

3rd International Conference on Through-life Engineering Services

On architecting and composing through-life engineering information services to enable smart manufacturing

Nenad Ivezic, Boonserm Kulvatunyou, Vijay Srinivasan*

Engineering Laboratory, National Institute of Standards and Technology, Gaithersburg, MD, U.S.A.

* Corresponding author. Tel.: 301-975-3508; fax: 301-258-9749. E-mail address: vijay.srinivasan@nist.gov

Abstract

Engineering information systems play an important role in the current era of digitization of manufacturing, which is also known as smart manufacturing. Traditionally, these engineering information systems spanned the lifecycle of a product by providing interoperability of software subsystems through a combination of open and proprietary exchange of data. But research and development efforts are underway to replace this paradigm with engineering information *services* that can be composed dynamically to meet changing needs in the operation of smart manufacturing systems. This paper describes the opportunities and challenges in architecting such engineering information services and composing them to enable smart manufacturing.

© 2014 The Authors. Published by Elsevier B.V.

Peer-review under responsibility of the Programme Chair of EPSRC Centre for Innovative Manufacturing in Through-life Engineering Services.

Keywords: Through-life engineering; information services; standards; architectures; service composition; SOA.

1. Introduction

In a keynote paper at the 2nd International Through-life Engineering Services Conference, McMahon and Ball [1] addressed the role of information systems in improving the through-life support of long-lived, complex artifacts. They pointed out the promise offered by information systems in a number of areas including productivity and more accurate and responsive assessment of artifact conditions. They also stressed the need for understanding the complexity and interlinked nature of the engineering information involved in through-life engineering services.

In this paper, we delve a little deeper into the engineering information that is shared among different phases in a product's lifecycle and across its supply chain. We also explore how different aspects of the information can be offered as services. In particular, we examine the role of open engineering information and messaging standards that are relevant to through-life engineering services.

The idea of sharing engineering information as services is not new [2, 3]. When Web Services – supported by service-oriented architecture (SOA) – became a reality more than a decade ago, such engineering information services offered an attractive, alternative avenue to support integrating various engineering activities. Since then, two major developments have accelerated this trend. The first is the wide-spread digitization of the entire manufacturing sector that positions information at the front and center of all modern manufacturing. This, in turn, has heightened the need for engineering information standards in the manufacturing sector. The second is the virtualization of computing and communication resources using ‘clouds.’ This has moved the engineering service functions to the clouds with several attendant opportunities and challenges.

We start by setting the stage with the modern digitization of manufacturing, also referred to as smart manufacturing, in Section 2. Section 3 positions several standards, some of which have been extensively updated recently, as exemplar enablers of smart manufacturing systems. Section 4 provides a brief introduction to service-oriented

architecture, which can be used to compose various engineering information services to implement a scenario such as the one described in Section 5. Some concluding remarks are made in Section 6 after a brief summary.

2. Digitization of manufacturing

In April 2012, the Economist magazine published an influential article that proclaimed that the Third Industrial Revolution, in the form of the digitization of manufacturing, is well underway [4]. By its reckoning, the first industrial revolution began in Britain in the late 18th century, with the mechanization of the textile industry. The second industrial revolution came in the early 20th century, when Henry Ford mastered the moving assembly line and ushered in the age of mass production. In the third industrial revolution currently under way, manufacturing is going digital.

A year later after the Economist article, using a slightly different counting method, the German manufacturing industry came up with the nickname Industrie 4.0 to refer to the current era in manufacturing [5]. By its count, the first three industrial revolutions came about as a result of mechanization, electricity, and information technology; now, the introduction of Internet of Things and Services into the manufacturing environment is ushering in a fourth industrial revolution called Industrie 4.0. The German manufacturing industry predicts that in the future, businesses will establish global networks that incorporate their machinery, warehousing systems, and production facilities in the shape of Cyber-Physical Systems (CPS).

Irrespective of how we choose to count, it is clear that a new manufacturing era is upon us, and it is driven by information – a lot of information, more popularly known nowadays as ‘big data.’ In an opinion piece in a special issue of the Economist magazine, the chief executive of IBM argued that data is the ‘natural resource’ for the 21st century – just as steam power was for the 18th, electricity for the 19th, and hydrocarbons for the 20th [6]. She predicted that a new model of the firm will rise in 2014 using data as the natural resource, and called it the ‘smarter enterprise.’

While the private sector is preparing to exploit the digitization of manufacturing, many countries are investing in public-private partnerships to stimulate manufacturing innovation and get ahead in the new era. The United Kingdom has set up sixteen Centres for Innovative Manufacturing. They range from Additive Manufacturing to Ultra Precision, including Through-life Engineering Services. The German government, manufacturing industry, and academia are teaming up under the Industrie 4.0 umbrella, and are investing to preserve and advance their manufacturing leadership. Several Fraunhofer Institutes have demonstrated successfully the German model of public-private partnership to bring scientific ideas to industrial practice.

Since 2012, the United States of America has embarked on a major investment in a national network for manufacturing innovation [7], starting with four public-private partnership institutes. More such institutes are

expected to join the national network soon. Several U.S. national research laboratories, including the National Institute of Standards and Technology (NIST), are investing in manufacturing-related research and development projects. In particular, NIST is investing in Smart Manufacturing, which is characterized by a heavy use of information, communication, and network technologies as befitting the needs of the new manufacturing era. Some of the enablers of smart manufacturing systems are described next.

3. Standards to enable smart manufacturing systems

Smart manufacturing systems require representations of engineering information that are entirely machine readable. However, the tradition of engineering drawings and textual documents still dominate engineering practice throughout a product’s lifecycle. Even if the venerable paper is replaced by a (portable) display screen, the computer-generated drawings (e.g., using a computer-aided drafting system) and rich-text files (e.g., using a modern word processing system with graphics) are the means by which much of the information is communicated to through-life engineering services. This then requires human reading and interpretation, which are error prone and time consuming.

Smart manufacturing systems demand something better. They require engineering drawings to be replaced by augmented, three-dimensional (3D) geometric models; and, rich-text files of functional requirements, materials, processes, and maintenance to be replaced by structured information based on formal models. These replacements enable machine readability that results in fast and error-free processing of engineering information from the beginning to the end of a product’s lifecycle.

Recent developments in standards provide some of the necessary tools and technologies to move towards machine readability. It is clear that no single software vendor or organization can cover the entire breadth and depth of a product’s lifecycle. So, standards have emerged as the natural choice to link disparate software systems and services. We describe some examples of the enabling standards in the following subsections.

3.1 Model-based 3D engineering

The International Organization for Standardization (ISO) has completed a major effort on a new standard ISO 10303-242 titled ‘Managed Model Based 3D Engineering.’ It belongs to a family of standards called STEP (STandard for the Exchange of Product model data). ISO 10303-242 is also called the STEP Application Protocol 242 (STEP AP242, for short). STEP AP242 combines many of the functionalities of its predecessors AP203 and AP214, and offers more [8]. Some of the new and improved functionalities in STEP AP242 that are of interest to through-life engineering support are described below.

Product Manufacturing Information (PMI) is a phrase used by the Computer Aided Design and Manufacturing (CAD/CAM) community to refer to Geometric

But non-geometric data, such as bill of material (BOM), about a product are important for manufacturing and through-life engineering services. The BOMs are managed by Enterprise Resource Planning (ERP) systems and various other engineering information systems, such as Manufacturing Operations Management (MOM) systems and software systems that support maintenance and service. Some of these needs are addressed by Business Object Documents (BODs), which are engineering and business message specifications developed by the Open Application Group Inc. (OAGi) [12]. The entire suite of specifications is called Open Application Group Integration Specification (OAGIS). OAGIS data models are created using the ISO 15000-5 Core Components Specification (CCS) as the modeling methodology [13]. OAGi has recently released OAGIS Version 10.

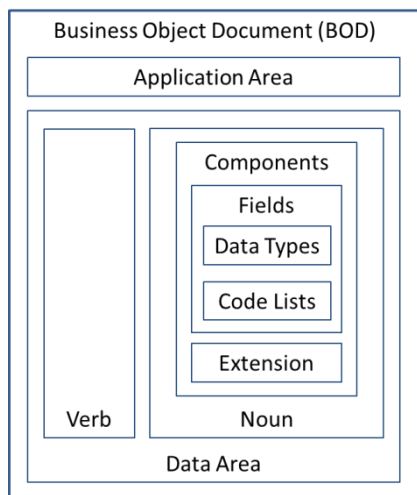


Fig. 3. Business object document (BOD) architecture.

The architecture of BODs is illustrated graphically in Fig 3. A BOD contains two areas: one devoted to application and the other to data. The Application Area contains information needed by the communicating infrastructure to deliver and track the message. It also contains context information that the receiver application may need in order to process the message correctly. Examples include the engineering or business process it is a part of, and whether it is a production or a test message. The Data Area contains the message content, which comprises Verbs and Nouns. The Verb indicates the action to be performed on the Nouns; the Noun conveys business-specific data to be acted upon by the receiver application.

Nouns are made up of reusable elements including Components and Fields. Components convey business data that have a complex structure. They are in turn made up of other Components and Fields. Fields convey business data that have a simple structure; i.e., a single value. Each Field is bound to a Data Type or a Code List that restricts its value domain. An important feature of OAGIS is its extension capability. OAGIS has a built-in extension capability for every component including the application area (which is not illustrated explicitly in Fig. 3).

OAGIS has recently adopted a model-driven approach (MDA), which separates the models from language-specific implementations. Fig 4 illustrates MDA realization in OAGIS 10. The figure shows the packaging structure of OAGIS content. This results in two benefits to OAGIS users. First, OAGIS 10 defines the OAGIS Model, which is then derived into three OAGIS Expressions that are optimized for various deployment environments. For example, OAGIS JSON (JavaScript Object Notation) allows light-weight messages optimized for cloud and mobile deployments. This is an important development because till recently OAGIS focused exclusively on XML. Second, OAGIS Model packages reusable content into the Platform package. The package also includes BODs and Nouns that are agnostic to business and engineering domains. The Platform package allows for more pervasive adoption of OAGIS through other consortia that lead to greater interoperability.

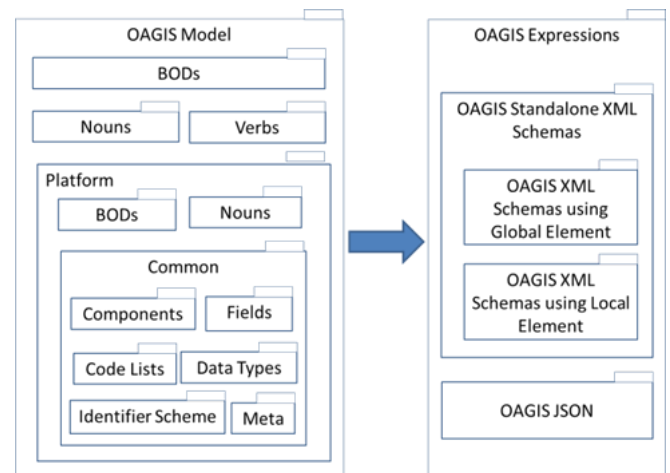


Fig. 4. OAGIS MDA realization and delivery structure.

Although BODs begin with the word ‘business’, they also support transactions in various engineering functional areas throughout a single enterprise or across multiple enterprises. Example transactions include design, manufacturing, supply chain, finance, sales, and accounting. OAGIS support for manufacturing integration is also extended by the Business-to-Manufacturing Markup Language (B2MML) message standard [14] published by MESA International. Recently, OAGi has set up a smart manufacturing working group to push this envelop further; this group will investigate how a reference model may be used to improve the reuse of information services relevant to manufacturing. OAGi has also started a semantic refinement working group to improve the precision of OAGIS-based services in declaring their interface capabilities.

The breadth of verbs and nouns coverage, software vendor support, and model-driven approaches have all enabled OAGIS BODs to support composition of engineering services distributed over the cloud. In a recent

OAGIS implementation case study, Fraunhofer Institute has used OAGIS in the cloud computing for logistics [15]. The goal of that case study was to provide a marketplace where users could compose logistics software services using cloud computing to satisfy their business process requirements.

3.3 Model-based systems engineering

Long-lived, complex artifacts are designed, built, and serviced using systems engineering principles. Thus far the requirements, realization, and maintenance of such systems have been managed largely using documents that are only human readable. Model-based systems engineering (MBSE) tries to change this practice by using machine-readable models instead of these traditional rich-text documents [16]. SysML is a standardized systems modeling language to enable MBSE [17].

SysML is an extension of the Unified Modeling Language (UML), which is well-known in software engineering. Fig. 5 shows the relationship between UML and SysML using a simple Venn diagram. SysML defines additional diagrams, which are not contained in UML. These diagrams capture requirements and parameters that enable engineers to represent complex requirements, and to link them to systems simulation and analysis programs such as SIMULINK and MODELICA. SysML Version 1.3, which was released recently, has been implemented by several leading systems engineering software vendors.

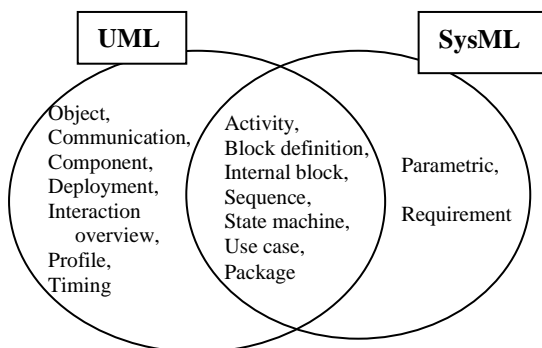


Fig. 5. Relationship between UML and SysML diagrams.

SysML is closely related to ISO STEP AP233 [18], which deals with systems engineering. ISO STEP AP233, in turn, has several common features with ISO STEP AP239 [19] that deals with product life-cycle support, which is of considerable interest to through-life engineering services. Therefore, we turn to that next.

3.4 Product life cycle support

Product Life Cycle Support (PLCS) [20] is the domain of ISO STEP AP239. At the minimum, PLCS provides standardized representations for product configurations during various phases of a product lifecycle (e.g., as-designed, as-built, and as-maintained). But, it provides much more. PLCS also deals with in-service support

requirements (hence the connection to model-based systems engineering in Section 3.3), and related resources such as maintenance plans, schedules, job cards, and work request/orders. In fact, recent versions of PLCS are defined using UML/SysML.

The relationship between STEP AP233 (Systems Engineering) and PLCS is shown in Fig. 6, where some of the functionalities of these two standards are also outlined. It is clear that these two standards share considerable capabilities.

PLCS has found strong support in the defense sector, where sustainment of weapon systems is paramount. Several pilot implementations of PLCS by major defense contractors are underway [21]. But the capabilities of PLCS extend far beyond defense applications. Section 5 outlines a scenario in a generic manufacturing plant floor (i.e., not restricted to the defense sector) that can benefit from the PLCS capabilities.

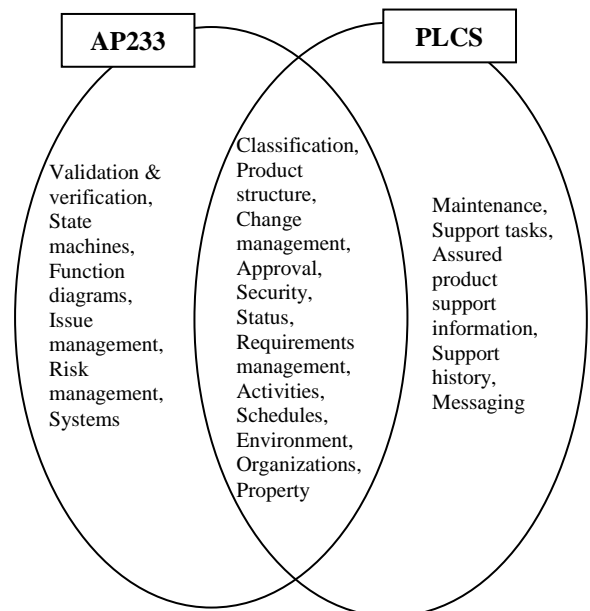


Fig. 6. Relationship between ISO STEP AP233 and PLCS.

3.5 MTConnect

Smart manufacturing systems need smart machines and devices. However, machines and devices are typically designed to function independently with limited intelligence. Consequently, coordinated intelligence is even more difficult. MTConnect is an open standard [22] to enable intelligence to be built on top of existing machines. Applications of MTConnect have enabled more efficient manufacturing production and through-life engineering processes by providing machine-readable data to intelligent applications.

MTConnect is developed by the MTConnect Institute for networking manufacturing devices and applications. It allows device data including subcomponents information,

measurements, and events to be uniformly communicated to applications such as Manufacturing Operation Management (MOM), Performance Diagnosis and Prognosis (PDP), and predictive (e.g., condition-based) maintenance. MTConnect standard is relatively easy to use because it relies on the popular HyperText Transfer Protocol (HTTP) and XML standards to deliver data.

Fig. 7a shows the types of data that may be provided by an *MTConnect* device. Fig. 7b shows a hierarchical machine structure and available data (in *DataItem*); the *Component* and *DataItem* can be cascaded into multiple levels in a hierarchy as necessary. The *DataItem* specifically describes the *Streams* (in Fig. 7a) available to the client. The *Streams* is a set of *Samples*, *Events*, or *Condition* for components or devices.

The *Samples* is a set of measurement values (e.g., temperature, spindle position) at a time point determined by a measurement frequency. The *Events* are discrete changes in a device's state, while the *Condition* indicates health and ability of a device to function such as *Normal*, *Warning*, *Fault*, or *Unavailable*. Multiple *Faults* and *Warnings* may be reported for a single data item while only a single value can be reported for *Samples* and *Events*. *Assets* are mobile equipment that can be moved from one device to another such as cutting tools and fixtures.

MTConnect defines four services for clients to retrieve the data: *probe*, *current*, *sample*, and *asset*. The 'probe' service provides the *Devices* data. The 'current' and 'sample' services provide the most recent read and a time-window-based *Streams* data, respectively. The 'asset' service provides *Assets* data. As new versions of MTConnect are developed, more components, data items, and assets can be added to the standard.

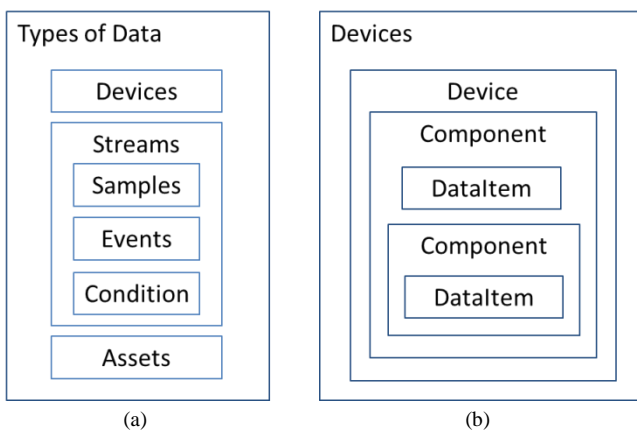


Fig. 7. (a) Types of data in MT Connect; (b) Device data structure.

4. Service-oriented architecture

Standards, such as those described in Section 3 and others, have been useful in enabling interoperability among disparate engineering software systems. But the trend is to regard the functionalities provided by these software systems as services. This trend has accelerated recently with

the arrival of cloud computing, which virtualizes computing and communication resources.

Service-oriented architecture (SOA) aims to achieve a distributed, loosely-coupled environment such as a cloud-based offering of software components. In the service-oriented paradigm, software components are viewed as providing functionalities through services that are independently owned. Services are virtualizations of software components. That is, service consumers do not need to know how service providers offer their services – from where, by which, or by how many software components.

The service-oriented paradigm emphasizes visibility and semantics that enable (1) the matching between needs and capabilities, and (2) the composition of capabilities to address those needs. The visibility and semantics are enabled by service descriptions and service contracts that capture the essential information the service consumers and providers need to be aware of and agree upon.

SOA is commonly implemented using Web Services, which refer to a suite of standards from multiple standard development organizations; these standards include Web Service Description Language (WSDL) [23] and Business Process Execution Language (BPEL) [24]. However, such services may also be implemented using other strategies. Recently, SOA implementation using Representational State Transfer (REST), also known as RESTful Web Services, has gained widespread acceptance [25]. The RESTful implementation is regarded as simpler and easier to use than the WSDL-based counterpart.

Although SOA provides the paradigm and technology to enable dynamic composition of engineering information services, it is not itself a solution to domain-specific problems. The following section describes a through-life engineering service scenario to illustrate how several engineering information services can be composed using SOA to provide a domain-specific solution.

5. Composing services

Any engineering information system can provide a service. An important question we should ask is whether such services can be composed to provide a bigger service that matters to a customer. In addition, we should ask how quickly such a composition can be put together or modified in a dynamic industrial and business environment. The best way to answer these questions is (1) to gather realistic scenarios from customers for existing or anticipated problems, and (2) to test the hypothesis of dynamic service composition on these scenarios through experimentations with service-based solutions. Consider the following scenario that describes a service call affecting a production line in a manufacturing plant [26-28]:

“A fault from an Electrical Control Unit (ECU) for the motors powering the plant's central conveyor line is detected by a Performance Diagnosis and Prognosis (PDP) system, which monitors and brokers all critical plant equipment over the plant's wireless local area network (WLAN). An 'event' notice is instantly dispatched to a

Manufacturing Operations Management (MOM) system, where an operations manager uses a Decision Support system to determine if the fault is a false alarm, a new alarm, or a recurring problem. The motor's calibration and instrument reading, also monitored by PDP and SCADA (Supervisory Control And Data Acquisition) systems via the WLAN, confirms that the fault is real. PDP has compared the ECU's signal history with the manufacturer's specifications; and, while it remained within performance limits, PDP determined that it is likely to fail soon.

"Plant operators issue a high-priority work order through MOM, alerting an on-duty field technician to the problem via a Smart Phone message. The technician uses his (mobile) tablet to review the work order, identify the ECU's unit number, physical location, safety notifications and a brief description of the fault type.

"MOM automatically prepares an audit report of the ECU's previous maintenance and performance. MOM determines from its ERP (Enterprise Resource Planning) system interface that there is no warehoused replacement ECU. However, a direct query of the ECU manufacturer finds another vendor's part that is equivalent. There also is a field performance upgrade that improves the current ECU's operational characteristics.

"Meanwhile, the technician locates the faulting ECU and takes the motor off-line by locking out its power system, a standard safety procedure appearing in his tablet's checklist. The technician also uses his tablet to access the vendor's PLM (Product Lifecycle Management) system to retrieve design specification, installation, configuration, and testing procedures. He notices an optional, performance-enhancement service bulletin and compares output signals with the failing ECU. After consulting with Operations, he applies the optional upgrade to bring the conveyor motor back into a no-fault operating condition.

"The technician downloads the performance package to the ECU along with the vendor's recommended testing and startup procedures. The installation and pretest are quickly completed. He refers to the standard restart procedures and brings the conveyor back on line. Then, the ECU is monitored locally to ensure that the startup sequence has not stressed the ECU or motor beyond performance standards.

"The technician uploads the ECU's operational history and diagnostic outputs at the time of the fault. The ECU's manufacturer will investigate the circumstances to determine if there is a fundamental design flaw. The service request is closed out and standard operations resume."

The scenario described above illustrates several key ideas. Humans play important supervisory and collaborative roles; but, humans should not be required to reenter information that already resides in a trusted source. Also, humans should not be required to read and interpret textual or graphical information. That information should be represented in a machine-readable form that can be interpreted quickly and correctly by a computer. These are some of the key elements of smart manufacturing. In a realization of smart manufacturing, the reader can envision

the automation of several processes that are manually carried out in the scenario outlined above.

Implementing even this relatively simple scenario as a valuable composite process involves several engineering information systems whose services need to be composed. It is highly unlikely that one single software vendor or organization will be able to provide all the engineering information systems, and integrate those using proprietary data and interfaces.

The trend is to use standardized data, such as those described in Section 3, and standardized service interfaces using SOA as described in Section 4. As the scenario indicates, such data can come from different PLM, ERP, MOM, and SCADA systems. Considerable data analytics are also employed to monitor equipment health, diagnose problems, and suggest corrective actions. These data and systems are now moving to clouds, and the scenarios are changing fast to reflect demanding business needs. Hence, we face the urgent need for dynamically composing these engineering information services in the cloud.

6. Summary and concluding remarks

In the current era of digitization of manufacturing, also known as smart manufacturing, engineering information systems play a central role. No single software vendor or organization can provide all the necessary software and services. Therefore, proprietary data and interfaces are no longer a viable option to serve the lifecycle and supply networks of complex, long-lived products. Hence, standards have assumed an important role.

In this paper, we described some of the standards that have been created, or upgraded recently, to meet the demands of smart manufacturing. These standards are based on information models with representations that are machine readable. By avoiding human interpretations and interventions as much as possible, costly and time-consuming errors can be avoided.

With the aid of service-oriented architecture, these standards also enable composition of engineering information services to meet more complex and fast changing engineering and business needs. We have already seen some success in deploying such services in industry; but, many challenges remain before we can realize the full potential.

Cloud-based engineering information services are still in their infancy. Breaking the proprietary hold on data and interfaces still remains a problem in manufacturing. As open standards for data and interfaces become more popular, innovative entrepreneurs will use them to open up new markets. This is especially important for small- and medium-sized companies who cannot afford costly solutions. We need more software technologies and tools to define and compose the engineering information services in manufacturing, which places a higher premium on timeliness and reliability. So, we also need a better communication infrastructure (e.g., more deterministic Ethernet), and better cyber security for both wired and wireless communication.

Acknowledgements and a disclaimer

We thank our colleagues in several standards development organizations involved in developing and upgrading the standards described in this paper. We are especially grateful to Dr. Albert Jones (NIST) for his timely reviews and comments on several drafts of this paper. Any mention of commercial products is for information only; it does not imply recommendation or endorsement by NIST.

References

- [1] McMahon C, Ball A. 2013. Information systems challenges for through-life engineering. 2nd International through-life engineering services conference, *Procedia CIRP* 11, 1-7.
- [2] Srinivasan V, Lämmer L, Vettermann S. 2008. On architecting and implementing a product information sharing service. *Trans. ASME JCISE*, Vol 8.
- [3] Srinivasan V. 2011. An integration framework for product lifecycle management. *J of CAD*, Vol. 43, pp. 464-478.
- [4] The Economist. 2012. April 21 issue on the Third Industrial Revolution.
- [5] Recommendations for implementing the strategic initiative INDUSTRIE 4.0. 2013. Securing the future of German manufacturing industry. Acatech, Germany.
- [6] Rometty V. 2013. The year of the smarter enterprise. *The Economist*, The world in 2014 edition.
- [7] Advanced manufacturing portal. <http://manufacturing.gov>
- [8] STEP AP242 project. <http://www.ap242.org>
- [9] Barnard Feeny A, Freschette S, Srinivasan V. 2014. A portrait of an ISO STEP tolerancing standard as an enabler of smart manufacturing systems. 13th CIRP Computer Aided Tolerancing Conference, Hangzhou, China.
- [10] Long term archival and retrieval. <http://www.lotar-international.org>
- [11] Hunten K, Barnard Feeny A, Srinivasan V. 2013. Recent advances in sharing standardized STEP composite structure design and manufacturing information. *J of CAD*, Vol. 45, pp. 1215-1221.
- [12] Open Applications Group. www.oagi.org
- [13] ISO 15000-5: 2014. Electronic business extensible markup language (eBXML) – Part 5: Core components specification (CCS), Geneva, Switzerland.
- [14] MESA International. Business to Manufacturing Markup Language. www.mesa.org/en/B2MML.asp
- [15] Fraunhofer cloud computing for logistics. www.ccl.fraunhofer.de/en.html
- [16] Model Based Systems Engineering Wiki. www.incosewiki.org.uk/Model_Based_Systems_Engineering/index.php?title=Main_Page
- [17] Systems Modeling Language. www.omg.sysml.org
- [18] ISO 10303-233: 2012. Industrial automation systems and integration – Product data representation and exchange – Part 233: Application protocol: Systems engineering, Geneva, Switzerland.
- [19] ISO 10303-239: 2012. Industrial automation systems and integration – Product data representation and exchange – Part 239: Application protocol: Product life cycle support, Geneva, Switzerland.
- [20] Product life cycle support. plcs-resources.org
- [21] UK MOD and PLCS. www.eurostep.com/news/plcs-implementation-made-easier-by-uk-mod-sponsored-project.aspx
- [22] MTConnect standard version 1.2.0. www.mtconnect.org/getting-started/developers/standards.aspx
- [23] Web Services Description Language. www.w3.org/TR/wsdl20-primer
- [24] Business Process Execution Language. docs.oasis-open.org/wsbpel/2.0/Primer/wsbpel-v2.0-Primer.html
- [25] Representational State Transfer Web Services: The basics. www.ibm.com/developerworks/webservices/library/ws-restful
- [26] Srinivasan V. 2009. Sustaining manufacturing assets through smarter utilization of information and communication technologies. 5th Annual IEEE Conference on Automation Science and Engineering, Bangalore, India, Aug. 22-25. Pp. 478-482.
- [27] Popko E, Luyer E. 2009. Asset management to support product lifecycle management (PLM) – leveraging asset management to benefit PLM projects. IBM White paper.
- [28] Ouertani ZM, Srinivasan V, Parlikad AK, Luyer E and McFarlane D. 2009. Through-life active asset configuration management. 6th International Conference on Product Lifecycle Management, University of Bath, Bath, U.K.