EL Program: Systems Integration for Manufacturing and Construction Applications (SIMCA)

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Strategic Goal: Smart Manufacturing, Construction, and Cyber-Physical Systems

Summary: The world is experiencing a digital renaissance, which is changing manufacturing in dramatic ways. It will soon be possible to perform all manufacturing activities using digital data models instead of drawings. If these data models were provably correct, easily exchanged, and computer interpretable, they could improve productivity significantly across the entire production network. Nevertheless, test methods and tools to prove correctness do not exist, standards to facilitate model exchange are still being developed, and software applications to interpret and use those standards are too expensive for most network partners. The SIMCA program is developing measurement science to remove those barriers.

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DESCRIPTION

Objective: To develop and deploy advances in measurement science for integration of engineering information systems used in complex manufacturing and construction networks to improve product and process performance by 2016.

What is the problem? The Third Industrial Revolution is underway and it is driven by digital information[1]. This Third Industrial Revolution is fundamentally changing manufacturing by enabling a transformation to digitized manufacturing – where 3D digital data models replace traditional 2D drawings and documents. This transformation will make possible a new vision for manufacturing called *Smart Manufacturing*[2]. Smart manufacturing can rapidly change the global competitive landscape by marrying industrial automation with information technology (IT) to optimize the efficiency of factories and manufacturing supply networks[3]. Smart manufacturing uses digital data models and intelligent decision-making software to optimize resource utilization, improve time to market, and reduce costs.

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[1] "The Third Industrial Revolution," *The Economist*, April 21, 2012
[2] "Implementing 21st Century Smart Manufacturing," *Smart Manufacturing Leadership Coalition*, June 2011.
[3] "Insourcing American Jobs: The Importance of Smart manufacturing, Broadband, and IT," Aneesh Chopra, www.whitehouse.gov, January 14, 2012.

Implementing smart manufacturing is proving to be difficult because formal methods and critical standards for making optimal use of digital information are not in place. Integrating advanced materials and new production processes requires effective use of large quantities of manufacturing data and sophisticated data processing[4]. New information models are needed for smart manufacturing especially when it comes to the information needed for advanced manufacturing processes such as composites and additive manufacturing. Smart manufacturing relies on provably correct information models traceable to standards. The transformation from document-based practice to model-based practice will not be complete until data models can be validated using formal mathematical methods. The measurement science needed to develop formal mathematical methods to standardize and validate manufacturing data models is lacking. The SIMCA program *Digital Manufacturing Research Thrust* will focus on research to enable formal standard representations for digital manufacturing information.

Only a handful of engineering software applications can use and exchange digital models. These applications are expensive and require substantial training – making them prohibitive for small manufacturers. Open standards for digital manufacturing data are needed to give users affordable choices for engineering software. This is especially a problem for small manufacturers (SMEs) since OEMs (original equipment manufacturers) are starting to require their suppliers to use data models in all interactions. Current approaches to integration do not work for software applications used by U.S. SMEs. The measurement science needed to define manufacturing supply chain service models for integrating SMEs is lacking. The *Manufacturing Services Research Thrust* will conduct research to enable new service-based interface mechanisms for manufacturing.

Why is it hard to solve? For the *Digital Manufacturing Research Thrust*, measurement science barriers exist in all phases of the manufacturing life cycle beginning with product requirements. Currently, requirements are captured in a number of different text-based documents. Resolving these differences is difficult, but essential to creating accurate data models. These data models are critical to the execution of all life-cycle processes – the first of which is systems engineering. Systems engineering uses product requirements to create models of high-level design requirements. Current languages for creating those models cannot represent complex relationships typical of new manufactured products. [5,6]

Standards for 3D data-models exist, but formal methods and tools to prove correctness exist for only a few of those standards. Furthermore, standards to represent non-geometric data such as material specifications and other annotations are being developed without a sound mathematical foundation. The situation for composites and additive manufacturing processes is far different. Proprietary geometric and material data models exist for composites; but users cannot share them. A design data model for additive manufacturing exists, but it has known deficiencies.

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[4] "A National Strategic Plan for Advanced Manufacturing," *Executive office of the President National Science Technology Council*, February 2012.

[5] "INCOSE Systems Engineering Vision 2020," Available at http://www.incose.org/ProductsPubs/products/sevision2020.aspx.

[6] "Systems-2020 Study, Final Report," *Booz Allen Hamilton*, 16 August 2010. Available at http://www.acq.osd.mil/se/docs/BAH-Systems-2020-Report-Final.pdf.

The hard problem in the *Manufacturing Services Research Thrust is* small manufacturers need easy to use, low-cost software applications to process complex digital data models. Vendors who develop applications for SMEs traditionally provide no automated integration mechanisms because there are no agreed upon open standards. A new approach will be needed to create a simplified service interface that satisfies data requirements for manufacturing.

How is it solved today, and by whom? The measurement science problems that inhibit development and deployment of information systems for smart manufacturing have not been solved. While there are examples of smart manufacturing elements within some companies, these have limited factory and supply chain effectiveness. Product requirements originate from many groups. Each group describes requirements from its own viewpoint, and usually in text-based document forms. These forms are subject to interpretation; and, agreement on their exact meaning requires substantial negotiations. Agreement is necessary because these forms are the major input into the systems engineering process. To date, that process also has been mostly a manual, document-based process. A standardized systems modeling language called SysML is being used to develop digital data models of requirements. Where they exist, these models have enabled automation of some systems engineering processes.

The outputs from systems engineering drive all downstream manufacturing processes. Companies that specialize in machining are moving toward standard, 3D product models and away from blueprints. Since that transition is ongoing, these companies are forced to employ a hybrid, error-prone, approach that combines 3D models, drawings, and other documents. Companies doing composites or additive manufacturing still use the stereo lithography (STL) standard. However, STL has several limitations; i.e., it cannot represent detailed product properties. A new ASTM F42 standard, addresses these limitations. It was released in 2011, but to date only a few commercial products support it.

Most SMEs have computer-aided design (CAD) systems that can accept standardized product models. A small, but growing percentage of SMEs use those models directly to drive their operations. Most SMEs still create drawings from 3D digital models, which takes time and causes errors. Most software applications require manual entry of data contained in drawings and other documents.

Why NIST? NIST has the statutory authority under the Enterprise Integration Act[7] to work with the private sector to pursue the technical activities in this program. White House reports identify NIST as a key implementing agency for advanced manufacturing[8]. The SIMCA program is aligned with the EL mission to promote U.S. innovation and competitiveness by anticipating and meeting the measurement science, standards, and technology needs of U.S. manufacturing industries. EL is in an excellent position to leverage its strong ties to U.S. industry and standards development organizations to address the measurement science barriers mentioned above. EL has the needed technical expertise and an international reputation for excellence in the technical areas of manufacturing systems integration.

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[7] Public Law 107-277 (116 Stat. 1936-1938), known as the Enterprise Integration Act
[8] "A National Strategic Plan for Advanced Manufacturing," *Executive office of the President National Science Technology Council*, February 2012.

What is the new technical idea? The new technical idea for the *Digital Manufacturing Research Thrust* is all manufacturing information is encoded in the form of digital data models (no documents or drawings). These models will be formal mathematical representations of manufacturing information and will be directly processible by software applications. The new technical idea for the *Manufacturing Services Research Thrust* is to enable small manufacturers to use these digital data models by creating service interfaces for the manufacturing supply chain. These service interfaces will allow SMEs to use lower cost software to process digital manufacturing data from their OEM customers.

In the future, all manufacturing life-cycle information will be represented, simulated, and visualized as digital data models. The *Digital Manufacturing Research Thrust* focuses on the measurement science barriers impeding the transition from documents to those digital models. The SIMCA program will develop the scientific foundations needed to speed that transition. These foundations will facilitate the development of standards, test methods, and tools needed to ensure that accurate data models are available throughout the entire manufacturing lifecycle. These models include requirements models, product information models, and process simulation models. Some of these models have been standardized, many have not. For those already standardized, the SIMCA program will develop the measurement science needed to develop validation, conformance, and interoperability test methods and tools. For those not yet standardized, the SIMCA program will develop the measurement science needed to ensure that the resulting standards are mathematically sound and provably correct.
To be viable partners in future production networks, SMEs must have access to software applications that can use digital data models to drive their manufacturing processes. These applications must be able to accept, input, modify, and, when necessary, output models to other network partners. The *Manufacturing Services Research Thrust* will develop the measurement science needed to develop a new integration mechanism based on apps-like manufacturing services. A service-based structure is a very powerful enabler. Internet and software-based services, by their nature, are designed for integration. A "service" is defined by its interface specification and pre-defined integration methods are part of the service itself. A service combines an IT interface with a manufacturing resource. The interface uses a service description language to define resource capabilities and the input-output specifications needed to use that resource. Existing apps-like services are designed to be hardware independent making them easier to deploy. The SIMCA program will develop the architectures and measurement science needed to implement this new apps-like service integration mechanism at both the factory and the network levels.

Why can we succeed now? New White House and Department of Commerce reports have reiterated the importance of manufacturing in the United States[9,10]. New U.S. investments in manufacturing initiatives have been proposed. Recent reshoring efforts have caused manufacturing companies to make substantial investments as well. These same companies recommend an increased use of data models as a way to facilitate integration, improve productivity, and manage complexity. Many of these companies are willing to collaborate with

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[9] "The Benefits of Manufacturing Jobs," *The U.S. Commerce Department's Economics and Statistics Administration*, May 9, 2012
[10]"Capturing Domestic Competitive Advantage in Advanced Manufacturing," *Executive Office of the President President's Council of Advisors on Science and Technology*, July 2012.

public/private consortiums, and are already participating in a number of relevant standards development activities. The software industry is investing in "3D only" processes. Many small software companies are developing software products to accept the open standards for model data. 3D modeling technology and integration methods have matured significantly in the last 5 years. Additionally, new members in the manufacturing workforce expect to work with 3D modeling applications.

What is the research plan?

Digital Manufacturing Research Thrust

The *Collaborative Requirements Engineering (CRE) Project* will develop formal methods for representing customer requirements and test the use of these methods in industry use cases. "Formal" implies the existence of a mathematical foundation for characterizing the validity and completeness of the data models generated by the methods. The models developed in the CRE project will provide requirements for both systems engineering and model-based engineering. The *Systems Engineering (SE) for Smart Manufacturing Project* uses CRE models to generate high-level design requirements. The systems engineering community has begun to develop standard modeling languages for representing these requirements as digital data models. Current languages cannot capture all of the complex relationships typical of manufactured products. This project will develop new modeling constructs with mathematical foundations necessary to extend those languages to meet the needs of smart manufacturing.

The *Model-Based Engineering (MBE) Project* will make critical technical contributions to the standardization of Product and Manufacturing Information (PMI) models and develop methods for testing their implementations. This information is critical for automating optimization of smart manufacturing of high-quality parts. The MBE project provides major inputs to the EL Smart Manufacturing and Construction Controls (SMCC) program, which is developing foundations for smart factory optimization. The *Product Information for Composite and Additive Manufacturing Project* (PICAM) will develop measurement science to improve the quality of the data models that drive advanced manufacturing processes. The project will focus on composite-structures manufacturing and metal-based additive manufacturing. These processes are fundamentally different, but share a common 3D model data structure in that they are layered, non-uniform processes that can combine multiple materials in a single part. Both processes require very thin geometry objects that can cause data model quality problems. The project will develop the measurement science (models, metrics and tools) for assessing process data integrity. These tools will be developed in partnership with commercial application providers to ensure broad deployment. This work will be done in close cooperation with the EL Smart Manufacturing Processes program.

Manufacturing Services Research Thrust

The *Manufacturing Services Network Models (MSNM) Project* will develop the measurement science needed for new service-based standards that facilitate rapid supplier integration. These new standards will enable the seamless exchange of data models involved in interactions between OEMs and suppliers. Those exchanges involve suppliers providing their manufacturing services – including material processing and information processing capabilities. The *Smart Factory Architecture (SFA) Project* will work with SMCC program to define and demonstrate an architecture, based on services, that supports factory optimization. This architecture will support a new integration mechanism for accessing and using engineering apps. The architecture will marry ideas from service-oriented architectures with ideas from hierarchical control theory. The architecture will also specify the interfaces between the two.

How will teamwork be ensured? The SIMCA program relies on contributions from a variety of partners, both internal and external to the Engineering Laboratory. Each project is working with experts from both U.S. industry and academia to achieve project objectives. Regularly scheduled meetings of those teams are included in the project plans. Where appropriate, the program will have formal cooperative agreements with academic partners. To encourage collaboration among the NIST Smart Manufacturing programs, program managers will hold meetings with project leaders to identify shared measurement challenges. SIMCA projects are closely coordinated with the projects in the Smart Manufacturing Control Systems program. Project plans include tasks that require internal EL collaborations and collaborations with other NIST Laboratories. SIMCA projects include cooperative research tasks with both NIST ITL and NIST PML. Regular meetings with project leaders will enable coordination between project teams.

What is the impact if successful? Work being conducted under the SIMCA Program will result in the adoption of new measurement science and critical manufacturing information standards. It will advance industry practice from documents to models and increase the productivity of U.S. manufacturers. There are over 330,000 manufacturers in the U.S.; 86% of these are small manufacturers. Many of the technical barriers faced by U.S. small manufacturers today are information barriers. Eliminating these barriers will enable U.S. SMEs to compete more effectively.

Critical standards for systems engineering and digital manufacturing will improve productivity and time to market. New measurement science to assess the trustworthiness of engineering data will reduce errors and time wasted on redundant activities. Prawel[11] estimates that up to 50% of engineering time is wasted manually validating data. New manufacturing service models will enable U.S. SMEs to use digital manufacturing processes. This will result in faster integration of SMEs into U.S. supply chains and more opportunities to compete for manufacturing work.

What is the standards strategy? The top standards needs for SIMCA *Digital Manufacturing Research Thrust* are new data exchange standards for model-based engineering, new product manufacturing information (PMI) standards, and extensions to systems engineering standards to include manufacturing. A top standards priority for the manufacturing industry is alignment of new PMI standards with new manufacturing data exchange standards. One standard defines the PMI data representations and a different standard defines the data exchange format. The top standards need for the *Manufacturing Services Research Thrust* is information models for defining service-based manufacturing interfaces for supply chain integration.

Digital Manufacturing Research Thrust

For model-based engineering, NIST will provide critical PMI models and testing results needed to complete ISO 10303 AP242 “Managed Model Based 3D Engineering.” The leading engineering software systems used by U.S. manufacturers are implementing this standard. A new version of this standard is expected in 2013; new PMI models developed by NIST provide a

[11] Prawl, David, “Lost in Translation,” *Mechanical Engineering,* September 2011.

basis for aligning this new standard with ASME PMI standards. As industry moves beyond traditional manufacturing, NIST will provide technical input to new standards for composites and additive manufacturing. NIST staff members are currently working on an ASTM 42 committee developing new standards for additive manufacturing.

For product manufacturing information (PMI), NIST will work with ASME, ISO, and key industry stakeholders. A number of standards are in various stages of development both at ASME and ISO. We are making critical technical contributions to these standards, and are serving in leadership positions on several committees. Current contributions include new measurement tools to determine conformance to the ASME and ISO tolerancing standards. These tools are critical to future deployment of these standards. These tools will be completed for ASME by FY14 and for ISO by FY15.

To advance manufacturing extensions to systems engineering standards, the SIMCA program will continue its leadership roles in both INCOSE and OMG, which are the leading systems engineering organizations. The systems engineering standard that is having the most impact is the SysML standard. SIMCA staff are leading one of the committees for SysML and the program is making technical contributions to several other OMG standards that are needed for implementing SysML.

Manufacturing Services Research Thrust
NIST has initiated a new working group at the Open Applications Group (OAG), a U.S.-based standards organization. This working group will develop and architecture and standard for manufacturing service capability information to enable digital communication of manufacturing information for production and data processing.

How will knowledge transfer be achieved? Knowledge will be transferred to U.S. industry, the research community, and standards organizations. SIMCA program staff routinely report program results to manufacturing industry organizations including the Automotive Industry Action Group, the Aerospace Industries Association, and PDES, Inc. Where appropriate, SIMCA staff will hold workshops with participants from leading U.S. industry organizations. Software tools developed by the program will be made publicly available. The SIMCA program conducts joint research with leading U.S. academic institutions. Project teams train research associates – post docs, guest researchers, visiting professors, and students. Program staff will publish articles in technical journals and present research results at broad-based manufacturing conferences. Program staff will take the results of their research to the appropriate standards development organizations. Measurement knowledge gained in the area of PMI conformance testing will be transferred in the form of standard test cases and testing services.

MAJOR ACCOMPLISHMENTS

Outcomes:

- Achieved EL 2012 Priority Budget Objective. Model-Based Engineering Enterprise: New draft international standard to support manufacturing enterprise data exchange developed in partnership with industry.

- Committee Draft standard published (ISO 10303 AP242 – Managed 3D Model-Based Engineering). The new standard enables model-based engineering and removes barriers for U.S. small manufacturers.
- New ISO product and manufacturing information (PMI) standards (10303-1052 and 1051) published. NIST delivered new information models that encode manufacturing information into new ISO standards for 3D model-based engineering.
- The Object Management Group released a new version of the SysML standard based on NIST research. NIST delivered information models for defining components used to engineer complex systems (SysML enables conversion of graphical representations of systems engineering into a formal language that can be processed by software).
- The Object Management Group established an interoperability-testing program based on software compliance assessment tools developed by NIST.
- Industry consortium members used product manufacturing information (PMI) test models and testing tools developed by NIST to validate commercial engineering software.
- Commercial engineering software vendors used the NIST STEP File Analyzer to detect errors in manufacturing data exchange files.
- Draft ISO standard for terminology for complex systems (ISO 15926 Part 6 – Lifecycle data) published. NIST led the U.S. industry review of this standard.
- Commercial engineering software companies used 3D tolerancing test models developed by NIST to identify non-conformance to ASME geometric and dimensional tolerance standards. Tolerance errors can cause costly rework and scrapped parts.

Recognition of EL:

The Systems Integration Division received an Outstanding Contributing Organization Award from the Open Applications Group. Allison Barnard Feeney and Peter Denno received an INCOSE award for their work developing information standards for systems engineering.