOM Systems requires new technologies. A key missing part in existing technologies is the lack of methods that provide for (1) precise management of reference domain semantics and (2) reliable interpretation of context-specific domain information. We have named these methods Reference Models Life-Cycle Management (RM LCM) methods. Without them, there will be no basis for Composable SOM systems.

Significant scientific and engineering work is needed for achieving RM LCM. Measurement science, including a testbed to support hypothesis testing and experimentation, is needed to establish a basis for standards representations of manufacturing information and knowledge bases. Formalization of these representations will build on results from logic- and rule-based knowledge systems; taxonomy/ontology development; knowledge, taxonomy, and ontology management systems; category theory; and other areas.

Standards will be critical to move research results from the testbed into industrial use. They will enable the needed interoperability and provide guidelines for development and implementation of new technologies. Standards cover terminology, definitions, methodologies, metrics, specifications, testing, and other issues.

[1] Nenad Ivezic, Boonserm Kulvatunyou, Dennis Brandl, Hyunbo Cho, Yan Lu, David Noller, Jim Davis, Thorsten Wuest, Farhad Ameri, William Bernstein. NIST/OAGi Workshop: Drilling down on Smart Manufacturing -- Enabling Composable Apps. Available at http://nvlpubs.nist.gov/nistpubs/ams/NIST.AMS.100-8.pdf

In summary, the underlying hypothesis for this workshop and the new workshop series is that measurement science, information standards, and technology advancements are needed to deliver RM LCM methods that are necessary to enable *Composable SOM Systems*, and the vision of *SOM-based Smart Manufacturing*.

1.2 Workshop Motivation and Objectives

The National Institute of Standards and Technology (NIST) hosted the *2017 NIST/OAGi Workshop: Enabling Composable Service-Oriented Manufacturing Systems* at its Gaithersburg, MD, campus on April 10-11, 2017. The event brought over 100 participants from industry, government, national laboratories, and academia to identify measurement science, standards, technology challenges, and research and development (R&D) needs for the vision of Composable SOM systems. The objectives were to:

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

1.3 Workshop Technical Sessions

1.3.1 How were session topics selected?

Figure 1.1 illustrates the previously identified standards and technology R&D issues[2] that prevent our vision. The 2016 workshop started to address these issues through five separate breakout sessions. The table shows (in bold font) the names of the 2017 workshop sessions addressing the top five R&D issues. Some of the sessions from 2016 have been adapted, indicated by their previous year titles shown in parentheses. The sessions, their objectives, and key outcomes are the subject of this report.

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

Figure 1.1 – Workshop sessions and issues addressed

[2] 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.

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 both structured and unstructured descriptions and specifications of manufacturing systems, processes, and products in computer-processable forms. The computer-processable representations capture information, know-how, guidance, and standards that enable Composable SOM systems.

- **Smart Manufacturing (SM) Model-Based Message Standards Development (MBMSD) Methods** provides knowledge-model-based methods for conveying intended usage – both customization and context – for messages used by SOM Systems. This novel approach to specification is used to support new message standards life-cycle-management (MSLCM) capabilities.

- **Smart Manufacturing Systems Characterization (SMSC) Methods** develops knowledge-model-based characterizations of the manufacturers' maturity and the technologies' capabilities to implement composable applications and SM systems. These novel methods will be utilized to support reasoning about the composability of these technologies within Smart Manufacturing Systems based on their interface designs.

- **Smart Manufacturing Reference Models and Architecture** (**SMRMA**) brought standards developers, technology providers, and manufacturers together to discusses reference models and architecture of ICT-enabled smart manufacturing systems. In addition to briefing the existing development efforts on smart manufacturing reference models and reference architectures, the participants of the session explored the feasibility of service-oriented architecture and how knowledge models could be used to specify services registration, discovery, orchestration, and data interchange for service-oriented manufacturing systems.

- **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 of Composable SOM Systems.

- **Industrial Ontology Foundry (IOF)** investigates new knowledge-model-based approaches to develop a collaborative framework and platform for submitting, validating and sharing ontologies for the industrial and manufacturing domains. In this way, the knowledge will be captured and refined to facilitate smart manufacturing practices and resources.

1.3.3 Sessions charge

The workshop participants were given charge to discuss and report on the topics in their respective breakout sessions to support structured presentation of roadmap material:

- Develop succinct descriptions of the session, business or market goals, 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 indicate a need to advance the state of knowledge on a specific topic.

- Discuss 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 aspects to them.

Where it makes sense, the session leads were asked to address change that has occurred since the previous workshop and to report on the updates of the state of knowledge by answering the following:

- What has stayed the same?
- What has changed (added or removed) since the last workshop and why – what was learned since last year's roadmap?

1.4 Workshop Report Organization

The ideas presented in this report reflect the different perspectives given by the workshop attendees. They can thus, at best, be viewed as a representative sampling of the entire industry. We envision follow-on workshops in this series 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 identified goals, capability gaps, technology characteristics, priority working items, and next steps that discuss priority roadmap topics. Section 7 offers a conclusion and next steps for the workshop series. Appendix A provides definitions of key terms describing Composable SOM Systems.

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

2.1 Overview

This breakout session focused on developing advanced reference model life-cycle management (RM LCM) methods for a new generation of message standards. The research discussions centered on Model-Based Message Standards Development (MBMSD) methods. These MBMSD methods will provide knowledge-model-based methods for conveying intended message usage – both its context and customization – for system service operation. 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 new MBMSD method properties are then utilized for advancing message standards life-cycle management (MSLCM) capabilities. In this way, the MBMSD methods focus on improving MSLCM efficiencies and precision by exploiting the usage information for the message 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.

Overall, the planned knowledge-based work and overall capabilities have not changed from the previous year.

2.2 Goals

Table 2.1 identifies goals for this session. The work of the MBMSD session supports these goals with the end objective in mind – to improve systems integration and the performance of MSLCM processes. All the goals from the last workshop have been maintained, with one change – a new goal is introduced this year: To provide usable contextual information for efficient systems integration (i.e., data exchange).

This stability of the goals is due to the relative maturity of this research area and the fact that the goals are acknowledged and supported within directly corresponding R&D activities by NIST and OAGi.
At the same time, the newly added goal is a result of the recent reinforcement obtained through the R&D activities that context information is essential for achieving MBMSD methods. Consequently, the notion of “context” was elevated from a Technology Characteristic to a Goal.

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. • **To provide usable contextual information for efficient systems integration (i.e., data exchange).**
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

2.3 Capability Gaps

Table 2.2 summarizes the Capability Gaps preventing attaining the above Goals. All Capability Gaps have been maintained from the previous year. The two added Capability Gaps (in bold font) include: (1) Methods to provide business process model-based context (metadata); and (2) Methods to allow the context (metadata) to address varied business scenarios.

The stable state of the Capability Gaps was expected since all the corresponding Goals (that drive the required capabilities) have been maintained as well. The two added gaps correspond to the newly added goal: *To provide usable contextual information for efficient systems integration (i.e., data exchange).* These Capability Gaps reflect the belief that the business processes contain significant information content that may be captured for the purposes of context identification and its use towards enhanced systems integration performance. In addition, it is essential to accommodate the extensive range of business scenarios that would be encountered upon wide adoption of message standards across differing enterprise functions and industries.

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. • **Methods to provide business process model-based context (metadata).** • **Methods to allow the context (metadata) to address varied business scenarios**.

2.4 Technology Characteristics

Table 2.3 provides complete set of Technology Characteristics put forward by the MBMSD session participants as guidance on how to address the Capability Gaps. All Technology Characteristics have been maintained from the previous year. One added Technology (in bold font) is included: MSLCM should allow connection between design-time specification and run-time data via mechanisms such as 'eventing.'

The stability of the Technology Characteristics is reinforced by positive feedback obtained through the on-going R&D activity addressing the MBMSD area and the fact that the corresponding Capabilities have been maintained from the previous year. Equally, there is little change in the technology space in the past period to warrant any change in the direction of Technology Characteristics investigations. The single addition reflects insight from the industry that a promising way to achieve the Capability "to allow the context (metadata) to address varied business scenarios" is through "eventing" in which signals travel to/from processes, to/from middleware, and to/from the business integration layer via specific business process-related events.

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. • **MSLCM should allow connection between design-time specification and run-time data via mechanisms such as 'eventing.'**
Tool decisions: • MSLCM should be supported by an accessible (e.g., SaaS-based) repository of message 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

Table 2.4 summarizes all the Priority Actions items introduced for the MBMSD session. Again, the new ones are indicated by bold font. All changes are additions. The following are descriptions of the provided additions along with technical suggestions how to go about these priority actions:

- Explore classification scheme exchange standards. There are no known standards presently. OWL language is a candidate in general; however, it needs to be seen if an OWL profile is meaningful.
- Explore including association with business process to capture 'How' the message standard (e.g., BOD component) is used. Investigate rendering of OAGIS BOD components as OWL expressions. Also, explore value of exposing 5WH (Why, What, Where, Who, When, and How) classification values in OAGIS components.
- Explore benefits of a shared upper ontology to annotate the message standard components. Consider this as an Industrial Ontology Foundry (IOF) use case. (See the corresponding session.)
- Define Integration-Focused Business Process Metamodel. The metamodel should be driven by integration/message profiling requirements. The metamodel needs to be mapped onto BPMN metamodel.
- Advance Use of Business Process Models. (1) Use BPMN model to identify all meta-data (e.g., activities, roles) relevant to the actual document exchange to identify the target noun of the message standard. (2) Use BPMN models to introspect information relevant to the contextual information. (3) Design rules for the BPMN model so they can be introspected correctly so that tags are correctly used (e.g., address synonym usage). (4) Implement search for BPMN models using 5WH questions. (5) Implement search for BOD profiles using 5WH questions. (6) Identify gaps in BPMN metamodel compared to our BP metamodel by introspection. Identify if a special BPMN profile or extension is needed to accommodate requirements.
- Manage and use meta-data. Extend OAGIS role specifications. Explore use of ISA 95 (www.isa.org/isa95) for role definitions in manufacturing enterprise; consider same for farm operations in agriculture.
- Provide smart design user interface to offer context-aligned selection options.
- Define conceptual solution for tool integration. For the two tools in development (i.e., MSSRT & BPCCS, discussed in the next section) explore the following: (1) Submit new BPMN model for introspection and tagging (minimum requirements – inclusion of 5WH keywords). (2) Find existing BPMN model for BOD profiling; select data object and use included activities to select terms, synonyms; find existing profile or create new. (3) Find existing BPMN for reuse,

production coding in middleware. (4) Find and adapt existing BPMN; submit as rendition; introspection and tagging.

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.
Tools Detailed Design • **Explore classification scheme exchange standards.** • **Explore including association with business process to capture 'How' the MS (e.g., BOD component) is used.** • **Explore benefits of a shared upper ontology to annotate the message standard components.** • **Define Integration-Focused Business Process Metamodel.** • **Advance use of Business Process Models.** • **Manage and use meta-data.** • **Provide smart design UI to offer context-aligned selection options.** • **Define conceptual solution for tool integration**

Retention of the previous activity items provides positive feedback that the proposed direction in R&D activities – development of tools and methods driven by Technology Descriptions – was appropriate. The extensive additions to the Priority Activity Items is the consequence of the lively R&D activities (within NIST and OAGi) addressing the MBMSD area. The fact that all additional Priority Activity Items fall within the Priority Activity Topic 'Tools Detailed Design' was to be expected in the light of the progress within the MBMSD R&D activities, where tool development has reached these stages.

2.6 Conclusion and Next Steps

NIST, in collaboration with the OAGi consortium, has been developing both the Message Standard Semantic Refinement Tool (MSSRT) and Business Process Cataloging and Classification System (BPCSS). Development of these tools is aligned with the goals of the MBMSD session.

The major conclusion of this breakout session was that work on capturing and providing contextual information for efficient systems integration is required. That was the only new goal provided by the participants. To achieve the goal, the participants have confirmed the conclusion from last year that business processes are main source of contextual information, which drives requirements for, and discovery of, reuse of integration and message standards artifacts.

The other major conclusion of the session is that effort towards integration between the two tools – MSSRT and BPCCS – is required. All the proposed Priority Action Items to greater or lesser extent support or are related to this idea. Some detailed thoughts on how to go about achieving this have been discussed and submitted by the participants, as detailed in the Priority Action Topics section.

At this point, both the MSSRT and BPCSS development activities may be seen as executions of their corresponding PRT (essentially the specified Priority Action Items identified in this session). The maturity levels of the MSSRT and BPCCS PRTs are high as they each have developed and validated respective prototypes with respect to the industry requirements.

The next steps involve continued execution of the MSSRT and BPCCS PRTs within NIST and OAGi activities where continued development of the prototype, industry validations, and the tool integration 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 and 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.

The new SMSC methods are a form of Reference Model for Life Cycle Management (RM LCM) methods, as they provide both an indicator model and a measurement process used to characterize a manufacturing system. They define its readiness to deploy SM technologies or be part of a SM network. This provides new capabilities for SMSC which help 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 new SMSC capabilities are then utilized to enable reasoning about composability of these systems and components within a manufacturing system and with respect to their interface designs. This enables Composable SOM Systems for message-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 (and summarized in Table 3.1).

The essential goal of the SMSC methods and area of work is to enable a meaningful and usable Smart Manufacturing Systems Characterization approach and related methodologies. However, to accomplish that goal, a clear definition and common understanding of what constitutes Smart Manufacturing Systems must 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, at least, as a proof of business value. Another relevant goal is to identify the steps required to be ready for SM. When a company develops a SMS and subsequently gains experience in using it, an opportunity to measure how the SMS is used emerges. This characterization (or SMSC) can ideally lead to a descriptive and prescriptive approach to identify improvement strategies and enable prioritization for investment in 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 — as well as production strategies (Assembly to Order, Make to Order, Engineering to Order, etc.). 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 meaningful and usable approach & methodologies to Smart Manufacturing Systems Characterization (SMSC), with the aim to characterize a company's readiness and/or maturity levels for utilizing Smart Manufacturing Systems.
Business/market processes change goals • To better convince manufacturers that Smart Manufacturing Systems lead to competitive advantages, as supported by comparative analysis. • To increase efficiency and effectiveness of architecting/designing of Smart Manufacturing systems. • To identify an assessment method to check the prerequisites for implementing Smart Manufacturing Systems. • To identify steps required to be ready for implementing Smart Manufacturing by determining the readiness level, or capability maturity level of the business. • To facilitate the availability of information on the business opportunities, so that a company can make better improvement decisions.
Resources needed for the market/business performance objectives • A clear definition and common understanding of the elements that make up a Smart Manufacturing System (SMS). • A quantifiable definition for Return-On-Investment (ROI) for investment in SM. • A descriptive and prescriptive approach to identify improvement strategies and enable prioritization for investment (i.e., ROI is the final measure but more resources are needed before making a ROI or, in general, a Cost Benefit Analysis)
Business/market performances non-technical goals • To raise awareness of digitization at all levels of the organization, as the real change in a company is going to be driven by business (not technology). • 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 / solution types for Smart Manufacturing developments. • To increase efficiency of Standards Life-Cycle Management (SLCM) processes. • To enhance the focus on processes required by different Life Cycle viewpoints (i.e. different life cycles in scope, such as asset, product, supply chain, etc.…), in order to highlight priorities and facilitate an adequate balance of digitization among them. • To develop descriptive models and methods for SMSC solutions that will be meaningful to enterprises of all sizes. • To define readiness-level and maturity level metrics usable in SMSC methodologies.

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.

Furthermore, there is a need of a systematic approach to SMS understanding and development in a company. The main gaps hindering such a systematic approach are: (1) the availability of a toolbox to support the different steps of SMSC (from readiness / maturity assessment to improvement strategies, including, at the end, a quantifiable ROI or a proof of business value); (2) a unified framework of SMSC methods (as different, complementary methods could be available, covering different aspects of a SMS); (3) the systematic involvement of all the relevant roles and competencies of stakeholders for process change.

Overall, there was a common feeling that (1) everything is moving fast and it is hard for the standards development organizations (SDOs) 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: • Alignment of standards from different industries for their effective use in the characterization methods (e.g., MT Connect, OPC UA, data historian standards).
Tools: • A usable toolbox, easily accessible and widely covering different steps of the SMSC, i.e., from readiness / maturity assessment to improvement strategies. The toolbox should include tools such as cost-efficient, available data analytics methods; educational and training systems to develop the needed skill sets for Smart Manufacturing solutions (e.g., controls, automation, IT); methods for strategic analysis of technology opportunities; etc. • Technical means to capture the state of a manufacturing organization in regard to Smart Manufacturing solution types and/or reference models. • Systems to collect data relevant to Smart Manufacturing solutions and provide the data to customers. SMSC methods: • Unified framework to fully support SMSC in a systematic way (note: SMSC methods may be "individually owned" by specific organizations, while there is no unified framework to fully support SMSC in a systematic way). • Methods to involve all the relevant roles and competences of stakeholders for process change (IT & automation process engineering) in a systematic way.

3.4 Technology Characteristics

Some technical method to capture the current state of a manufacturing organization in regard to SM and/or reference models is needed. The concern is that small and medium enterprises (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.

Overall, SMSC methods should be capable of characterizing digital readiness / maturity in a wide scope of work, utilizing various Life Cycle viewpoints and dimensions of analysis. As more methods could provide complementary viewpoints and dimensions of analysis, more methods may be usable for supporting decisions.

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:
• SMSC methods should be capable of characterizing digital readiness / maturity in a wide scope of work, according to the Life Cycle viewpoints, therefore more methods may be usable for supporting decisions:
    o 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.).
    o Supply Chain Integration Readiness Level (SCI-RL).
    o Product Lifecycle Management Integration Readiness Level (PLMI-RL), possible equivalent of General Recipe models in ISA 88.

o Manufacturing Operations Management Capability Maturity Model Level. o DREAMY (Digital REadiness Assessment MaturitY model). o SMSRL (Smart manufacturing readiness level). • SMSC methods should be capable of characterizing different dimensions of analysis. • SMSC methods could be applied in different ways according to the purpose, e.g., self-assessment done by the manufacturers, meeting between SM experts and manufacturers, a third-party assessment for certification program as a next step of this activity, etc.

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 definition of SM. • Develop a unified framework to fully support SMSC in a systematic way (including unifying scales to identify similarities in measurement of readiness / maturity levels). • Develop a ROI model that can be applied to SM (ROI is a final measure of the improvement strategy, it should be integrated in the unified framework, with other methods). • Develop SM Readiness / Maturity Level metrics. • Develop common terminology for SMSC (e.g., start standardization of Resource Definitions, …).
Deploy, maintain standard definitions • Develop validation tools (or certification) to ensure standards are correctly applied or readiness / maturity level correctly assessed. • Guidelines for using the readiness / maturity metrics. • Process to evolve and improve the readiness / maturity 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 definition of SM (For example, the Industrie 4.0 definition is '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), Smart (Cyber-Physical) Manufacturing Asset definitions, and standard ways to describe the equipment capabilities (Bill of Capabilities).
- Develop a unified framework to fully support SMSC in a systematic way, comprehensive of the SMSC methods required by the characterization of digital readiness / maturity in a wide scope of work, according to the different Life Cycle viewpoints and dimensions of analysis.

4 Breakout 3 – Smart Manufacturing Reference Models and Architecture (SMRMA)

4.1 Overview

Smart Manufacturing Reference Models consist of a minimal set of unifying concepts, axioms, and relationships within a smart manufacturing environment, and provide common language for understanding important features of SM. A **Smart Manufacturing Reference Architecture** is a reference system architecture which defines the structures**,** a list of functions, their interfaces (or APIs), and interactions with each other and with external functions for smart manufacturing systems. SMRMS does not address the issues involved in constructing, using, or owning a SMS.

There could be many uses of a smart manufacturing reference model and reference architecture (SMRMA). By breaking up the smart manufacturing space into basic concepts and identifying basic functions and interfaces in that space, SMRMA provides not only templates for concrete architecture design, but also provides consistent context to analyze standards and establish standards requirements for smart manufacturing.

Specifically, SMRMA methods are expected to provide an organizing framework that facilitates new capabilities to coordinate development of standards, platform/component, and implementation. 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 new capabilities are then utilized to allow development of the service-oriented Smart Manufacturing Reference Architecture style and corresponding information standards and system interfaces. Both the reference model and architecture enable 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.

SMRMA can be defined at different levels of abstraction. To enable effective communications among stakeholders and to allow for prescriptive standards capability analysis, SMRMA should not be defined too abstractly. However, SMRMA should also avoid the situation of "failing to see the forest for the trees", since excessive worries about details can make agreements on concepts impossible and, hence, no clear roles and responsibilities can be defined among stakeholders.

This session is divided into three sub-sessions. During the first sub-session, participants from standard development organizations and industry presented their ongoing SMRMA development efforts. The second sub-session focused on the enabling technology for service-oriented architecture for smart manufacturing. The last session was open for discussions about how to unify different smart manufacturing reference models and how to address the challenges of service-oriented manufacturing.

4.2 Goals

Standards development organizations (SDOs) are searching for the right directions and the best strategies for developing standards in order to accommodate increasing needs of applying smart manufacturing technology and new business models into manufacturing industry. Existing manufacturing standards include those from traditional SDOs such as IEC, ISO, ASTM, and ASME, as well as those created by special-interest groups such as some newly formed consortia that are taking opportunities to create specialized standards in a more open way, faster, and with wider adoption potential. To avoid redundant development efforts and the resulting overlapping/conflicting standards, maintaining communication among these SDOs and developing a joint smart manufacturing standards roadmap is critical to the evolution of today's standards. Development of smart manufacturing reference models and reference architecture would serve to improve communication among smart manufacturing stakeholders and to allow the greater manufacturing standards community to better define roadmaps to achieve its business goals.

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

Table 4.1. Goals for Smart Manufacturing Reference Model and Reference Architecture Methods
Business/market performance objectives • To provide SM stakeholders a vision for smart manufacturing, which shifts from mass production to mass customization, and the corresponding requirements for a smart manufacturing reference model and reference architecture • 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 a collaborative and systematic standards development process, from requirements collection to development and maintenance. • To engage manufacturing stakeholders in building a 'Big Picture' of smart manufacturing and investigating the feasibility and challenges of applying service-oriented architecture to smart manufacturing before implementation.
Results of business/market processes • Agile product development to support increased consumer demand for greater product variation, shorter production durations, and the need for improved quality and lower costs. • Reuse of existing manufacturing capabilities to improve overall resource efficiency • Better use of the large amounts of data that exist in historical and other systems (ERP, PLM, CRM, etc.), as the data are currently hard to use for decision making. • Lean/coordinated standards development processes, improved standards coverage, and less conflict and overlap.

4.3 Capability Gaps

In last year's workshop, we identified the first smart manufacturing standards capability gap as the lack of smart manufacturing reference models (SMRM) and reference architecture (SMRA specifically for SOM). Other SM gaps identified last year are the need for an extensive survey of existing manufacturing standards and, following that, continuous maintenance of the list. Since then, substantial progress has been achieved in filling these standards capability gaps by both SDOs and the industry, including both national efforts and international efforts. The table below summarizes a list of reference models/architecture discussed in this breakout session.

SM Reference Models /Architecture	**Developers**	**Description**
NIST EcoSystem	NIST, USA	The Smart Manufacturing Ecosystem deconstructs manufacturing systems along three dimensions: product, production, and business. Each dimension is concerned with a multi-stage lifecycle with the information flows and controls beginning at the early stage and continuing through to the end-of-life of the cycle. Each of these dimensions comes into play in the vertical integration of machines, plants, and enterprise systems in what we call the Manufacturing Pyramid. The combination of these perspectives and the systems that support them make up the ecosystem for manufacturing software systems. By deconstructing a large manufacturing

		space into smaller domains, standards can be identified, mapped, categorized, and analyzed in a consistent context.
RAMI 4.0	Germany	The Reference Architectural Model Industrie 4.0, abbreviated RAMI 4.0, abstracts manufacturing systems in a different three-dimensional coordinate system that describes all crucial aspects of Industrie 4.0. The three aspects include Hierarchy Levels, lifecycle and value stream, and component property layers. Within these three axes, all crucial aspects of Industrie 4.0 can be mapped, allowing objects such as machines to be classified according to the model.
IMSA	China	Intelligent Manufacturing System Architecture (IMSA) also defines a 3D intelligent manufacturing system framework, to capture 'the general abstract features of all kinds of intelligent manufacturing application systems". The three dimensions include lifecycle, system hierarchy, and intelligent functions. Th purpose of IMSA is to guide the construction of intelligent manufacturing standard system and the approval of relevant standards.
IIRA	IIC	Industrial Internet Reference Architecture (IIRA) for Industrial Internet of Things (IIoT) systems uses a common vocabulary and a standard-based framework to describe the viewpoints of business, usage, functionality and implementation. It also depicts the relationship among IIRA viewpoints, application scope, and system lifecycle in a 3-dimenstional cube. This Industrial Internet Reference Architecture is intended to provide the foundational framework for all other technical documents and technical activities of Industrial Internet Consortium. It also provides guidance and assistance in the development, documentation, communication, and deployment of IIoT systems to the broader IoT community.
CPS Framework	CPS Public Working Group, USA	CPS framework define three facets and nine aspects as a foundation for a CPS analysis. A facet is a collection of activities that produce artifacts that are driven by aspects and their concerns for a CPS. The three facets defined in CPS framework comprise the traditional systems engineering process: Conceptualization, Realization, and Assurance. The aspects are categories of concerns. Each aspect represents a set of similar efforts that drive the activities within facets. The nine aspects are Functional, Business, Human, Trustworthiness, Timing, Data, Boundaries, Composition, and Lifecycle. CPS Framework also defines the areas of deployment of CPS as domains.
Smart Manufacturing Framework and System Architecture	IEC TC 65	IEC TC 65 Ad-hoc Group 3 is tasked to develop smart manufacturing framework and system architecture to rationalize all the different industrial automation-relevant standards seen as being concurrently applied to a system that has wide design, operational, and connectivity boundaries. The ongoing effort includes terms definition, smart manufacturing use case development, and smart manufacturing landscape development.
Big Picture	ISO TC184/IEC TC 65	Initiated by ISO TC 184 and later joined by IEC TC 65, the "Big Picture" effort defined, populated, and used a set of tools to identify the place and role of the developed standards and/or projects of standardization projects in the universe of discourse of both ISO TC184 and IEC TC65, presented using a graphical representation. The Big Picture model captures three dimensions (business domains, life cycle and value chain) and multiple facets (sector or activity, standard types, etc.).
ISA 95 Function Hierarchy	ISA	ISA 95 Part 1 defines hierarchy models that describe the levels of functions and domains of control associated within manufacturing organizations that are based on The Purdue Reference Model for CIM. Part 1 describes a general model of the functions within an enterprise that are concerned with the integration of business and control. As manufacturing systems are getting smarter, ISA 95 is also working on filling the gap of horizontal integration, by adding message service models.
IEEE P2413	IEEE P2413	IEEE P2413 is working on providing an architecture framework which captures the commonalities across different domains and provides a basis for instantiation of concrete IoT architectures. The framework will describe various IoT domains, definitions of IoT domain abstractions, and identification of commonalities between different IoT domains. It also addresses the quality "quadruple" — protection, security, privacy, and safety.
MESA	MESA	As an educational association, MESA has developed several models over the years that help those from a variety of levels and disciplines within the manufacturing and production enterprise to converge on common views of what they need to accomplish and how enterprise solutions can assist. The current model, developed in 2008, spans from enterprise-level strategic initiatives to business operations to plant operations and actual production. It shows the interrelationships between strategies, enterprise-level operations, and plant operations. Objectives cascade down, and results are reported up against those objectives. It also provides a conceptual illustration of how events in the plant operation feed and inform all other events, and how aggregate views from the enterprise can drill down through operations to the real-time production views.
IBM	IBM	IBM presented a three-layer architecture to separate functions from deployment. The three layers are Edge layer (CPS), Platform/Plant layer, and Platform/Enterprise layer. When the

		architecture is mapped to manufacturing domain, the three layers are instantiated as CPS layer, Plant Layer, and Enterprise Layer.
Rockwell	Rockwell	Rockwell advocates using "Connected Enterprise" to make smart manufacturing possible. In this session, Rockwell presented a model depicting multi-stage evolution paths for various key entities within a manufacturing enterprise: equipment, workforce, supply chain, business functions, platform, and facility and environment. The evolution moves from "Manual Static", to "Connected and automated monitoring", to "Intelligent and predictive", to "dynamic and ecosystem driven", and ultimately arrives to the state of "Self-organizing, dynamic and demand driven". To enable the paths, value-add should be demonstrated.
Hitachi	Hitachi	Hitachi has been working on a Unified Reference Model – Map and Methodology to merge existing reference models/architectures into unified models by eliminating overlaps and clarifying their core contents. URM-MM defines the development process defined for each use case at appropriate scales and granularity. It helps users select an appropriate model from pre-categorized models for each development process to fulfill their aim and it lists relevant international standards for the selected model which come from existing reference models/architectures.

SDOs and industry have created a variety of reference model efforts. However, existing reference models/architectures have been developed for diverse scales/granularities with various domains/life-cycles at multiple organizations. For effective communication and joint standards development, it is necessary to either unify the existing reference models/architecture or create consistency among these models. Table 4.2 lists gaps that prevent reaching session goals.

Table 4.2. Capability Gaps for SMRMA Methods
Methods: • Common Smart Manufacturing Reference Models (SMRM) are necessary to categorize standards and identify gaps. • A smart manufacturing reference model shouldn't be too abstract nor too concrete. The primary use case of a reference model is to classify standards, but it can be used to identify missing or overlapped standards and to develop collaborative smart manufacturing standards roadmaps. • A minimal set of terms and definitions must be agreed on first. • An inventory of use scenarios should be collected and clustered, where the roles and responsibility should be well defined. • The reference model should be defined from the view point of a manufacturer, instead of equipment or product suppliers, etc. • A reference model/architecture should not only list all the elements of smart manufacturing system, but should also consider the relationship and information flows between any two elements.
Tools: • A use case repository. • Common SM standards meta-model and lifecycle management tools.
Definitions: • Key SM terms and definitions across different manufacturers.

4.4 Technology Characteristics

It emerged during the session discussions that many SDOs and consortia have already started to develop the smart manufacturing reference model and architecture listed in the previous section. The results from those individual efforts will provide a solid foundation for the coordinated effort to be taken by the SDOs and consortia. Table 4.3 shows some related technology presented and discussed during the breakout sessions.

Table 4.3. Technology Characteristics for SMRMA Methods
General technology decisions: • SMRM should rely on/reuse RAMI model, NIST Smart Manufacturing ecosystems. • A unified reference model is not the only option. There could be multiple reference models representing different views or concerns. However, these models should be consistent with each other.

• The development of SMRM can refer to CPS framework to consider multiple facets and aspects. For example, SMRM should consider both process models and information flow models. • SMRA should include communication layer and assess IIC, DMDII, MT Connect, OPC UA, MQTT, DDS, and other alternatives. • SMRA could be developed jointly by SDOs and industry consortia. • SMRA should consider service-oriented manufacturing architecture style and define 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 NIST, IEC, and ISO work. • 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.

4.5 Priority Action Topics

The identified priority action topics were focused on unification of smart manufacturing reference models and development of service-oriented manufacturing reference architecture and the tools for a smart manufacturing standards map. Table 4.4 shows several tasks with top priorities.

Table 4.4. Priority Action Topics for SMRMA Methods
Review & Analyze Related Work • Merge all the use cases from different organizations, add new use cases, and highlight those characterizing smart manufacturing • Analyze and map existing manufacturing reference models (ISA 95/RAMI/NIST/Japan/China, etc.). Identify the gaps between existing reference model and make decision on uni-reference model or multi-reference model. • Rework the existing standards landscape and implement a tool for standards discovery, application, and verification. • Develop service-oriented smart manufacturing system architectural framework.
Define Terms and Concepts • Merge SDO terminology from ISO SMCC, IEC SEG 7, IEC TC 65, and ISA TC 184. • Define semantic models for SOM for easy service integration.
Organizational Items • All the organizations are encouraged to join ISO and IEC joint working group (IEC/ISO JWG21) to define common SM reference models.

4.6 Conclusion and Next Steps

Many joint efforts are emerging to work on the Priority Action Topics listed above. IEC and ISO have already formed a joint working group, JWG 21, to develop SM reference models. Terms and definitions were defined by IEC and ISO as well as at the TC levels. ISO and IEC have already developed standards classification systems for SM standards landscaping. However, more SDOs and industry consortia should get involved to contribute to the work. The contribution from supply chain areas is critical to success. In addition, the participants of the breakout session agreed on the feasibility of service-oriented manufacturing based on cyber-physical manufacturing services. The next step is to develop use scenarios of SOM, from which enabling technology and standards can be identified and studied.

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

5.1 Overview

Last year's session on *SM apps and services marketplaces* considered the general functionality and barriers for a rich set of marketplace services by focusing on: (1) functions, components, and requirements, (2) a systems perspective, (3) challenges and barriers, and (4) the role of standards. The session also clarified definitions and offered views of Smart Manufacturing (SM) and marketplaces based on technologies and practices (where "practice" refers to the business and technology applications and activities that are needed to produce desired operational and business outcomes).

This year's session considered the technology, business, and security landscape of commercial and non-profit SM marketplaces, operational scope, and the operating definitions of "open" marketplace. The momentum of (I)IoT and SM over the past year contributed to significantly increased intensity of interest and discussion. In the context of "open" operational scope for marketplace services, the session brought a much sharper focus on operational data, data contextualization, constructs for composability, systems engineering practices, and security practices. Furthermore, the importance of an overarching business perspective, especially the need to provide a clear value-add, was emphasized throughout the different discussions of the session.

5.2 Goals

The breadth of concept and full scope of today's Smart Manufacturing Apps and Service Marketplace(s) are still evolving and are in development with open questions for which there is no convergence by stakeholders. Table 5.1 summarizes the primary goals outlined by the 2017 workshop session participants:

Table 5.1. Goals for Smart Manufacturing Apps and Service Marketplaces (SMASM)
Marketplace & cloud • Assuming Marketplace and Cloud are associated, what is the nature of services vs. applications (application implying licensed or purchased software operational on premise)?
Landscape of marketplaces • What is the landscape of Marketplaces, definitions of open, security, and the range and scope of operations and business models?
Advance data and modeling systems, composed apps and operational data • What is the nature of operational data, how is it contextualized; what are the data structures, e.g., data streaming, involved in composed apps?
Cybersecurity for manufacturing cyber-physical systems • What is the nature and current state of data security in the context of apps and service marketplaces?
Reference architecture • What are the constructs and reference architectures for composability of data-based apps for manufacturing operations? What do we mean by operational apps; what is composed; what are the possible constructs for composition; and how and what are the considerations of this kind of operational security?

5.3 Capability Gaps

Manufacturing is seeing a sharp rise in demand for customized products and/or specialized value-adds to products while improving precision and quality as well as accelerating (on-time) delivery. Current sensor and modeling solutions are in effect maximizing complexity with the highest-demand customers and increasing barriers to implementation. There is a need for a different implementation paradigm. Market agility requires partnerships that are difficult to achieve in the current landscape. There is a need to share services without unnecessarily sharing data – a kind of service execution flow. SM puts pressure on the software industry to produce software that is more customizable, interoperable, in smaller lots, and can execute with greater precision, just like the manufacturers of products. The user experience with an SM marketplace is critical and it is important to augment the user experience rather than replace it. The marketplace needs to bring tools to the workers and not scale the workers to the tools. It needs to integrate competence and culture, and align to the needs of the (diverse) users. To be successful, the marketplace needs to provide a wide spectrum of discoverable applications and services, and then let true market forces bring out the best tools.

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 Smart Manufacturing Apps and Service Marketplaces (SMASM)
• An ***accepted vocabulary*** for substantively describing SM is still critical and nontrivial. It remains very difficult to talk about (I)IoT, IIC, Smart Manufacturing, Intelligent Manufacturing, Smart Factory, Digital Manufacturing, Industry 4.0, and cyber-physical manufacturing systems in an understandable and actionable way. The vocabulary that has evolved around compartmentalized, facilities-focused manufacturing is not adequate for the horizontal, enterprise, and supply chain views that are emerging. Cyber-physical systems that marry IT and OT vocabularies are inadequate in describing the integrated technologies, effects, and behaviors. The term "Marketplace" is itself an inadequate descriptor. • The marketplace provides significant new opportunity and benefit to supporting the engineering of systems and going beyond just resources. This view opens the opportunity of approaching manufacturing with the manufacturing equivalent of a web browser to find the right application resource rather than generate the resource, "keeping it simple." This approach could lead to a similar burst in innovation and not-seen-before opportunity similar to what the internet/web 2.0 provided for content creators by making the tools easy to use, even (and especially) for non-domain experts. The level, diversity, and number of skills required today to design and implement advanced manufacturing systems limit use and growth. There is a clear need to lower the skills needed to implement advanced SM systems. Also, the complexity of manufacturing systems interoperability has reached the point that it is impossible to manage the thousands of individual applications in use in manufacturing. Many have been in use for 20 – 40 years and are not going to be replaced soon. This complexity is now substantially increased with higher levels of product customization, dynamic change, and demands for speed and precision. ***There needs to be change in paradigm to deal with complexity, dynamics and market velocity and product precision.*** • There is an important psychological dimension to SM in that people need to be nudged into change. SM is good, but the concept alone is not sufficient for acceptance. The user experience is a key driver. Concerns of losing intellectual property (IP) need to be addressed and trust in the cloud needs to markedly improve. Manufacturers can learn from other sectors such as financial and healthcare. For example, an ATM network is an open platform. While each of these sectors has their own specific requirements, creating a transparent and structured comparison to the manufacturing domain might allow a transfer of lessons learned and of certain applications and services that can be adapted or used "as-is". • An enterprise architecture needs to be addressed to bring the shop floor, IT, and management together. Integration needs to occur at all levels and communications are essential. A key task is to define the minimum enterprise architecture. Market alignment and the customer experience are the "sticky engines" for growth. Manufacturers do not want experiments. They want quantitative analysis and time scales of risk. Critical analysis is important. Software development kits are critical. Small and medium enterprises would hopefully buy in. The change is substantial and there needs to be a change management strategy.

5.4 Technology Characteristics

The following technology characteristics have been identified as necessary for resolving the capability gaps:

Table 5.3. Technology Characteristics for Smart Manufacturing Apps and Services Marketplaces (SMASM)
• ***Cybersecurity*** is absolutely critical and needs to be embedded in SM as an enterprise value and a focus of economic and performance opportunities. Despite this importance, many companies, especially SMEs, do not perceive security to be a risk. In general, addressing security is considered a conformance cost rather than valued as a competitive performance advantage. Looking forward though, manufacturing cybersecurity needs a paradigm shift and must be intrinsic and not a bolt-on. The marketplace can help drive, but the software and hardware need to include trust anchors – trusted modules for compartmentalizing and managing data. There need to be methods to secure the "edge" even when the edge is an individual sensor and there need to be methods to secure the software and the flows of data. IT organizations will not be able to manage the growing number of devices and software applications effectively and efficiently with a centralized approach in the future. Decentralized management needs to be peer-to-peer (P2P), peer-to-multipeer, and on demand using trust anchors that incorporate business rules about who gets which data and who can modify, change, and/or read/access the data. There need to be anchors that manage who can modify a device, a model, or a data set.

- ***Business-to-business data sharing*** is growing in benefit and therefore need. Developing better ways to exchange data and address the beneficial impacts of data are important. Just copying and transmitting data remains problematic. There need to be ways to work with shared data in read-only and algorithmic formats at much greater levels of granularity and selection. There are also huge opportunities with de-identified/anonymized data. Trusted third-party marketplace clearinghouses that do not own data are important. De-identified/anonymized data may still contain (new) insights to drive, e.g., process and product optimization or manufacturing knowledge creation. Marketplaces are useful for establishing the framework for managing data and they can expose data-sharing methods and limitations of products.

- ***Data analytics*** require the ability to seamlessly utilize data regardless of physical location. There needs to be managed but ready access to understandable 'data lakes'. Specialized sensor vendors need to move away from a business model that locks-in data with proprietary formats. Analytical applications (apps) need to be structured so that data can interrogate the applications to find the best application (and not just promote the pet app). There needs to be greater interoperability between data and many applications, and applications need great ability to handle uncertainty. An ability to query apps for security is critical. Apps need to be assembled into logical sequences and there need to be tools to analyze, verify, and validate the assembly.

- ***Visualization*** is another key systems function at all levels of the business and a critical outcome of data composability. It is the result of the analytics and an understood means of storytelling for a variety of stakeholders, each with individual requirements for insights from data. This leads to individualized data visualization as a key means of communication. Successful data visualization also improves efficiency as it allows the direct and targeted value-added use of data analytics results for each role, whether on the shop floor or the executive suite. As a training mechanism, visualization has a huge impact. There is a significant need to move toward interfaces for real-time human interaction with data so that humans are integrated with the analytics and visualization and playing a role in operational decision making supported by data and modeling. There is a huge need to lower the barriers to visualization being applied much more extensively for small, medium, and large enterprises.

5.5 Priority Action Topics

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

Table 5.4. Priority Action Topics

Conceptualization "inventory" needs

- More precise vocabulary that does not alienate
- Know-how from other domains – e.g., gaming, financial, and medical
- Industry use cases (different industry & company sizes, locations!) for conceptualizing based on authentic experiences

Potential areas for NIST-involved activities include:

1. Extend the specifications and definitions of cyber-physical systems to include an SM data and applications marketplace that supports the themes identified.
2. Define standards-based trust anchors for hardware devices, software applications, and data sets for managing interoperability and data sharing with granularly managed security, ownership, business agreements, and regulatory requirements and with a wide range of data sharing formats
3. Take the concept of systems design and implementation by search to a next level of specification for an SM data and applications marketplace.
4. Define the categories of standards that are required for this kind of data and applications environment and specify those infrastructure standards that are required for this environment to satisfactorily operate as shared infrastructure.
5. Define the role of the reference architecture in promulgating standards vs. the role of the marketplace.

5.6 Conclusion and Next Steps

When combining cyber-physical systems into a SMS, there are key understandings about data analytics, data, apps, services, and composability that drive development and capability. Composability is a fundamental need for which there has been a great deal of research, e.g., domains, requirements, and user functionality. Most composability mechanisms use drag and drop, mash up, or workflow approaches. Services imply compositions. Data services imply data composition. Cyber Physical (Production) System (CP(P)S) services imply digital twin services where there is a need to compose physical and cyber to form predictive behavioral models. Although reusability is hard because the level of abstraction required must match the level of use and/or development, generating new methods each time is even more difficult. Composing from or modifying existing methods can reduce workload. Physical systems are hierarchical in that components make up systems which in turn make up processes, and so forth. The digital twin concept needs to expand to address hierarchical structures and levels of abstraction as well as devices and processes. The value of the digital twin lies in its ability to be interrogated.

First and foremost, data must be good. A small amount of "bad" data (different data/information quality dimensions) is a harder problem than a big, "good" data problem. Sharing and modeling aggregated data are also difficult due to a variety of factors, including a lack of non-problem-specific (reason for collecting data) metadata. Federations of shared data are important, but need a data model and the granularity to enact an electronic contract. Other domains are doing composability and orchestration, e.g., IT and financial. Manufacturing is managing many views and levels of granularity. There are different model dimensions — structure, function, and behavior, approaches, and methods that can be defined in taxonomies of methods and tools and supported with templates, infrastructure, and services to increase reusability.

An external, shared cloud marketplace that reflects reference architecture standards can drive best practices and make it possible to select the best tools. A reference architecture will also act as an authoritative source that can appropriately restrain implementation. A reference architecture that is too prescriptive, too hard to achieve, and/or restricts application development will have a negative impact. Likewise, a reference architecture that is too general is not useful. Nevertheless, there is a consensus that there is a sweet spot for a reference architecture that will be incredibly useful in driving the appropriate convergence on useful practice and standards.

In proceeding with a SM reference architecture, we note that an IT reference architecture is farther along and there has been a lot of work on composability. The NIST work on cloud, security, cyber physical systems, etc., offers paths forward with a common vocabulary and frameworks for reference architectures. The marketplace needs to reflect and support the reference architecture, especially with respect to the plumbing: the ports and how services talk; endpoint definitions – edge, data, service, buffer, security, and transport; how to use standards; how information technology (IT) resources follow operation technology (OT) needs. There is an important distinction between intrinsic marketplace standards and services that manage standards. Systems, data, application, and collaboration need to be baked into the reference architecture. The lifecycle management of the reference architecture is itself important.

6 Breakout 5 – Industry Ontologies Foundry (IOF) (Previously Crowdsourcing of Manufacturing Knowledge)

6.1 Overview

This session was the second workshop held on behalf of the Industry Ontologies Foundry (IOF), and the first as part of the NIST/OAGi workshop series. Like its direct predecessor, Crowdsourcing of Manufacturing Knowledge (CMK) for Smart Manufacturing Systems, this session focused on the need and directions for development of formal knowledge models to support smart manufacturing systems (SMS).

The first IOF workshop was held on December 8, 2016. This workshop resulted in the creation of two IOF working groups — Governance and Case Studies. These two groups worked over the following few months to lay the foundation for the Industry Ontologies Foundry (IOF).

In this second workshop to support the establishment of the IOF, the organizers invited practitioners and other interested parties to discuss the use of ontologies in industrial settings, and how we may leverage a more centralized approach to further new and ongoing efforts. Presenters from various backgrounds discussed their experiences and the potential impact of the IOF on future work. The objective in this workshop was to share experiences and continue to find the best path forward to establish the Industry Ontologies Foundry as the go-to resource for industry ontology implementations.

The session was divided into 4 main parts with discussion sections incorporated.

6.1.1 Session 1: Revisiting BFO as Top Level Ontology - What has worked in the past

One starting point for the IOF is the successful strategy of the Open Biomedical Ontologies Foundry, which uses BFO (Basic Formal Ontology) as its upper-level architecture. Users of BFO shared their experiences in adopting it to support interoperability of ontologies from different domains. Barry Smith concluded by discussing how these successes might translate to industry ontologies.

Panel Moderator: Barry Smith

Speakers: Darren Natale (Georgetown U: BFO in the OBO Foundry); Lowell Vizenor (Securboration, Inc: BFO in the Military Domain); John McDowall (Intelligence Support to Command and Control)

6.1.2 Session 2: Industrial Implementations - What has worked in the past

This panel of practitioners had successfully leveraged semantic technologies to support Industrial software implementations in the past. Panelists came from software developer and service provider communities. Each panelist spoke for 5-7 minutes with a joint discussion at the end.

Panel Moderator: Evan Wallace

Panelists: Chris Gregory (CIMData); David Krieger (SRI); Hyunmin Cheong (Autodesk); Justin Fessler (IBM Watson); Steve Ray (CMU); David Price (TopQuadrant);

6.1.3 Session 3: Industry Implementations - More In-Depth Discussion from Industry Users

This session consisted of six 25-minute presentations (15’ presentation/10’ discussion) on ontology adoption from industry perspectives. The sessions are meant to provide insight into how industry has successfully implemented semantic solutions in the past. A mind map that was developed from the first workshop was leveraged to drive the IOF context for these presentations.

Panelists: Karl Hribernik (BIBA); Ana Teresa Correia (ATB); Venkatesh Agaram (CIMData); Richard Sharpe (Loughborough Case Studies); Sam Chance (Cambridge Semantics); Fernando Mas and Jean-Bernard Hentz (AIRBUS)

6.1.4 Session 4: Recap/ Moving forward Discussions (Focus on Mind Map topics)

Dimitris Kiritsis led discussions on topics that had been identified during the previous workshop and subsequent meetings. These topics were organized and summarized as part of a mind map by Dimitris.

6.1.5 Starting Points for Discussions

The IOF supports four levels of ontologies: (1) the hub ontology, (2) the foundry ontologies, (3) ontologies not accepted as meeting Foundry requirements but acceptable for the repository, and (4) derivative ontologies, both open and of restricted access. Domain ontologies, or "spokes" will be developed on a needs-driven basis. As new domains are modeled by experts, they can be submitted for consideration as Foundry ontologies. Domain ontologies must also be approved by a designated panel of experts before becoming a Foundry ontology. Ontologies that are not a core Foundry ontology, including those that do not initially pass the panel review, can be submitted as an IOF repository ontology.

Derivative ontologies may extend one or more of the core IOF ontologies or another ontology in the repository. Derivatives allow for needs-based customizations while continuing to conform to the IOF model. If not adopted as a core ontology in the IOF, an ontology may still be curated in the IOF repository. This ontology may be resubmitted later as it matures, or perhaps derivative ontologies will occur at lower layers of the foundry.

The proposed hub ontology is the Basic Formal Ontology, or BFO. The BFO has provided a common reference for many of the ontologies developed in the medical community, specifically the Open Biomedical Ontologies, or OBO. The OBO has demonstrated the ability to successfully leverage a core ontology to extend across multiple domains, while also providing a common language and research platform for multidisciplinary interactions.

These ontologies may be application-driven, and may be either open or access-restricted, depending on the intended user community.

6.2 Goals

The primary purpose of the IOF is to develop a collaborative framework and platform for submitting, validating, and sharing ontologies for the industrial and manufacturing domains. In this way, the knowledge will be captured and refined to facilitate smart manufacturing practices and resources.

The IOF workshops have focused on the adoption of ontologies and semantics for SMS-type applications. As with the previous CMK session, the IOF addressed challenges in developing formal knowledge models with the ability to efficiently elicit knowledge from distributed resources and form a coherent body of knowledge that can be validated and extended by user communities. The CMK session explored the requirements, challenges, and opportunities regarding capturing knowledge from "the crowd." The IOF takes a similar approach, though the IOF approach specifically adopts ontologies and will require validation by core-domain experts before accepting contributions. As a "specification of a conceptualization," the IOF will exclusively leverage ontologies in development of explicit formal information models. Ultimately, the objective of the IOF is to develop a domain-driven, community-centric repository that supports the development, sharing, and growth of reference models and knowledge bases for SMS.

The IOF will establish an open platform where interested parties can leverage and contribute to industry-driven domain models and vocabulary. The IOF has proposed a hub-and-spoke model in development of sets of ontologies to support different aspects of engineering. The hub, an "upper ontology," will provide a domain-agnostic common reference which domain-specific ontologies can reference. Like its CMK predecessor, the IOF will take a crowdsourcing-like approach to ontology development. The spokes, or the Foundry, will consist of domain-specific, application-agnostic ontologies contributed by various efforts in respective fields. A requirement of any spoke, or core IOF ontology, is that it will remain application-agnostic and openly available to all interested parties. The IOF approach 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.

The IOF approach is modeled to some extent after the OBO Foundry. The OBO Foundry for biomedical ontologies is an organized group with active volunteers. The operating support teams for the OBO foundry include: Operations, Editorial, Technical, and Outreach working groups. The foundry consists of 150 active ontologies and approximately 40 obsolete ontologies, and is hosted by the University of Buffalo. Different objectives were anticipated and satisfied early on. It was important to keep foundry ontologies as domain-independent as possible to facilitate reuse, and BFO facilitates the objectivity. A lesson learned (from Protein ontology) is that the objectives of the ontology may change as ontology use evolves.

Table 6.1. Goals for Industry Ontologies Foundry
Business/market performance objectives • To enable common reference for industry domain specialization. • To enable elicitation of tacit knowledge. • To enable cost-efficient, extensible re-usability of knowledge models. • To provide IP-issue-free domain references.
Business/market processes change goals • To distribute usability and accessibility of domain knowledge.
Business/market performances non-technical goals • To allow clear value proposition for participation in ontology development. • To identify role for a neutral party. • To enable participation of resource-constrained SMEs. • To enable equal access and benefits to all users. • To provide visibility of ontology efforts through increased awareness. • To enable resolution of conflicts of interest among multiple types of organizations.
Results of business/market processes • To allow resolution of information and domain issues that are not organized, too aggregated, or distributed problems.

6.3 Capability Gaps (focus on discussions on IOF domains)

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. Topics focus on core domain concepts that are used in industry. The core concepts that are captured should be available for reuse, meaning that the concepts should extend beyond one-off or specialized applications. When possible, the concepts should support industry in a generalized manner that can be later specified to meet specialized or individual needs.

Domains discussed extended across the product lifecycle, from design to manufacture to use. Supporting ontologies discussed included decision-based ontologies and materials ontologies. No specific domains were eliminated from consideration, though any domain under consideration fell under the notion of "industry" or a supporting domain, such as materials.

In discussing the hub and spoke concept, an overview of upper-level ontologies was given. Requirements of these ontologies where that they were small, open, and top level. Those discussed included DOLCE, SUMO, 15926, BFO, CYC, and HighFLEET.

BFO is the common upper level ontology adopted by the OBO Foundry. BFO benefits the ability to leverage existing ontologies as circumscribed domains will reduce confusion in integration. It was difficult to talk about BFO in the forefront as it is so integrated into the background. However, such a discussion had to be initiated to avoid confusion.

Much discussion was held on previous BFO experiences across multiple domains. The BFO enables quasi-independent domain ontology development, providing common semantics for communication across domain boundaries. One common application was for "content intelligence," or the use of ontologies to add structure to unstructured data. Such enhancements support semantic searches such as document similarity, machine learning with ontologies, and domain modeling for big-data analytics.

Applications for the IOF were widely discussed. One application discussed was how to leverage the IOF in search problems, e.g., how the IOF can expand and standardize design search by using techniques such as data tagging and semantic mediation. Semantic mediation is data-source agnostic and introduces semantics on top of existing data sources. Semantic mediation supports advanced query methods such as SPARQL queries and other semantic searches. By providing a common terminology for associating different domains, the IOF can enhance search spaces. An example discussed was using a semantic media wrapper on a production plant to support real-time data interoperability.

Some AI -related applications were discussed in the context of IBM Watson, where the IOF could be leveraged to contextually search data. Ontologies of terms have been fed to Watson to provide context to data to support facet exploration, a combination of structured and unstructured data. Potential IOF-enhanced methods included the use of semantics in fault tree analysis, systems diagnosis, collaborative mapping, text and exploratory analytics, and other machine learning type of correlations.

The use of the IOF as a reference architecture and to support interoperability was discussed. As a reference architecture for systems knowledge, the IOF could support the adoption of the over 220 PLM standards, some of which overlap. A similar approach has been demonstrated in the financial domain with the FIBO financial ontology to alleviate inconsistencies caused by multiple navigation paths. Other multi-domain applications discussed included ontologies for Smart Manufacturing and a Digital Twin Ontology.

Table 6.2 reflects known IOF capability gaps. Some of these are still research questions.

Table 6.2. Capability Gaps for Industry Ontology Foundry
Non-Functional properties: • IOF ontologies: 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 to allow specialization from contributors (internal vs. external). • Methods to measure completeness of knowledge in a repository. • Methods and tools for maintenance of IOF knowledge base. • Reasoning and problem-solving methods and tools.
Standards: • A common domain reference for the marketplace. • Protocol for testing expertise levels. • Validation mechanism for ontologies.

• Uniform knowledge representation that supports a variety of tools.

6.4 Technology Characteristics (focus on implementations and applications)

IOF attributes allow knowledge-based models, methods, and tools to play a key role in gathering and managing manufacturing knowledge that can be more readily used in the new distributed-manufacturing SOA architectures. This enables composable systems for manufacturing systems by supporting interoperable integration, search for and discovery of relevant manufacturing services, and configuration and reconfiguration of these services.

The syntax in which ontologies will be stored and developed has not been decided, but it is presumed that OWL 2 will serve as the de facto language. Although representations in OWL (in xml) can be difficult for human consumption and readability thus often depends on toolsets, transitioning to OWL can add semantic advantages along with the benefits of an open format.

IOF has made note of the tools such as Protégé and Topbraid Composer as ontology development tools. Some of the presentations discussed tools that would take advantage of the IOF, including those that support semantics-based analytics. Development requirements exist for such systems, including graphical user interfaces (GUIs), application programming interfaces (APIs), and possibly plug-ins into existing computer-aided engineering (CAE) systems.

The platform that will host the IOF and its repositories has not been decided, but the University of Buffalo has offered the OBO Foundry platform to begin the development activities.

Table 6.3 lists high-level characteristics specifically for technology-related needs for IOF methods.

Table 6.3. Technology Characteristics for IOF
Standards Decisions: • Standards representations should be consistent across analysis tools. • Standard mathematical descriptions of models. • Guidelines on hierarchical construction, extension, reuse, and analysis of performance models. • Validation procedures/guidelines for KB contributions. • Guidelines for use (with use cases and examples).
Tool Decisions: • Library of ontologies that are modular and complementary. • Core 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 the workshop included lively discussions, many questions remained unanswered and several action items remained at its conclusion:

Creating an IOF Charter. A finalized charter is necessary to provide a common understanding on how the IOF will move forward. An initial charter was discussed as part of this workshop, to include a governance model and clear statement of work. These discussions continued after the workshop.

Creating initial set of IOF ontologies. A decision has not yet been made on what domains will be considered IOF core ontologies (geometry, manufacturing, design, etc.). Several domains were presented as part of "lightning talks" to investigate what industry-related ontologies have been developed.

Defining IOF ontology acceptance criteria. What are core competency questions to ensure an ontology will conform to IOF ideals? What metadata is necessary for an IOF ontology to communicate its domain? Metadata is necessary for IOF application, and every IOF term has to have a definition.

Establishing a home for IOF. Much of the ongoing IOF work has been supported by a few main contributors. To succeed, a "permanent" home (including a virtual address) needs to be established where IOF ontologies can be properly established and curated. A centralized, host URL is necessary for providing a common interface to IOF ontologies, and this is currently offered by the University of Buffalo.

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 set of IOF ontologies. • Align with core BFO ontology. • Decide on governance model.
Analyze best practices & methods: • Conduct literature review (existing industry ontologies). • Review existing commercial tools (what's out there?). • Identify case studies. • Identify best practices for IOF ontology development.
Design methods: ▪ Create industry ontologies and test their use.

6.6 Conclusions and Next Steps

This section presented key takeaways from the IOF breakout session. Both potential IOF developers and adopters were invited to share their experiences, and much discussion was held around these experiences. It is evident that there is substantial interest in the area and that significant investment is required.

As was done with the OBO Foundry, a governance model needs to be established to include a charter and working groups (governance, outreach, etc.). Assigning individuals to specific roles is critical to continuing the growth of the IOF activities. Outreach is a large part of those roles, as both contributors and benefactors must be identified moving forward. Governance is crucial to establishing the charter and addressing issues such as IP and ownership rights.

Use cases are necessary to demonstrate the utility of the IOF effort while also providing insight into where gaps remain. Business use cases are necessary to demonstrate the IOF is worth investing in. Domain use cases provide insight into what the different domain needs are, and where initial ontology development efforts should be focused.

Similar to its CMK predecessor, IOF risks include: gaining a critical mass of people, gaining a critical mass of knowledge, commitment of the leadership, staying power of the used technologies, quality of the content, livelihood of the content, breadth of KB, and discipline of the contributors.

7 Summary

This document reports on the *2017 NIST/OAGi Workshop: Enabling Composable Service-Oriented Manufacturing Systems*, which is third 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 workshops explore the needed technical foundation for achieving the vision. The following are main findings from the workshop and next steps planned for the workshop series. Where relevant, to provide continuity of reporting in the workshop series, we describe what remains essential for the session and what has changed from the previous year and why.

7.1 Key Findings

7.1.1 Extensive New Technical Capabilities Are Needed for Composable SOM

Realizing the vision of Composable SOM requires many advances in underlying technologies to build more capable systems-integration approaches. The focus of the workshop and the community is on (1) providing new reference model life-cycle management (RM LCM) capabilities and (2) using those capabilities to build required new technologies.

Each breakout session, within its respective area of interest, discussed advances in RM LCM capabilities for the new 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 Systems:

- **Smart Manufacturing (SM) Model-Based Messaging Standards Development (MBMSD) Methods** provides knowledge-model-based specification for conveying customization and context information for manufacturing services within SOM Systems to advance message standards life-cycle-management (MSLCM) capabilities. There are no significant changes in the direction of the session from the previous year.
- **Smart Manufacturing Systems Characterization (SMSC) Methods** develops knowledge-model-based characterizations of both the manufacturers' requirements and the technologies' capabilities in order to support reasoning about the composability of these technologies within SM systems based on their interface designs. There are no significant changes in the direction of the session from the previous year.
- **Smart Manufacturing Reference Models and Architecture (SMRMA)** 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 multiple aspects of SOM systems, apps, and marketplaces to support the identification and analysis of current technological and other challenges as well as requirements from the stakeholders for Composable SOM Systems.

- **Industrial Ontology Foundry** investigates new knowledge-model-based approaches to develop a collaborative framework and platform for submitting, validating, and sharing ontologies for the industrial and manufacturing domains. In this way, the knowledge will be captured and refined to facilitate smart manufacturing practices and resources in Composable SOM Systems.

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 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. Stakeholders are expected to make use of this and future workshop reports to update and align their R&D programs relevant to Composable Service Oriented Manufacturing systems.

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

- **Smart Manufacturing Model-Based Messaging Standards Development (MBMSD) Methods** discussed (1) Common processes for developing and maintaining message standards for service-oriented integration; (2) Tools for developing collaborative and traceable message standards; and (3) Methods for discovering, documenting, and sharing context-dependent standards-usage experiences. No significant changes in high-level direction for the session discussions occurred since last year.
- **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 regard 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. No significant changes in high-level direction for the session discussions occurred since last year.
- **Smart Manufacturing Reference Models and Architecture (SMRMA)** 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. One significant change from last year was a greater focus on Reference Models and Architectures.
- **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. No significant changes in high-level direction for the session discussions occurred since last year.
- **Industrial Ontology Foundry** discussed (1) Common ontology and definitions in support of the SM marketplace; (2) Validation mechanisms for ontological models; and (3) Ontology-based knowledge-representation that supports a variety of knowledge-management tasks. One significant change was the greater focus on Ontological approaches to distributed knowledge management for SMS.

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

For each of the workshop sessions, target Priority Roadmap Topics (PRTs) are identified. A 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 and practice for the session domain. A PRT allows planning of needed resources to achieve tangible outcomes and desired impacts on measurement science (necessary for advancements in standards development), enabling the needed technology, new capabilities, and goals.

The workshop sessions develop Priority Roadmap Topics (PRTs) from the identified Priority Action Items (PAIs) that reflect perceived shortcomings in the knowledge within a session area. Priority Roadmap Topics contain measurement-science-relevant aspects. For example, in the MBMSD session, the PRTs are the MSSRT and BPCCS products, which advance science and engineering of message standards development and management. Also, in the IOF session, the PRT is the IOF itself, which advances science and engineering of ontologies as a formal foundation for standards development.

The PRTs in all sessions except 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. These PRTs provide a needed focus for future discussions, and they will continue to be refined. They may also serve to refocus interest on other areas and PRTs in the future.

The following are potential PRTs identified for each session:

- **Model-Based Messaging Standards Development (MBMSD):** Message Standard Semantic Refinement Tool (MSSRT) and Business Process Cataloging and Classification System (BPCCS). MSSRT has been explicitly added to BPCCS, which was the previous year's PRT.
- **Smart Manufacturing Systems Characterization (SMSC):** Classification Model of SM Systems Requirements and Capabilities
- **Smart Manufacturing Reference Models and Architecture (SMRMA):** Smart Manufacturing Reference Architecture
- **Smart Manufacturing Apps and Service Marketplaces (SMASM):** SM Service Marketplace Requirements Engineering Method
- **Industrial Ontology Foundry (IOF):** Repository of curated manufacturing ontological resources.

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

The NIST Smart Manufacturing Systems Design and Analysis (SMSDA) program plans to continue to work with the stakeholder community in all the five 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)		

Message Standard Semantic Refinement Tool (MSSRT) & Business Process Cataloging and Classification System (BPCCS)	++	
Smart Manufacturing Systems Characterization (SMSC)		
Classification Model of SM Systems Requirements and Capabilities		++
Smart Manufacturing Reference Models and Architecture (SMRMA)		
Smart Manufacturing Reference Architecture	++	
Smart Manufacturing Apps and Service Marketplaces (SMASM)		
SM Service Marketplace Requirements Engineering Methods	+	
Industrial Ontology Foundry (IOF)		
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 governance 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. In that sense, the workshop series identifies Priority Roadmap Topics (PRTs) that are used to initiate new R&D projects not only in NIST R&D programs, but also in other industry, academia, and government R&D programs.

This workshop series aims 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 will be identified and used to drive stakeholder 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, SDOs, and government agencies

Working Session / PRT Name	**Potential impact (including changes since last year)**
Model-Based Messaging Standards Development (MBMSD)	
Message Standard Semantic Refinement Tool (MSSRT) & Business Process Cataloging & Classification System (BPCCS)	Enabling new generation of efficient model-based OAGIS standard at the OAGi and other SDOs. No changes from previous year.
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 Reference Models and Architecture (SMRMA)	
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
Industrial Ontology Foundry	

Industrial Ontology Foundry	Enabling Multi-Industry & Government (AutoCAD, USAF, Dassault, etc.) technology advancements.

Appendix A – Key Terms

- **Composable Service-Oriented Manufacturing (SOM) –** High-value SOM approaches with the core capability to efficiently search for and discover relevant manufacturing services, integrate services in interoperable ways, and configure and re-configure these services to meet changing requirements.
- **Knowledge-based Modeling –** Modeling of information, functions, processes, organizations, and other aspects of man-made systems that allows capture and sharing of both structured and unstructured information as well as specifications of manufacturing systems, processes, and products in computer-processable forms. The computer-processable representations capture information, know-how, guidance, heuristics, and standards that enable reasoning necessary for realizing Composable SOM systems.
- **Reference Models Life-Cycle Management (RM LCM) Methods** – A critical part required by new technologies to achieve Composable SOM. The methods address activities ranging from creation to adaptation to use of reference models. These 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. Techniques used in the LCM methods need to support high-level abstractions, separation of concerns, and loose coupling. They may use declarative approaches, including information- and knowledge-based models, rule-based systems, and taxonomy- or ontology-based systems.
- **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.
- **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 that meet changing consumer demands, market conditions, and supply chain capacities.
- **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).