EL Program: Systems Integration for Manufacturing and Construction Applications

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

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Summary: U.S. manufacturing faces significant challenges because of global competition and the loss of high-tech jobs. Improved productivity in creating innovative, high-tech products is critical to meeting these challenges. The strategy for making improvements involves a rapid transformation from isolated islands of automation to highly integrated production networks. The potential increase in productivity from a successful transformation is great. However, current systems integration technologies and standards are no longer adequate to meet new network integration requirements. The SIMCA program will develop the measurement science needed to meet those requirements. Major outputs include new standards, validation methods and tools, conformance test methods and tools, and measurement techniques. The program is composed of six projects in three thrust areas. The thrust areas are Engineering Applications Integration, Production Network Systems Integration, and a cross-cutting thrust on Manufacturing Data Quality Measurement. The projects will address fundamental integration barriers in model-based engineering, systems engineering, production network information flow, and data quality measurement.

EL Program: Systems Integration for Manufacturing and Construction

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

Objective: To develop and deploy advances in measurement science for integration of engineering information systems that enable productivity and agility improvements in complex manufacturing and construction networks by 2017.

What is the problem? Manufacturers today use sophisticated software applications to facilitate new product creation and production network management. These applications, and the supporting manufacturing knowledge-base form the foundation for "Smart Manufacturing"[1]. Smart manufacturing has the potential to (1) significantly increase competitiveness of U.S. manufacturing by improving the agility and productivity of U.S. companies; and (2) increase the number of high-quality jobs[2] and long-term wealth generation for the U.S. economy[3]. To realize these benefits, production network applications must exchange information and knowledge seamlessly and without errors. A comprehensive infrastructure to enable such exchanges does not yet exist[4]. Major challenges to implementing a complete smart manufacturing infrastructure include better production network integration, greater affordability for small manufacturers, and more effective engineering systems interoperability[1,5].

Production networks are become increasingly dynamic, increasingly complex, and require increasingly more sophisticated information integration. They now execute all functions in the product life cycle including design, engineering, fabrication, and maintenance. They, not OEMs, are the major source of innovation in the United States. Productivity improvements, therefore, must occur at the production-network level. To realize these improvements, networks must deliver innovative, high-value products faster, cheaper, and better than their competitors.

Partners in these networks are no longer just suppliers of components, parts and assemblies. They also provide design, engineering, and logistics services. To provide these services, partners must consume, produce, and often exchange large amounts of information while adding value to products. Unfettered and efficient information integration across production networks, therefore, is essential to achieve breakthrough productivity improvements. This level of integration and information flow, however, is not achievable given (1) the current state of integration standards and testing technologies and (2) the rapid change of engineering applications that use them.

As noted above, the second major challenge is the continued evolution of cyber-physical products. The complexity of these products is beginning to surpass the ability of designers and

[1] *Implementing 21st Century Smart Manufacturing*, Smart Manufacturing Leadership Coalition, June 2011.
[2] *Ensuring American Leadership in Advanced Manufacturing*, The President's Council of Advisors on Science and Technology, June 2011.
[3] Tassey, G., *R&D and Long-Term Competitiveness: Manufacturing's Central Role in a Knowledge-Based Economy*, National Institute of Standards and Technology, 2002.
[4] *Implementing 21st Century Smart Manufacturing*, Smart Manufacturing Leadership Coalition, June 2011.
[5] *Ensuring American Leadership in Advanced Manufacturing*, The Presient's Council of Advisors on Science and Technology, June 2011.

engineers to fully characterize and control their behavior[6]. Design and engineering processes are evolving and the software applications associated with them are adding new capabilities to meet the complexity challenge. Since these processes and applications are now distributed across the production network, maintaining the quality of the required information is a top most concern. Finding and correcting quality problems can cause substantial delays in bringing products to market – negatively impacting productivity and cost. According to a Gartner Research Report[7], 25 % of Fortune 1000 companies have such problems resulting in total annual losses of several billion dollars.

The lack of measurement science (including new standards, validation methods, conformance tests, and measurement techniques) for integrating production networks is a substantial barrier to implementing smart manufacturing and realizing breakthrough productivity improvements. The lack of new science-based standards and tools to integrate engineering applications limits the effective use of smart manufacturing tools and applications. New measurement science is needed to integrate applications across multiple engineering disciplines to design and analyze complex cyber-physical systems. A lack of measurement science to standardize and communicate systems engineering requirements causes substantial delays in bringing new products to market.

Why is it hard to solve? To substantially increase the productivity of production networks, manufacturers need to optimize engineering processes from concept through production. As noted above, those processes are executed collaboratively by partners distributed across the network. These partners have different views of those processes and use different software applications to support those views. The evolution to smart manufacturing, however, requires better alignment of these views and seamless integration of engineering knowledge into these applications. Meeting these requirements in an environment where partners join and leave networks regularly is a new challenge. To date, existing process and integration standards, and the technologies that implement them, have been unable to meet this challenge. Simple changes to these standards and technologies will be insufficient. Therefore, new modeling languages and standards for representing and exchanging engineering knowledge are needed. Methods and tools to validate and test implementations of these new languages and standards are also needed. Finally, new approaches are needed to ensure that the quality of engineering knowledge is preserved across partners, processes, and applications.

How is it solved today, and by whom? Existing standards have been implemented in numerous engineering software applications. Conformance-testing methods and tools developed by NIST have been very effective in reducing the implementation costs of these standards. However, many of these standards are incompatible and, hence, integration is hampered. Moreover, since the maturity level of integrated production networks varies across different industry domains, the rate of standards adoption and tool use is domain dependent[8]. As noted above, these standards and tools no longer meet evolving industry requirements. NIST is working with industry groups, software vendors, and other government agencies to develop the necessary measurement science underpinnings for new standards and test methods. But, that work is in the early development

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[6] *Systems Engineering Vision 2020*, International Council on Systems Engineering, INCOSE-TP-004-02, 2007.
[7] Gartner Business Intelligence Report (ISBN 0-9741571-1-2) , www.gartnerpress.com, 2004.
[8] M. Mallett, D. Stieren, *MBE Supplier Capabilities Assessment & Potential Certification Development*, MBE Education & Training Summit, Battle Creek, MI, May 26th, 2010

stage. NIST has developed tools for integrating selected standards, but more work is needed to develop an integration architecture that is more broadly applicable.

Why NIST? NIST has the statutory authority under the Enterprise Integration Act[9] to pursue the technical activities in this program. Moreover, its objective is closely 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 industry, standards development organizations, and public-private initiatives in systems engineering and cyber physical systems to achieve that objective. In fact, EL researchers already hold leadership position on committees developing manufacturing information standards, systems engineering standards, new modeling languages, and conformance tests. Additionally, EL's industry partners have requested NIST's help to develop validation, conformance, and interoperability testing methods and tools for those standards. By law[9], NIST is directed to work with the private sector to advance enterprise and systems integration to address the needs of U.S. manufacturing industries. EL has the needed technical expertise and an international reputation for excellence in the technical areas of manufacturing systems integration as a result of over three decades of technical work and collaboration with industry partners that will make use of the program results.

What is the new technical idea? The program is organized into three major thrust areas, each focusing on specific technical barriers. The emphasis of the work is to enable productivity improvements in advanced production networks through the development of science-based standards and measurements. The new technical ideas are described for each of the thrust areas below:

<u>Engineering Application Integration Thrust:</u> New research is being applied to the integration of engineering processes and the software applications that implement them. This work focuses on using a core data model (the set of data that completely defines a product) as the driver for all engineering and production processes. The core data model serves as the integrated source of requirements and knowledge for engineering applications. That model replaces traditional paper drawings. It provides a means for understanding, recording, and communicating requirements and knowledge in computer processable formats. As the complexity of cyber-physical products grows, testing requirements using physical production prototypes becomes increasingly impractical. The alternative is to use structural and behavioral models as virtual prototypes, embodying the accumulated engineering knowledge, and advanced simulation tools to evaluate those models against requirements. This approach is known as model-based systems engineering. This thrust will develop the measurement science needed for successful implementation of that approach.

<u>Production Network Systems Integration Thrust:</u> Manufacturing supply chains are quickly evolving into dynamic, global, production networks. As noted above, engineering processes are executed collaboratively by partners distributed across these networks. The seamless flow of engineering requirements and knowledge across these networks, therefore, is essential. Integration of the software applications that produce, consume, and use requirements and knowledge is still a major problem. This thrust will develop the underlying measurement science

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[9] Public Law 107-277 (116 Stat. 1936-1938), known as the Enterprise Integration Act

for (1) new architectures and standards that improve productivity and integration across production networks and (2) new methods and tools to validate and test these architectures and standards.

Engineering and Production Network Data Quality Thrust: New model-based systems engineering approachs will be implemented in production networks. Individual engineering processes will be executed by various partners in that network. Those processes and their associated technologies exchange and modify requirements, knowledge, and models – simply and collectively referred to as “data”. Ensuring the quality of that data – no errors are introduced as it moves from process to process - is a major problem. The principal reason is that data quality cannot be defined or measured in isolation. It must be defined and measured within the context of specific processes and technologies. Having standard rules for defining and science-based metrics for measuring data quality can prevent an organization from wasting time and resources on faulty data. This cross-cutting thrust will develop the measurement science needed to define those rules and compute those metrics. Several projects (see below) will contribute to this thrust.

Why can we succeed now? New White House and Department of Commerce reports have reiterated the importance of manufacturing in the United States[10]. Manufacturing industry workshops and roadmaps have identified engineering system integration as necessary for increasing productivity and controlling system complexity. Recently, a series of costly failures[11,12] have (1) heightened the importance of successful integration and new approaches for systems engineering and (2) increased the awareness of the benefits of data quality validation model-based engineering. As a result, industry is motivated. Additionally, more powerful information modeling languages are maturing, new systems engineering approaches have been proposed, technologies; and, new integration technologies are being developed.

What is the research plan? The program will develop the measurement science needed to enable productivity improvements in two areas:, manufacturing productivity, and production network agility. The program will use key performance indicators (KPIs) to drive resarech and standards development. An important method for measuring and improving manufacturing productivity is key performance indicators. Key performance indicators are quantitative measurements used to determine the performance of manufacturing enterprises and are the basis for productivity improvement planning. By evaluating how KPIs are calculated, requirements for new standards or improvements to underlying infrastructure can be identified. KPIs vary by industry sector. Several commonly used manufacturing KPIs are given below.

Productivity
- Time to Market
- Production Rate/Cost
- Sales per Employee
- Inventory Turns

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[10] US Department of Commerce, Manufacturing in America: A Comprehensive Strategy to Address the Challenges to U.S. Manufacturers, 2004.
[11] N. Schwartz , “Big plane, Big Problems,” Fortune, March 1 2007
[12] S. Holmes, “The 787 Encounters Turbulence,” Business week, June 19, 2006

Agility

- Percent Products Launched on Time/Budget
- Percent R&D Cost for New Products
- Supplier Lead Time
- On-Time Delivery by Supplier
- Percent Purchases from Certified Suppliers

NIST's past work has led to successful product data standards adoption, but that success has been limited to integration of computer aided design and computer aided manufacturing applications. The SIMCA program will expand to standards that have broader application to systems engineering and product lifecycle views – including concept, analysis, simulation, supplier integration, and product lifecycle management. The program will develop measurement science needed for emerging new work in the areas, such as, systems engineering and cyber-physical systems.

The program will be implemented in a phased approach. Projects in year one will focus on fundamental R&D for systems engineering, new standards integration architectures, new data models for critical infrastructure, and new theories for measuring manufacturing data quality. Projects in years two and three will build on this fundamental work by developing and validating new standards and new measurement tools. In years four and five the focus will be specific industry applications. The plan for each thrust area follows.

<u>Engineering Application Integration:</u> The *Systems Engineering Standards Project* will build on work done in FY11 in the *Model-Based Engineering Project* to develop the foundation for standardizing systems engineering models (FY12-14). New systems engineering standards and applications will be tested in pilot projects with partners from industry and academia (FY15). *The Model-Based Engineering Project* will develop fundamental product data models and standards needed to communicate production data efficiently across production networks. The project will focus on the development of a new standard for design information and product life-cycle support information (FY12), new standards for product manufacturing information (PMI) (FY12), and new techniques for PMI model validation (FY13-14). Based on input from our industry partners, the project will also develop tools for measuring product model quality (FY14). These tools will be developed in partnership with commercial application providers (predominately small businesses) to ensure ongoing support.

<u>Production Network Systems Integration:</u> The *Manufacturing Services Specification Project* will begin development of supplier capability models (FY12) that will serve as a basis for enabling agile, service-based production networks. The project will build on results from the *Model-Based Engineering Project* to develop new architectures for service-based supply networks (FY13) and begin testing these architectures to improve production network productivity (FY14). The *Collaborative Requirements Engineering Project* will begin development of methods for requirements representation (FY12) and demonstrate a framework for collaborative specification of design and production requirements. The *Cross-Standards Interoperability for Production Networks Project* will develop tools to capture mappings that facilitate harmonization between such interfaces and provide for mediation between systems that use them. The project will also

reuse and integrate the architecture and tools developed by the *Engineering Data Quality Measurement Project* in order to evaluate and test these mappings

Engineering and Production Network Data Quality: The *Engineering Data Quality Measurement Project* will complete the development of new data quality measurement techniques (FY12), which were started in FY11. These techniques will be evaluated using data from manufacturing supply chain scenarios. If successful, the project will continue in FY13 to refine these techniques and develop data quality measurement tools (FY13-14).

Each of the program thrusts includes an economic analysis of how the proposed work can improve productivity, agility and impact on manufacturing competitiveness. The analysis will first develop comparative statistics on the U.S. manufacturing industry. Second, it will identify and prioritize the manufacturing measurement science topics under the SIMCA program that will yield the largest potential return on investment in technology-intensive manufacturing sectors. These prioritized measurement science topics will be used to select one or more SIMCA projects for a future economic impact study. And third, the program will define metrics, tools, and data for measuring physical infrastructure delivery performance and productivity with a focus on how such measures can be developed.

How will teamwork be ensured? The projects that make up the SIMCA Program will involve EL staff and numerous outside partners from industry and academia. Projects will establish relationships with relevant industry consortia, professional society technical committees, and standards development organizations. Each project has specific plans for coordination and information exchange among participants. These plans include details for internal EL collaborations and also interactions with industry. Regular meetings with project leaders will enable high-level coordination and information exchange between project teams.

What is the impact if successful? The SIMCA program will contribute to measurable increases in production network productivity in manufacturing. Program impact will be measured by the use of NIST results in the development of new standards, the adoption of standards by engineering application providers, the use of standards by industry, and the observation of productivity trends in various manufacturing sectors. The program will also work with the NIST Manufacturing Extension Partnership Program to measure small business productivity in advanced production networks.

The following are the goals for program impact: 1) Increased productivity as a result of time savings from new standards for model-based engineering integration that are widely adopted by engineering software application developers; 2) reduced costs for SMEs by providing integration options for lower cost engineering software applications rather than the high end higher cost applications used by OEMs; 3) time savings and reduced risk for manufacturers and application developers by using NIST measurement tools to measure conformance to national and international standards for manufacturing information; 4) increased adoption of open standards for systems engineering data that increase the productivity of systems engineers and allow the aggregation of new and more powerful analysis tools for complex systems; 5) improved data quality that results in reduced costs and time to market for new products. New data quality measurement science will provide a computational basis for evaluating data quality and preventing errors that were previously not detectable, thus preventing costly manufacturing mistakes and substantial rework time.

Impact of Standards.

The ISO standard for 3-D model-based engineering (ISO STEP AP242) will provide new capabilities needed to represent design and manufacturing data in a standard format. The capabilities will include new manufacturing features, material specifications, manufacturing tolerance and quality control information, support for annotations, and support for data validation. Testing is underway and publication as an ISO committee draft is scheduled for FY12. Wide adoption of AP242 among engineering software application developers is expected based on adoption of the ISO standard that is being replaced by AP 242. The new capabilities in AP242 will lead to reduced cycle time from design to production. It will also lead to reduced costs for the SMEs involved in that production since SMEs will be able to use lower cost software applications based on standard interfaces rathe than the high-end high cost applications used by OEMs.

Conformance tests for ASME and ISO geometrical product specifications will be developed by NIST in FY13. These tests will be used by application developers to insure that commercial applications implement the standards correctly. Tests and testing tools will save development time and reduce risk for application developers and provide assurance for users purchasing those applications.

Major upgrades to systems engineering standards will support creation and maintenance of consistent models across multiple engineering disciplines and the various stages of systems development. These will significantly increase productivity and innovation in the systems development process. Tools for testing commercial implementations of systems engineering standards will be used by software application developers to speed both development and deployment and by standards organizations to increase the reliability of the standards development process.

What is the standards strategy? The SIMCA program's standards strategy is to focus on those critical standards that facilitate increases in the productivity, efficiency, and agility of production networks. As part of that strategy, SIMCA program actively engages with industry partners to determine requirements, identify gaps, prioritize participation, and evaluate proposals for high priority standards. SIMCA program staff collaborates with industry and standards development organizations to develop, validate, test, and implement high priority standards. EL staff members conduct fundamental research, develop new methodologies, build software tools, and conduct joint demonstrations in support of those standards. High-priority standards identified by the SIMCA program include new standards for model-based engineering (MBE), systems engineering (SE), production network modeling, and engineering data quality.

Engineering Application Integration thrust

New standards for model based engineering and systems engineering are needed to reduce the cycle time for product development and manufacturing.

Substantial extension of existing international standards for product design and manufacturing data exchange is needed to add new capabilities for exchanging manufacturing information including quality control and material information. Industry requirements identified by Aerospace Industries Association Long Term Archival program, PDES, Inc. members survey, and DoD Model Based Engineering workshop held in December 2010. Revised standard needed by FY12 (ISO STEP AP242 Model Based Engineering).

Next generation product manufacturing information (PMI) language standards (ISO and ASME) are needed to more accurately communicate design intent, manufacturing process data, and quality control information. Existing PMI standards are dated and do not support new 3D modeling practices, new manufacturing processes, or advanced measurement technology, such as, coordinate measurement machines (CMMs) and laser scanning. Initial ISO standard needed by FY13.

Harmonization of existing systems engineering standards for systems engineering modeling (OMG SysML) and systems engineering data exchange (ISO STEP AP233) is needed to build effective computational models of systems and build them more efficiently. Accurate computational models are critical for predicting product behavior and modeling manufacturing processes prior to production. Identifying problems during the the design phase will help avoid costly redesign during manufacturing or product recalls. Revisions to standards needed by FY13.

Enancements to a representation language for systems engineering (OMG SysML) and extensions for OMG UML (Unified Modeling Language, a parent language of SysML) are needed to meet industry goals for improved systems engineering modeling for cyber physical systems design. Enhancements will include additional data types and relationships. Revisions to these standards are needed by FY14.

Production Network Integration thrust

A typical manufacturing network looks very different than a typical business network environment when it comes to the diversity of data and the total number and variety of systems. The application diversity present at a single engineering and manufacturing location can easily exceed the number of applications in the business enterprise[13]. If cross site diversity is included, the complexity of the manufacturing quickly exceeds the corporate network environment. With this diversity, the need to provide commonality and standard interfaces is critical to leverage data from multiple systems. Standards needed to improve production network efficiency and agility are in early development. Improvements in production network interactions will reduce production and inventory costs and allow for increased product customization.

Requirements for standards to support production network services are needed by the end of FY12. The need is to determine requirements for sufficient infrastructure (standards) to support a market for manufacturing services that will enable increases in manufacturing productivity and lower supply chain costs. The program will develop use cases and reference

[13] Castro, S. *Manufacturing Service Oriented Architecture (SOA) Current and Future Strategy*, SAP Labs, SAP Community Network, 2009.

architecture for manufacturing services, identify standards and service oriented manufacturing business patterns, and analyze standards gaps and build roadmap.

Production network service information models are needed to define standard system interfaces by FY13. Production network information models will be derived from the infrastructure requirements and will be used to develop new standards. New standards to support information-based production network services are needed by FY14.

Engineering Data Quality thrust

Engineering data quality is a pervasive and cross-cutting problem in industry today. Data quality has been identified as a major barrier to improving manufacturing productivity. Data quality refers to the degree of completeness, validity, consistency, timeliness and accuracy that makes data appropriate for a specific use. Data are of high quality if they are fit for their intended use in operations and planning. In science and engineering, data are deemed of high quality if they correctly represent the real-world constructs to which they refer (i.e., the model of a manufacturing process accurately represents the behavior and output of the process). As data is used in more than one system, the question of internal consistency of data becomes paramount. Changes to data in one system must be propagated to any other system where there is a copy of the data. The SIMCA program is developing and testing new methods for quantifying the quality of engineering design models and manufacturing data.

Requirements for product model validation are needed to develop more effective tools to measure design data quality. Requirements will be in the form of well defined executable rules for two manufacturing data model usage scenarios – (1) model suitability for direct use in manufacturing processes and (2) derivative model equivalence to the master model. Requirements needed by FY12.

Extension of an existing ISO standard for product data quality (ISO STEP Part 59) is needed to provide a basis to develop new tests and measurement tools to effectively validate product data. Product data quality in the context of computer aided design (CAD) is defined as defects in the product model that would effect the accuracy of the model or effect ability of other applications to use the model. Examples include geometric anomalies which impede reuse of models in analysis or manufacturing processes; unrealistic modeling features requiring changes during model reuse; and unacceptable changes introduced during translation, migration, archiving or manual remastering. Extensions needed by FY13.

New measurement tools are needed by FY13 to determine conformance of engineering software applications to the American Society of Mechanical Engineers (ASME) and ISO standards for manufacturing tolerance information. These tools will provide an important conformance testing capability that has been lacking for these standards. Conformance tests and testing tools for the next generation of ASME and ISO tolerance standards will be need by FY15.

A new methods needed to provide a computational basis for data quality measurement of non-geometry product data. Methods for comparing text-based data and methods for evaluating text that is not identical, but may have consistent meaning. New measurement methods needed by FY14.

How will knowledge transfer be achieved? Knowledge and results from the program will be disseminated through technical contributions to industry standards, testing services for standards developers and users, archival journal articles, conference proceedings, NIST web resources, and downloadable software tools. The program will interact with critical stakeholders through participation in manufacturing industry consortiums, standards development organization technical committees, technical conferences, industry workshops, and inter-agency working groups. Guest resarchers from U.S. industry and post-docs from U.S. universities will allow exchange of experience and knowledge. Customer feedback is monitored by EL management and key stakeholders are supportive of NIST research. NIST works collaboratively with PDES, inc. to develop engineering data integration standards. NIST has leadership positions on ASME committees developing produc manufacturing information standards.

Major Accomplishments

Actual Impact:
An ISO standard for computer-aided design, STEP AP203 ed2, led by NIST, is currently being used by manufacturers and suppliers to exchange product design and manufacturing information. This standard is used by over 68% of U.S. small suppliers to receive manufacturing data from their customers[14]. Recently, U.S. aircraft manufacturers began using this standard to deliver digital-only aircraft design data to the Federal Aviation Administration. Digital-only delivery of aircraft design data reduces errors and saves significant time and cost by eliminating duplicative paper-based delivery mechanisms.

To reduce costs, the defense industry is moving from traditional engineering and manufacturing processes based on drawings to new processes based on 3D digital models. Work done by NIST on measuring design data quality is being used to improve the quality and reliability engineering data models. The capability to measure the quality of technical data reduces errors and improves efficiency of transferring data between engineering and manufacturing systems. A pilot study[15] by the U.S. Army, NIST, and participants from industry concluded that DoD can reduce lead times, error rates, and costs significantly for replacement parts by using data quality measurements prior to releasing manufacturing data to suppliers. Since most DoD suppliers also manufacture non-defense products these same benefits can be realized in non-defense sectors.

The initial version of the systems modeling language standard (SysML) has been broadly implemented and is used by systems engineers to improve the productivity of the systems development process. NIST-developed conformance tests and testing tools have been used by the major software tool vendors, users, and standards organizations to improve the quality of implementations of the standard. The OMG Model Interchange Working Group is using NIST tools to provide the capability to assess quality of XML data files. The tool identifies potential errors in UML or SysML files.

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[14] Stieren, D., *MBE Implementation Throughout the DoD Supply Base*, MBE Education & Training Summit, Chambersburg, PA, November 4, 2010

[15] Parimi, S., *3D Technical Data Packages and the DOD*, MBE Supplier Education & Training Summit, Manufacturing Innovations 2011 Conference, Orlando, FL, May, 2011.

Outcomes:

Made critical technical contributions to the development of ISO systems engineering standard (ISO STEP AP233). Served as editor on ISO committee responsible for the standard. Standard published by ISO.

Developed test framework for OMG systems engineering standard (SysML).

Devloped and tested new product manufacturing information models (ISO STEP part 503). Standard published by ISO.

New processes and infrastructure developed at NIST put in place for ISO SC4 standards to improve cycle time and quality control.

New metrics for engineering data quality measurement developed and tested as part of a joint project with the DoD Mantech program. Project outputs used by Army to improve quality of technical data packages for hard to source parts.

Recognition of EL:

Allison Barnard Feeney and Peter Denno received an INCOSE award for their work developing information standards for systems engineering.

Conrad Bock received an INCOSE award for his work developing a systems engineering modeling language.

Peter Denno received a NIST Bronze Medal for exceptional technical leadership and contributions to a new digital system for tracking logistics information in global automotive supply chains

Peter Denno received an Automotive Industry Action (AIAG) Outstanding Achievement Award for substantial contribution and leadership of supply chain standards development.