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Investigating the Impact of Standards-Based Interoperability for Design to Manufacturing and Quality in the Supply Chain

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National Institute of Standards and Technology
Gaithersburg, MD 20899

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Executive Summary

To achieve the industry vision of a Model-Based Enterprise (MBE), the MBE strategy must include model-centric data interoperability for design to manufacturing and quality in the supply chain. Even though there has been a move in industry to become model-centric, today there is still significant manual intervention in the supply chain to go from product design to manufacturing and quality inspection. The ISO 10303 Standard for the Exchange of Product Model Data (STEP) data standard can minimize much of the manual intervention. The majority of STEP implementations have been primarily focused on CAD-to-CAD and long-term data archival. Significant opportunity exists for STEP-based CAD-to-CAM and CAD-to-CMM data exchange.

The vision for this project was developed following a survey of small and medium enterprise (SME) suppliers. Despite being in the digital age, a large percentage of SME suppliers still receive OEM designs as full-detail-2-dimensional (2D) drawings or as a combination of 3-dimensional (3D)-shape-geometry models plus 2D drawings containing the product and manufacturing information (PMI). A large percentage of suppliers must either completely remodel the part or manually add the PMI to the imported shape-geometry model. Much of the CAD industry has implemented STEP AP242 with embedded PMI, reducing the need for drawings. The same degree of implementation has not occurred in the CAM and CMM industries. This project demonstrates the value of improved CAD-to-CAM and CAD-to-CMM data interoperability using STEP AP242 with embedded PMI.

This project was developed to investigate high-payback use cases in the supply chain and identify opportunities of model-centric standards-based data exchange to:

- Eliminate or reduce significantly the need to re-create downstream models,
- Reduce cycle time and cost,
- Reduce the risk of introducing downstream errors,
- Increase part yield, and
- Produce higher quality parts.

The project team consisted of an OEM, supplier, system integrators, as well as CAM and CMM system providers. The NIST Engineering Laboratory provided direction and guidance for this standards-based data exchange demonstration. Three data exchange scenarios were compared in the investigation:

- Full-detail-2D drawing
- 3D-shape-geometry model and a 2D drawing containing the PMI
- 3D model with embedded PMI

Metrics were established to assess the cycle time for CAD, CAM, and CMM model creation and the ease of data interoperability in each data exchange scenario. The results were compared and observations shared by the project team. There was clear cycle time advantage demonstrated with the use of a 3D model with embedded PMI for CAD-to-CMM data interoperability. Gaps were identified in tools, standards and interfaces, PMI-feature coverage, modeling knowledge, and best practices.

This project demonstrates the benefits of standards-based product-data interoperability in the supply chain for CAD-to-CAM and CAD-to-CMM. It also identifies gaps to be addressed to enable industry to achieve its MBE vision of becoming model-centric. This project can help industry push for commercialization of the demonstrated capability and achievement of the MBE vision.

Project Team

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Introduction

> ***The challenge:*** *Given industry's vision of MBE, why is model-centric data interoperability not more prevalent for design to manufacturing and quality inspection?*

The Model Based Enterprise

To achieve the industry vision of the model-based enterprise (MBE), the MBE strategy must include model-centric data interoperability for design to manufacturing and quality in the supply chain. The model-based definition (MBD) is created by the OEM using computer-aided-design (CAD) tools. This information is then shared with the supplier so that they can manufacture and inspect the physical parts. Much of the supply base consists of small and medium enterprise (SME) manufacturers. Today, almost all suppliers use computer-aided-manufacturing (CAM) and coordinate-measuring-machine (CMM) models respectively for these tasks. Traditionally, design data is provided by the OEM to supplier in the form of full-detail-2-dimensional (2D) drawings. More recently the data has also included a 3-dimensional (3D)-shape-geometry model. This shape-geometry model is often provided in a standards-based format, STEP AP203 is most prevalent. In addition to shape-geometry, the CAM and CMM processes require product and manufacturing information (PMI) to fabricate and inspect the part.

A Reliance on Drawings

Model-based exchange has primarily focused on CAD-to-CAD data interoperability and long term data archival. Even with the drive for industry to become increasingly model-centric, there is still significant manual intervention when going from OEM to supplier with product design for manufacturing and quality inspection. In part, this is due to the fact that the STEP AP203 model provides only shape geometry and does not contain the PMI necessary for CAM and CMM models and machine programs.

Despite the industry MBE vision to become model-centric and the model-based hype from major CAD suppliers, there is still a reliance on 2D drawings. A survey[1] of SME suppliers shows that many of those surveyed still receive design data from their OEM customer in the form of full-detail-2D drawings. Another large group receives a 3D-shape-geometry model combined with a 2D drawing containing the PMI. Only a small percentage of the SME manufacturers receive just a 3D model with embedded PMI. The design to manufacturing process is still very much drawing-centric. The very few data exchanges that are model-centric with embedded PMI use proprietary, not standards-based models.[2]

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[1] Hartman, N., Fischer, K., & Rosche, P. (May 21-23, 2012). Successfully Engaging Small and Medium Enterprises. *3D Collaboration and Interoperability Congress*. Englewood, CO.
[2] NIST MEP. (November 22, 2009). *Phase One Final Report - Assessment of Supplier Capabilities to Operate in a Model-Based Enterprise Environment*.

The Promise of STEP

Development of ISO 10303 Standard for the Exchange of Product Model Data (STEP) started in 1984. Its objective is to provide a mechanism that is capable of describing product data throughout the life cycle of a product, independent from any particular system. The nature of this description makes it suitable not only for neutral file exchange, but also as a basis for implementing and sharing product databases and archiving.[3]

STEP is developed with a series of integrated data models known as application protocols (AP's). There are dozens of STEP AP's, which can be roughly grouped into the three main areas design, manufacturing and life cycle support.

Today STEP AP203 *Configuration Controlled 3D Design* is still one of the most important parts of ISO 10303 and is supported by many CAD systems for import and export. According to another survey of SME suppliers, STEP AP203 is the most commonly used format for CAD-to-CAD data interoperability.[4] But, the STEP AP203 model contains only shape geometry, and not the PMI necessary for downstream processes.

In December 2014 ISO published the first edition of a new major application protocol, STEP AP242 *Managed Model Based 3D Engineering*, which combined and replaced the following previous AP's in an upward compatible way:

- AP201 *Explicit Draughting* (simple 2D drawing geometry related to a product with no association and no assembly hierarchy)
- AP202 *Associative Draughting* (2D/3D drawing with association but no product structure)
- AP203 *Configuration Controlled 3D Designs of Mechanical Parts and Assemblies*
- AP204 *Mechanical Design Using Boundary Representation*
- AP214 *Core Data for Automotive Mechanical Design Processes*

In addition, STEP AP242 edition 1 contains extensions and significant updates for geometric dimensions and tolerances, kinematics, and tessellation. In other words, STEP AP242 offers standards-based models with embedded PMI – exactly what is needed for model-centric downstream CAM and CMM processes.

An Impact to Cycle Time and Quality

With the continued reliance on full-detail-2D drawings or even 3D-shape-geometry models, a significant amount of time is spent recreating the product model or adding PMI data to an existing shape model. This significantly affects cycle time. Furthermore, there is an increased risk of error from incorrect or

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[3] ISO/TC 184/SC 4. (1994, December 15). ISO 10303-1:1994. *Industrial automation systems and integration -- Product data representation and exchange -- Part 1: Overview and fundamental principles*. International Organization for Standardization.

[4] Hartman, N., Fischer, K., & Rosche, P. (May 21-23, 2012). Successfully Engaging Small and Medium Enterprises. *3D Collaboration and Interoperability Congress*. Englewood, CO.

missing data when recreating or enhancing models for downstream purpose, potentially affecting model and part quality.

In the survey mentioned earlier, SME manufacturers reported spending 2-4 hours adding PMI to a simple CAM model. They also reported spending twice that time, 4-8 hours, adding PMI to the CMM model.[5] For more complex parts, an automotive engine block for example, the recreation of information for CAM and CMM might take weeks after receiving the OEM 2D drawing or 3D-shape-geometry model.

Barriers to Model-Centric Data Interoperability

Even with the introduction of STEP AP242, what keeps industry from moving toward the MBE vision? Especially, why can't industry achieve a vision that includes model-centric data interoperability when going from design to manufacturing and inspection across the supply chain? In the team's opinion, some of the barriers that keep industry from being more model-centric include:

- The 2D drawing is still considered the master versus the 3D model by many in industry.
- There is a significant learning curve to effectively embed PMI into a 3D CAD model.
- Many application program interfaces (API's) do not adequately support downstream processes due to lack of PMI.
- Major product lifecycle management (PLM) tool providers are concerned with losing market share due to easy data exchange through standards-based implementations.
- The CAM and CMM markets are distributed across many SME manufacturers and there is no significant aggregation of industry that drives CAM and CMM providers to implement standards-based solutions.

Opportunity for a Standards-Based Solution

> ***The hypothesis:*** *The ACIS and Parasolid modeling kernel can support CAD-to-CAM and CAD-to-CMM using STEP AP242 to exchange model-based definition with embedded PMI, reducing cycle time while improving model and part quality.*

This project team composed of Aerospace and Defense industry members, along with several CAD, CAM, and CMM solution providers, discussed possible approaches to more effectively enable model-centric data exchange for CAD-to-CAM and CAD-to-CMM. Many CAM and CMM systems are based on the ACIS®[6] modeling kernel and can already ingest model geometry and PMI data through their respective API's. They also ingest standards-based model geometry via STEP AP203. So, why can't they ingest standards-based PMI data now that STEP AP242 is available? Wouldn't this model-centric data

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[5] Hartman, N., Fischer, K., & Rosche, P. (May 21-23, 2012). Successfully Engaging Small and Medium Enterprises. *3D Collaboration and Interoperability Congress*. Englewood, CO.

[6] ACIS is a registered Trademark of Spatial Corporation.

exchange offer significant improvement in cycle time, model quality, and part quality? Can it be demonstrated that STEP AP242 minimizes much of the manual intervention and provides significant opportunity for standards-based CAD-to-CAM and CAD-to-CMM data interoperability? Lastly, could this demonstration plant a seed with the CAM and CMM industries to further commercialize STEP AP242 implementations?

This project will test the hypothesis that model-based data interoperability from CAD-to-CAM and CAD-to-CMM is practical and that there is significant value in implementation of STEP AP242 as a standards-based solution. The project will answer the questions of feasibility and value through demonstration and measured results. It will also provide for discussion and recommendations based upon the findings and observations. Finally, the project will draw conclusions toward the pursuit of industry's vision of the Model Based Enterprise and the feasibility of standards-based model-centric data interoperability.

Motivation for the Study

With a supported hypothesis, the team believes this project will motivate industry in its drive to achieve

> ***The motivation:*** Demonstrate the value of model-centric CAD-to-CAM and CAD-to-CMM data interoperability using STEP AP242 with embedded PMI.

the vision of the Model Based Enterprise. The goal of this project was to demonstrate the value of model-centric CAD-to-CAM and CAD-to-CMM data interoperability when using STEP AP242 with embedded PMI. The anticipated benefits from this standards-based approach between the systems and across the supply chain include:

- Eliminating or reducing significantly the need to re-create part models,
- Reducing cycle time and cost,
- Reducing the risk of introducing downstream errors,
- Increasing part yield, and
- Producing higher quality parts.

The technology developed by this project is extensible to include PMI-data items beyond those used in the project test models. The CAD, CAM, and CMM applications can successfully exchange more complex parts than the test models used in this project.

This project demonstrates the applications have achieved Technology Readiness Level (TRL) 6 and industry is pushing for further technology maturity. The current TRL scale runs from level 1 to 9. TRL 1, the least mature technology readiness level, is the state when basic research ideas are taking the first steps toward practical application. TRL 9 is the most mature technology readiness level and the product is in full production use. TRL 6 is the maturity level where a prototype capability is represented in a simulated operational environment. Organizations will typically begin to adopt technology as it achieves TRL 7 or higher. A full list of the TRL definitions is given in Appendix C.

Demonstrating the technology readiness for CAD-to-CAM and CAD-to-CMM data-interoperability provides motivation to commercialize tools that provide standards-based 3D models with embedded PMI to the CAM and CMM industry. Likewise, the CAM and CMM tools providers should be motivated to commercialize the ability to receive and utilize the standards-based 3D models with embedded PMI.

As the identified gaps in current tools and standards are addressed to achieve this level of commercialization, and the process and skill gaps are overcome by industry users, the opportunity to improve efficiency and effectiveness across the product lifecycle will be provided in design, bidding and quoting, manufacturing, inspection, and collaboration across the supply chain.

Method

Approach Outline

To test the hypothesis, the following approach was used:

- Consider the use cases creating or utilizing CAD, CAM, and CMM data.
- Develop metrics to compare results of current versus future model-centric processes,
- Map model-based PMI requirements to STEP AP242, map STEP AP242 to ACIS geometric modeling kernel, and identify gaps that hinder broad solution deployment,
- Develop prototype software to demonstrate data interoperability between CAD, CAM, and CMM tools using standards-based STEP AP242 models with embedded PMI,
- Test the current and future model-centric processes using representative industry part designs,
- Validate the CAM and CMM models against the original CAD model for any data loss during transformation and any missing CAM or CMM information,
- Refine the test cases and software following an analysis of the initial results, and
- Collect and analyze the metrics data to determine benefits associated with the process change.

Considering Use Cases

Various product lifecycle use cases were investigated as the project team explored how the benefits described earlier might manifest across the product lifecycle. The use cases were organized into two categories: (1) use cases that affect the OEM and (2) use cases that affect the supplier. Ultimately, a partial set of the use cases (those best aligned to the scope of this project) were used to define the project metrics and demonstrate the differences between current-state and future-state processes. Below is a description of the use cases that define and affect the metrics for this project. Appendix A includes the broader set of product lifecycle use cases discussed by the team, including those beyond the scope of this project.

OEM Use Case

CAD Model Creation

This use case centers on the creation or authoring of the CAD model. Traditionally, the 3D-shape-geometry model is created without embedded PMI. Once the shape-geometry model is generated, a drawing is created, and typically presented in 2D PDF format. It includes the PMI that is not part of the 3D-shape-geometry model. In the past, the 2D drawing was fully detailed and could be used by itself to manufacture the part. In more recent practice, a 3D-shape-geometry model and a 2D-partial-dimension drawing are required. The partial-dimension drawing contains only the PMI that is not embedded in the shape model. In the current-state scenarios either the full-detail drawing or the combination of the shape model and the partial-detail drawing is required for manufacturing processes. In the future-state process designers will create a 3D model with embedded PMI such that the model will completely support the manufacturing and inspection processes.

CAD Validation and Verification

This use case involves validation and verification of design intent, model correctness, and producibility. Persons with the appropriate subject matter expertise review the design at points in the lifecycle to determine that it meets design intent, follows best drawing or modeling practices, and meets desirable producibility expectations. The traditional way of visually inspecting drawings, and more recently models, does not always work. With model-based design it is not possible for a human (visual) inspection of the model to detect all issues. As a result, rules-based systems have been introduced to automate the process, especially for model and producibility analysis. In addition to analyzing the construct of a unique model, it is also necessary to compare two different models when data exchange occurs. This ensures the original design intent is correctly transferred to the downstream model, such as when a model is exchanged between design and manufacturing or inspection.

Supplier Use Cases

CAM Model Creation

The CAM-programming use case focuses on the import of a STEP AP203 model for the shape-geometry. The 2D drawing is referenced for the PMI not embedded in the model. In addition, the manufacturing specifications that are referenced in the drawing are also reviewed to determine additional machine programming and secondary operations.

CMM Model Creation

The CMM-model use case utilizes the 2D drawing and the STEP AP203 model to create the CMM model. All the PMI is manually entered into the CMM application. The demonstrated future-state directly imports the embedded PMI from a STEP AP242 model.

CMM Inspection

The CMM-inspection use case requires a significantly manual and time-consuming process to generate the first article inspection report. The inspector must review the CMM results and manually input the information into a spreadsheet that conforms to AS9102 FAI report standards.

Defining Metrics

The project team defined a set of metrics to understand the impact of more comprehensive model-based interoperability. The metrics for the use cases provide a way to compare the current state and future state of part design, manufacture, and inspection. The metrics support the investigation of the benefits and challenges of data interoperability when using 3D models with embedded PMI for downstream purpose. These metrics include cycle time, model quality, part quality, and cost. Table 1 provides the target metrics for each use case.

Table 1: Project use case and defined metrics

Use Cases	Metrics			
	Cycle Time	Model Quality	Part Quality	Cost
at OEM				
CAD model creation	X	X		
CAD validation and verification (design intent; model correctness; producibility)	X	X		X
at Supplier				
CAM programming	X	X		
CMM programming	X	X		
CMM inspection	X		X	

Cycle Time Metrics

The cycle-time metric measures the time to complete each use-case step and is a key to the project investigation. The use cases were divided into a discrete set of steps for the operator to record the time it took to complete the step.

Model Quality Metrics

Model quality includes completeness as well as comprehensiveness. One metric compares the number of PMI elements found in the models. The PMI data types are broken down by dimension, tolerance, datum feature, and notes (with no semantic data). This metric provides visibility into model quality and how well the data is translated from native CAD to STEP AP242, to ACIS, and ultimately to the CAM and CMM models. As each data model exchange occurs, the PMI elements for the models were compared for completeness and comprehensiveness.

Part Quality Metrics

Part quality metrics indicate when the part does not match the design intent. They are found through CMM inspection and documented in the FAI report. The metrics indicate the clarity of information, report generation, etc.

Cost Metrics

While cost is a derivative metric for many use cases, the actual base metric in most of those cases is the cycle-time to complete the process. Thus, cycle-time is the metric of focus. Cost is, however, the base metric directly affected in part validation, procurement and bidding processes. Cost is identified as a metric with direct impact on the accuracy of the bidding process. It also comes into play during a producibility reviews when considering design aspects that actually drive an increase or decrease in part fabrication costs.

OEM Metrics

The OEM metrics captured for part design include CAD modeling and validation as shown in Table 2.

Table 2: OEM metrics

OEM Process	Current-State Process (Metrics)	Future-State Process (Metrics)
CAD model creation	Create geometry model and PMI drawing (cycle time, model quality)	Create fully constrained model with embedded PMI (cycle time, model quality)
CAD model validation	Semi-manual validation (cycle time, model quality, cost)	Automated validation (cycle time, model quality, cost)

In particular, cycle time metrics were captured during the creation of the 3D model, 2D drawing, and embedded PMI. For this project, metrics were also captured and observations recorded for model issue resolution and designer education with regard to embedded PMI practices. Lastly, metrics were captured for the time required to understand and resolve issues discovered about 3D models with embedded PMI as the data was imported into the CMM system.

Supplier Metrics

The supplier metrics for part manufacture and inspection involves CAM and CMM programming, machining, and inspection as shown in Table 3.

Table 3: Supplier metrics

Supplier Process	Current-State Process (Metrics)	Future-State Process (Metrics)
CAM programming	Import part shape into CAM, manual addition of PMI (cycle time, model quality)	Import part shape and embedded PMI into CAM (cycle time, model quality)
CMM programming (input)	Import part shape into CMM, manual addition of PMI (cycle time, model quality)	Import part shape and embedded PMI into CMM (cycle time, model quality)
CMM Inspection (output)	Manually create inspection programming (cycle time, part quality)	Automate CMM inspection programming (cycle time, part quality)

The metrics captured for part manufacture includes cycle-time to import the shape-geometry data into the CAM system. The current-state process also captured the metrics for the manual addition of PMI, while the future-state process used embedded PMI directly from the 3D-model import.

The metrics captured for part inspection includes cycle-time to import the shape-geometry data into the CMM system. The current-state process also captured the metrics for the manual addition of PMI, while the future-state process used embedded PMI directly from the 3D-model import. Metrics and insight were captured during the learning curve and issue resolution for importing embedded-PMI models into the CMM system.

Create the Test Models and Data Sets

The project team reviewed five part designs submitted by Rockwell Collins as candidates for the test models. The team selected two of the parts as the test cases for this project. These were based upon the model features and also considered how each part would be machined and inspected given the geometric dimension and tolerance (GD&T) callouts. Furthermore, the team added new features to the models to test additional machining and inspection criteria.

The first part chosen was a rolled standoff shown in Figure 1. The design was altered to create a generic part using industry GD&T practices. Modifications were made to the part length. There were no additional features added to this part.

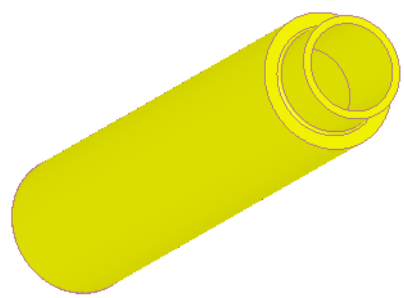


Figure 1: Rolled Standoff

The second part chosen was a heat sink shown in Figure 2. The design was altered to create a generic part using industry GD&T practices. The heat-sink-fin feature was changed to incorporate a chamfer on one end. A heat-sink-pin array with a spherical radius on each pin tip was added near the fins. There were standoffs, bosses, and a flatness callout added to the bottom side to drive additional machining and inspection elements. Material attributes were added to the models to support downstream system input requirements. These attributes included the thermal expansion coefficient, thermal expansion coefficient units, and material name.

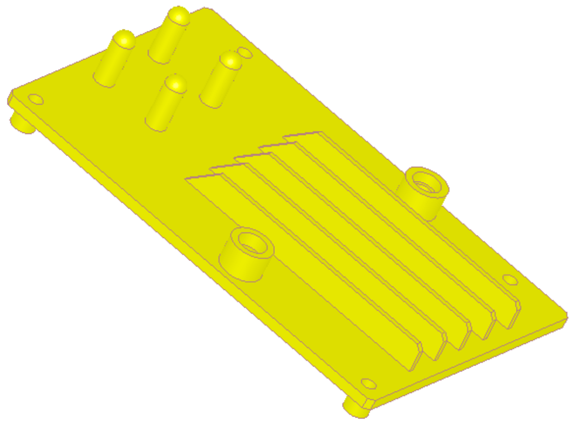


Figure 2: Heat Sink

The PMI data types included in the project models are shown in Table 4.

Table 4: PMI data types used in the models

PMI data types used in the models	
Datums	Tolerances
Dimensions	All Around
Angular	Cylindricity
Diameter	Total Runout
Linear	Flatness
Radius	Perpendicularity
Spherical Radius	Position
Thickness	Profile Surface
Dimension Origin Symbol	Angularity

After the shape-geometry modifications were incorporated into the models, three different data sets were created to investigate how part information is exchanged with a supplier. The first data sets (827-9999-905 and 827-9999-906) contain only the full-dimension-2D drawing with all of the GD&T callouts, per ASME Y14.5, and all other necessary PMI data types. The parts can be manufactured and inspected using just the drawings. The drawings are shown in Figure 3 and Figure 4.

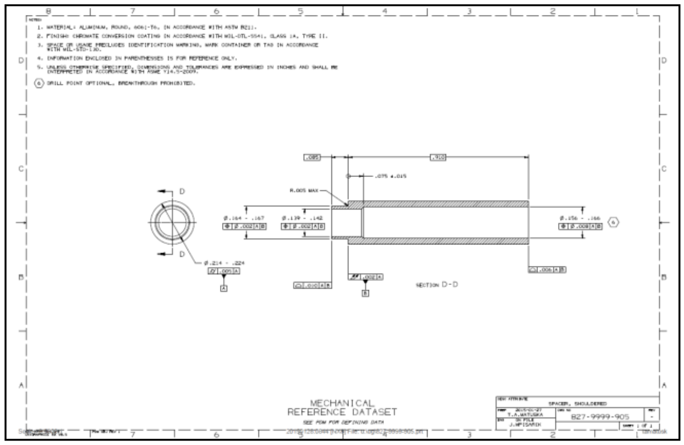


**Figure 3: Rolled Standoff 827-9999-905
full-dimension-2D drawing**

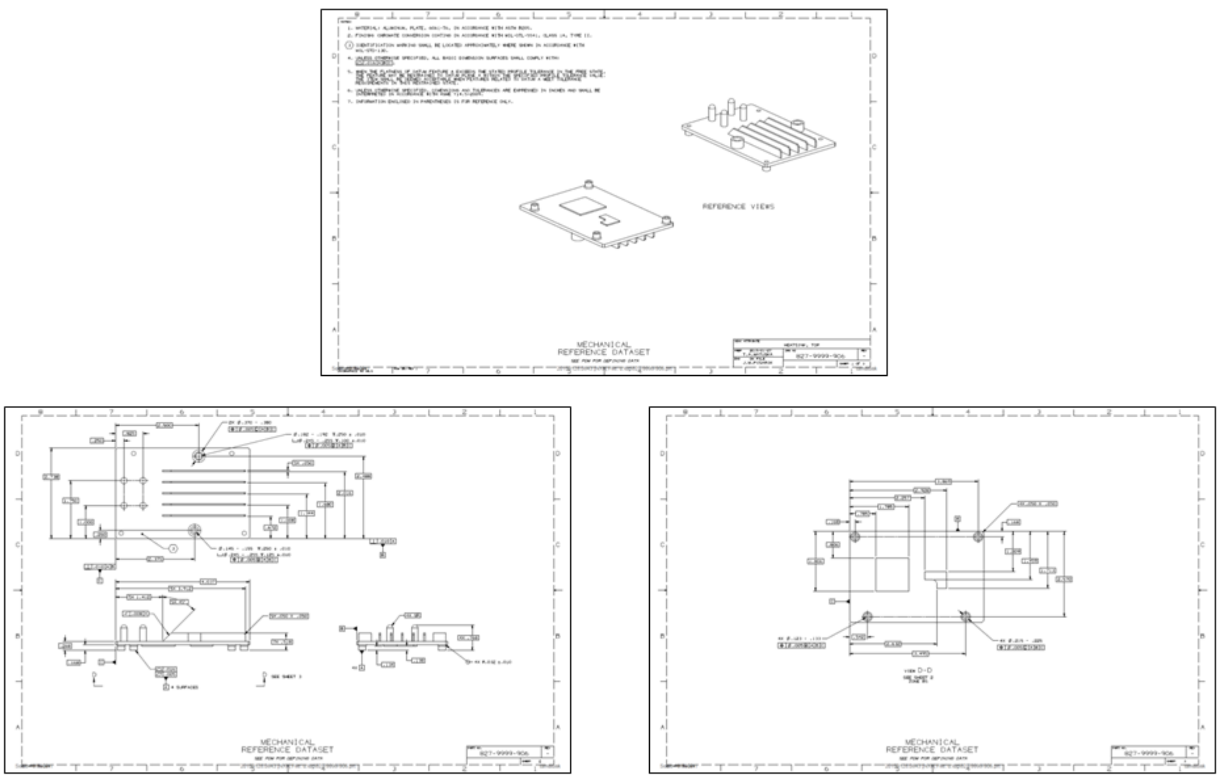


**Figure 4: Heat Sink 827-9999-906
full-dimension-2D drawing**

The second data sets (827-9999-907 and 827-999-908) align with ASME Y14.41 practices for creating digital-product-definition data. These data sets include a partial-dimension 2D drawing along with a 3D-shape-geometry model without embedded PMI (using the STEP AP203 format). Both the model and the drawing are necessary to manufacture and inspect the parts as shown in Figure 5 and Figure 6.

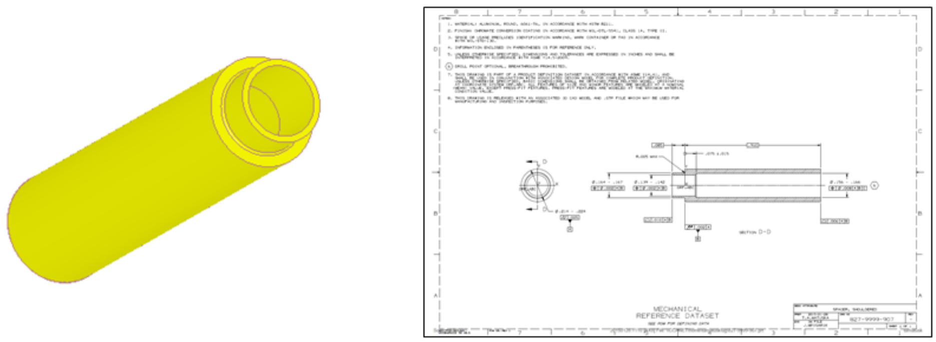


Figure 5: Rolled Standoff 827-9999-907
3D- shape-geometry model (STEP AP203) with partial-dimension-2D drawing

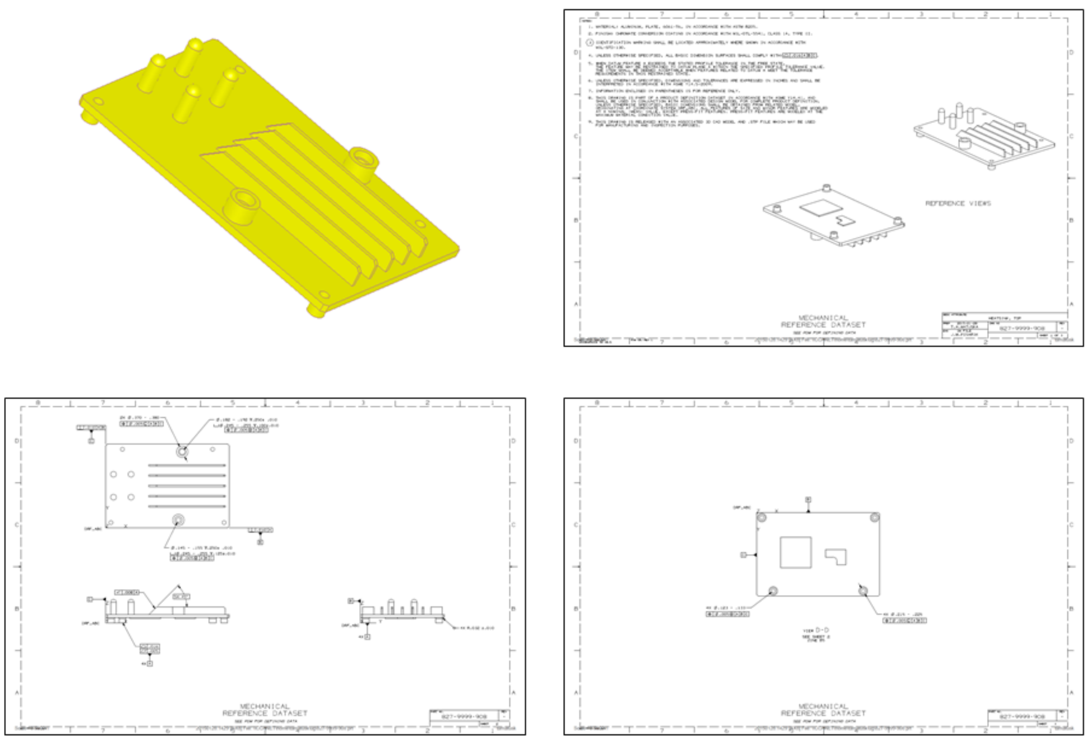


Figure 6: Heat Sink 827-9999-908
3D-shape-geometry model (STEP AP203) with partially dimensioned 2D drawing

The final data sets (827-9999-903 and 827-9999-904) contain a full-dimension-3D model with embedded PMI (using the STEP AP242 format). These parts can be manufactured and inspected completely with the 3D model, without the need of a supporting 2D drawing. These data sets are shown in Figure 7 and

Figure 8. The schema aligns with the MIL-STD-31000AAppendix B data structure for PMI presentation.[7] Once the native CAD model with embedded PMI was created, it was then delivered to the project team for translation into the STEP AP242 model used by the downstream CAM and CMM systems.

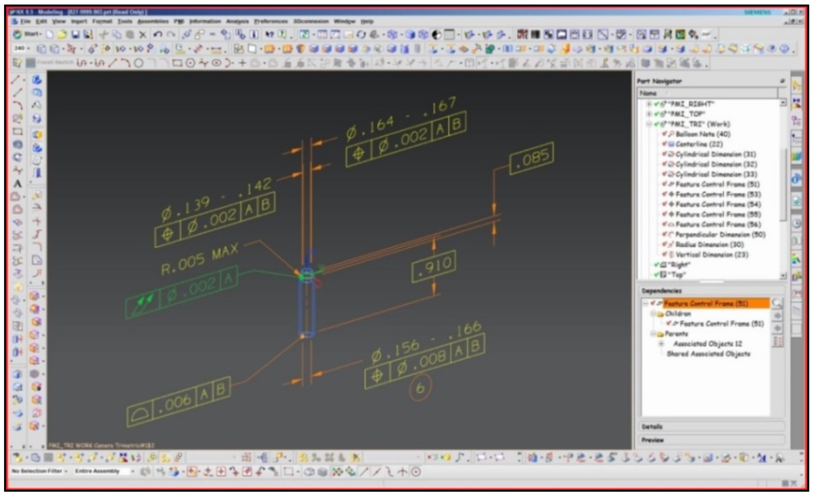


Figure 7: Rolled Standoff 827-9999-903 full-dimension-3D model (STEP AP242) with embedded PMI

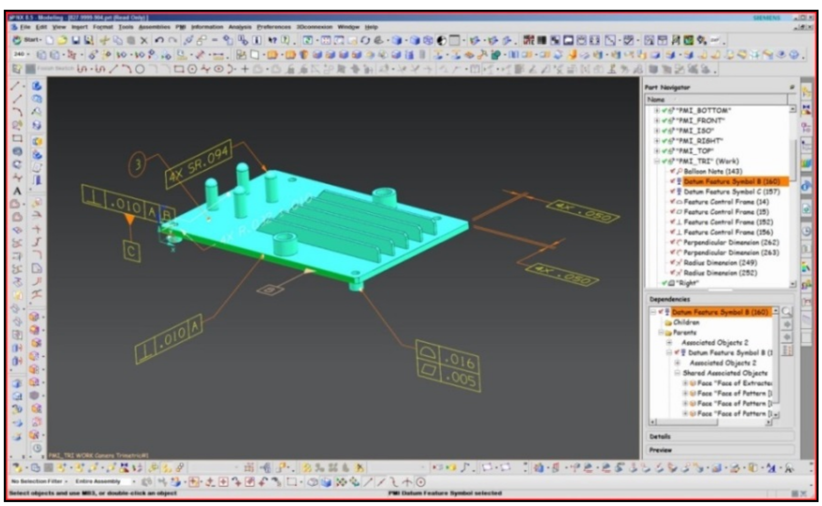


Figure 8: Heat Sink 827-9999-904 full-dimensioned-3D model (STEP AP242) with embedded PMI

Map the PMI into STEP and ACIS

According to Spatial Corporation, the 3D ACIS® Modeler geometric modeling kernel is used by many software developers, including the CAD, CAM, and CMM industries, to provide underlying 3D modeling

[7] United States Department of Defense. (2013, 26 February). MIL-STD-31000A. *Department of Defense Standard Practice: Technical Data Packages*.

functionality.[8] One project research task was to analyze the PMI elements in STEP AP242 and ACIS® to determine where gaps exist and what enhancements are needed to address those gaps. This analysis was performed and delivered to NIST as an early deliverable for this project. The mapping tables used as the basis for the analysis are included as Appendices B.1 and B.2. The gaps and subsequent issues are reviewed further in the results and discussion sections.

Demonstrate Standards-Based Interoperability

The flow diagram shown in Figure 9 demonstrates the data-exchange process from CAD-to-CAM and CAD-to-CMM, using commercially viable solutions. Rockwell Collins performed as the OEM. Rockwell Collins designed the test parts using Siemens NX™ CAD software. Geater Machining and Manufacturing performed as the supplier. Geater used CNC Software Mastercam® for numerical control programming for the manufacture (CNC machining and turning) of the test parts. Geater used Mitutoyo MiCAT™ Planner automatic measurement program generation software to enable inspection of the test parts. The data exchange process required the use of CoreTechnologie 3D_Evolution© to convert data from the native NX™ CAD shape, metadata, and PMI into standards-based STEP AP242 format. ITI PDElib® data exchange library was used to complete the import from STEP AP242 into Mastercam®. ITI eACIS utility library was used to complete the import from STEP AP242 into the ACIS® kernel used by MiCAT™ Planner.

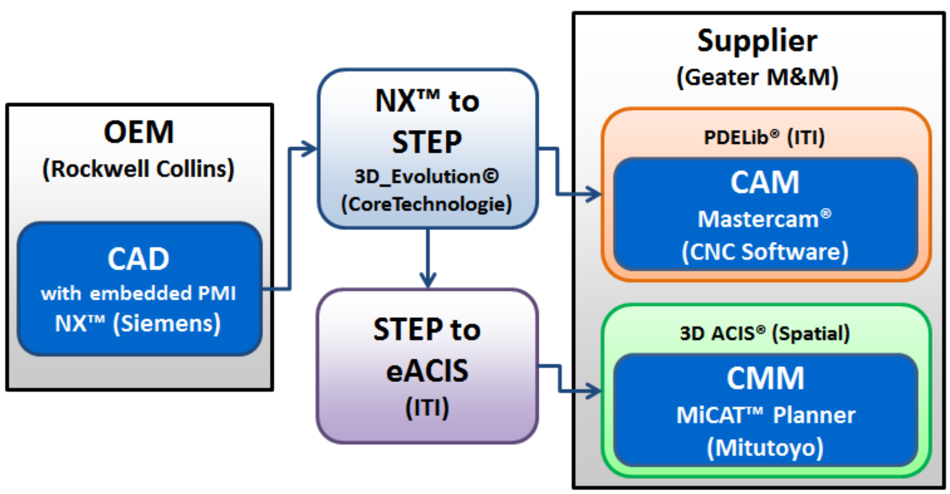


Figure 9: Data exchange process flow diagram

The software tools used for model conversion from CAD to CAM and CMM required algorithm enhancements to the currently available commercial versions to enable and fine-tune the exchange of the semantic PMI data. Issues were identified and resolved in order to successfully exchange the data. The project used an iterative approach in the issue resolution process:

[8] Spatial Corp. *3D ACIS Modeling.* Retrieved October 09, 2015, from Spatial Products: http://www.spatial.com/products/3d-acis-modeling.

- Perform data exchange for each process step,
- Evaluate the output for the required model entities at each process step,
- Identify errors encountered in the individual PMI elements,
- Modify each sub-process algorithm to address the issue, and
- Re-evaluate the updated output until each sub-process converged to a viable end-to-end data exchange solution.

CAD Process

The OEM use case process steps, referenced in Table 5, represent the activity most likely affected by the inclusion of embedded PMI in the CAD model necessary for downstream manufacturing and inspection. The OEM metrics captured for this project focus primarily on the CAD-model creation process steps, but also provide some insight into CAD-model validation and verification process. The project also provided anecdotal observations for the part-receiving-inspection use case, but those come mostly as a result of metrics captured for the CMM inspection and reporting use cases.

Table 5: CAD model creation process

Process Steps	OEM Steps
CAD Model Creation	CAD 3D model creation Model-embedded PMI 2D PDF drawing creation CAD tool issue resolution and designer education * CAD model resolution to address CMM issues *

* CAD model issues and designer education demonstrate the need to overcome gaps in current state of tools and knowledge

CAM Process

The supplier CAM use case process steps represent the activity involved in CAM model creation. The project focused on the most useful metrics to record for the supplier for CAM-related process steps. The metrics demonstrate the difference between the current-state and the future-state process steps. They must provide enough detail to demonstrate the process areas most significantly affected when ingesting models with embedded PMI for CAM programming. Finally, the metrics need to align with the supplier process steps such that they could be easily recorded. It was determined that cycle-time metrics would be most useful to compare current-state to future-state for the CAM process. The supplier completed the CAM model creation process steps using the three technical data exchange scenarios and manually recorded the cycle-time for the steps.

The project reviewed the manufacturing process steps identified in the NIST Testing the Digital Thread project.[9] The research compared these process steps to the manufacturing check-list steps used by the supplier. In the comparison, four general process step segments were identified. These became the

[9] Hedberg, Jr. T., Lubell, J., Fischer, L., Maggiano, L., & Barnard Feeney, A. Testing the Digital Thread in Support of Model-Based Manufacturing and Inspection. *Submitted for publication,* 2015.

segments for recording cycle-time measurement results for the project. Table 6 shows the comparison of steps for the CAM process.

Table 6: CAM model creation process

NIST Steps	Process Steps	Supplier Steps
Gather product definition Generate 3D model, if needed Gather manufacturing requirements Gather specification and standards requirements Digest the eBOM Generate mBOM Determine required manufacturing processes Determine required manufacturing resources Interrogate product definition Conduct manufacturing stacking process Determine form features and process requirements Determine manufacturing resource availability Adjust proposed manufacturing process based on resource availability	**CAM Process Preparation**	Manufacturing process preparation
Generate in-process 3D model for tooling and programming Determine and add manufacturing notes	**CAM Setup**	Draw a solid of the stock, fixture and tabstock Select correct machine post Set revision level in properties page Set tool settings Select stock model Save Mastercam file as part number and revision level less decimal points (xxx-xxxx-xxx, REVA)
Create tooling models (fixtures and gauges) Create tooling documentation Create CAM / NC program Add tooling to CAM / NC program	**CAM Programming**	Check material type Program part Program fixtures Check that coolant is on for all tools Add number of shifts and distance to macro programs Turn on shift cancel for any tools that run the full length of a strip (if applicable)
Create manufacturing work instructions Generate additional process documentation, as needed Create CAM and NC documentation Process review: verify final product definition (all dimensions, etc. covered by manufacturing process) Process review: verify all manufacturing, process, and engineering notes requirements are achieved Final process sign-off	**CAM Verification**	Make sure rapid retract is being used on all tiles Create VERICUT for fixture programs Create VERICUT for part programs and **make sure all hardware is in place** Run auto-diff in VERICUT and take time to ensure all excess and gouges are correct Double check all drill and tap tooling against print for correct sizes

CMM Process

The CMM process steps were identified in a similar way as the CAM process steps. Inspection steps previously defined in the NIST Testing the Digital Thread project were compared to the steps in the supplier check-list for inspection. In the comparison, five general process step segments were identified. These became the segments for recording cycle-time measurement results for the project. Table 7 shows the comparison of steps for the CAM process.

Table 7: CMM model creation process

NIST Steps	Project Steps	Supplier Steps
Gather product definition Generate 3D model if needed Gather inspection requirements Gather specification and standards requirements Determine required inspection processes Determine required inspection resources	**CMM Process Preparation**	Import model into CMM software
Interrogate product definition Balloon and identify characteristics from product definition Populate reporting documentation (e.g. AS9102, etc.) with characteristics Determine inspection resource availability Adjust proposed inspection process based on resource availability Generate in-process 3D models, if in-process inspection will occur	**CMM Setup**	Establish datum features
Create CMM measurement program Create CMM measurement work instructions Create CMM measurement documentation	**CMM Programming**	Measure all features on the model per print specifications
Verify final product definition (all characteristics are covered by Inspection process) Verify all inspection, process, and engineering notes requirements have been met Final process sign-off	**CMM Verification**	Verify for collisions
Populate reporting documentation (e.g. AS9102, etc.) with characteristic measurement results Compare and analyze conformance of product against product definition (capture deviation)	**CMM Data Analysis**	Run report

Data Exchange Issue Resolution

With the iterative data exchange approach, numerous issues were discovered and the majority resolved for the final demonstration of the CAD-to-CAM and CAD-to-CMM data exchange using models with embedded PMI. Examples of resolved issues for CAM and CMM are shown in Figure 10 and Figure 11.

Figure 10 is a snapshot of the in-development Mastercam environment with imported PMI data. Note the STEP geometric tolerance anomaly in the upper right of the image. This was corrected in a subsequent iteration.

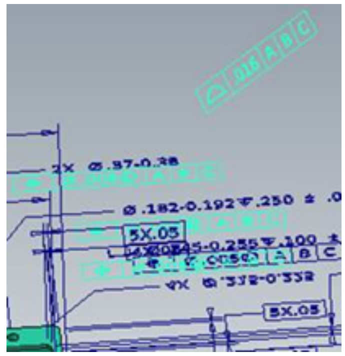
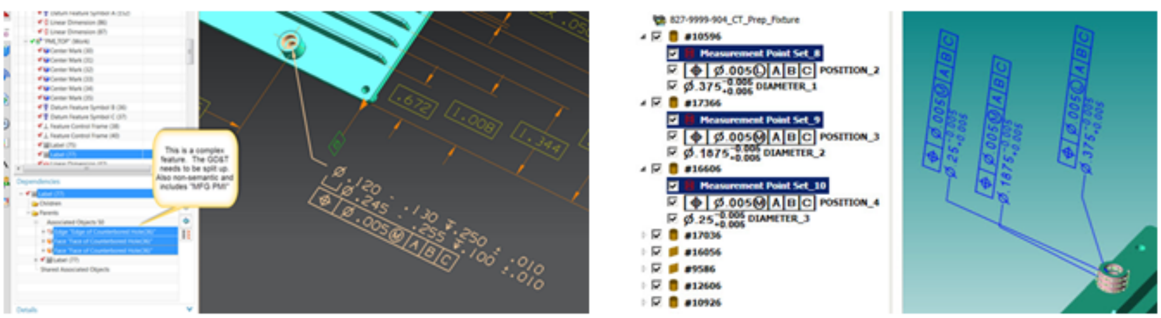


Figure 10: Snapshot of in-development Mastercam environment

Figure 11 is a snapshot of the in-development NX CAD and MiCAT CMM environments with PMI data. Note the items identified in the CAD data tree on the left. The common annotation is a complex feature that is presented in a human-readable format on the drawing. It is actually a combination of several features and characteristics presented in a non-semantic way, which is not machine-interpretable. The imported PMI with machine-interpretable representation is shown in the MiCAT view on the right.



Siemens NX CAD Presentation MiCAT CMM Representation

Figure 11: Snapshot of in-development NX CAD and MiCAT CMM environments

Note there were other identified issues that could not be addressed within the scope of this project. Those issues are reviewed further in the results and discussion sections.

Results

The results: *STEP AP242 with embedded PMI can successfully exchange model-centric data from design (CAD) to manufacturing (CAM) and inspection (CMM).*

Results from Mapping PMI between STEP and ACIS

The following PMI gaps were identified when mapping PMI between STEP AP242 and ACIS:

- Spherical dimension types (RADIUS, DIAMETER) are missing from ACIS
- Oriented and curved dimensions are missing from ACIS
- ACIS does not support angle selection (SMALL, LARGE, EQUAL) in an angular dimension
- Tolerance principal (ENVELOPE, INDEPENDENCY) is not supported by ACIS
- Dimension value with plus/minus bounds is not supported by ACIS
- Dimension value with qualifier (MAXIMUM, MINIMUM) is not supported by ACIS
- Very limited support for dimension modifiers (BASIC, REFERENCE, STATISTICAL) by ACIS, many are missing (CONTROLLED RADIUS, FREE STATE, ANY CROSS SECTION, etc.)
- Movable datum target is not supported by ACIS
- Geometric tolerance type (COAXIALITY) is missing from ACIS
- Limited support for tolerance zone types (DIAMETER, SPERICAL DIAMETER, PROJECTED) by ACIS, some are missing (NON-UNIFORM, RUNOUT, WITHIN A CIRCLE, etc.)
- Very limited support for tolerance modifiers (FREE STATE, LMC, MMC, RFS, STATISTICAL, TANGENT PLANE) by ACIS, many are missing (ANY CROSS SECTION, COMMON ZONE, etc.)
- Very limited support for datum reference modifiers (LMC, MMC) by ACIS, many are missing (FREE STATE, BASIC, TRANSLATION, etc.)
- ACIS does not directly support POLYLINE presentation

Results from Embedded PMI Data Exchange

Development and demonstration of a process to exchange standards-based models with embedded PMI from design to downstream systems was successful within the scope of the limited test models used in this project. The validation results, as defined by PMI element counts, for the downstream models are provided in Table 8. The validation shows that all dimensions, tolerances, and datum features were properly transformed and exchanged.

Table 8: Validation of model transformations using embedded PMI entity count

PMI Elements (by format)	NX		STEP		ACIS		Mastercam		MiCAT	
Model (827-9999)	**-903**	**-904**	**-903**	**-904**	**-903**	**-904**	**-903**	**-904**	**-903**	**-904**
Dimension	8	54	8	54	8	54	8	54	8	54
Tolerance	6	13	6	13	6	13	6	13	6	13
Datum Feature	2	3	2	3	2	3	2	3	2	3
Notes (not semantic data)	7	8	7	8	0	0	7	8	0	0
Total	23	78	23	78	16	70	23	78	13	68

Automated validation of the downstream models using analysis software during algorithm development was performed using techniques described in a separate NIST project.[10] As indicated in Table 8, general

[10] NIST Collaborative Agreement: 70NANB14H256. (2015). *Validation for Downstream Computer Aided Manufacturing and Coordinate Metrology Processes*.

notes could not be mapped to ACIS and were not transferable to the MiCAT Planner. Other development roadblocks are discussed later.

Results from CAD Model Creation

Results for CAD model creation are shown in Table 9. For each part, three data sets were generated. The future-state data set (-903 and -904) included the 3D model (STEP AP242) with embedded PMI. The current-state had two significant data sets to compare against the future-state. The first current-state data set (-905 and -906) provided a full-annotated-2D drawing with dimensions and PMI. The part is represented fully and can be manufactured from the drawing. The second current-state data set (-907 and -908) contains the 3D-shape-geometry model (STEP AP203) and a 2D drawing with the PMI. This data set requires both the model and the drawing together to manufacture the part.

Table 9: CAD model creation metrics

CAD Metrics	**Rolled Standoff** 			**Heat Sink** 		
827-9999	**-903**	**-905**	**-907**	**-904**	**-906**	**-908**
2D PDF drawing	---	full dimension with 2D PMI annotation	key 2D PMI annotation only (PDD)	---	full dimension with 2D PMI annotation	key 2D PMI annotation only (PDD)
3D model	includes embedded PMI	not provided	with no embedded PMI	includes embedded PMI	not provided	with no embedded PMI
Number of PMI entities	23 (24*)	---	---	78 (90*)	---	---
CAD model creation (modified existing part)	0.5 hours	0.5 hours	0.5 hours	0.5 hours	0.5 hours	0.5 hours
Model-embedded PMI	3.0 hours	---	---	6.0 hours	---	---
2D PDF drawing creation	0.5 hours	1.0 hours	0.7 hours	0.5 hours	2.4 hours	1.3 hours
CAD tool issue resolution and designer education	9.0 hours	0.5 hours	0.1 hours	4.9 hours	0.5 hours	0.1 hours
CAD model resolution to address downstream issues	2.3 hours + 4.5 hours to learn NX	---	---	3.0 hours + 1.3 hours to learn NX	original dwg missing dim – required ECO	---

* Original PMI entity count based on objects found in the NX Part navigator – eventually reduced count by issue resolution

Results from CAM Model Creation

The supplier steps defined earlier were the basis for the four general project steps that condensed into recordable metrics in Table 10. These metrics show the difference between the current-state processes and the future-state process. Recall that two current-state processes were demonstrated. The first data set (-905 and -906) contained a full-dimension-2D drawing including all PMI. The second data set (-907 and -908) contained a 3D-shape-geometry model (STEP AP203) and a 2D drawing with the key PMI annotations. The future-state data set (-903 and -904) contained a full-defined-3D model with embedded PMI (STEP AP242).

Regardless of the data exchange scenario, the CAM process preparation steps were the same for each and the cycle-time did not show any difference. Likewise, due to the simplicity of the rolled standoff, no significant cycle-time difference was recorded for the CAM programming and verification steps.

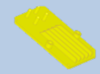
Table 10: CAM model creation metrics

CAM Metrics	**Rolled Standoff** 			**Heat Sink** 		
827-9999	**-903** 3D model with embedded PMI	**-905** 2D drawing fully annotated	**-907** 2D PMI drawing and 3D model	**-904** 3D model with embedded PMI	**-906** 2D drawing fully annotated	**-908** 2D PMI drawing and 3D model
CAM Process Preparation a) Gather information b) Analyze job c) Determine approach	**3.25 hours** a) 0.25 hours b) 0.50 hours c) 2.50 hours	**3.25 hours** a) 0.25 hours b) 0.50 hours c) 2.50 hours	**3.25 hours** a) 0.25 hours b) 0.50 hours c) 2.50 hours	**3.83 hours** a) 0.33 hours b) 0.50 hours c) 3.00 hours	**3.83 hours** a) 0.33 hours b) 0.50 hours c) 3.00 hours	**3.83 hours** a) 0.33 hours b) 0.50 hours c) 3.00 hours
CAM Setup a) Model preparation b) Pre-program setup	**0.45 hours** a) 0.00 hours b) 0.45 hours	**0.52 hours** a) 0.07 hours b) 0.45 hours	**0.45 hours** a) 0.00 hours b) 0.45 hours	**0.68 hours** a) 0.45 hours b) 0.23 hours	**0.64 hours** a) 0.52 hours b) 0.12 hours	**0.40 Hours** a) 0.28 hours b) 0.12 hours
CAM Programming a) Part programming b) Tooling preparation	**1.00 hours** a) 0.50 hours b) 0.50 hours	**1.00 hours** a) 0.50 hours b) 0.50 hours	**1.00 hour** a) 0.50 hours b) 0.50 hours	**3.23 hours** a) 3.01 hours b) 0.22 hours	**3.13 hours** a) 2.75 hours b) 0.38 hours	**2.30 hours** a) 2.08 hours b) 0.22 hours
CAM Verification a) Create work instructions (setup sheets) b) Review process (Run VERICUT)	**0.15 hours** a) 0.10 hours b) 0.05 hours	**0.15 hours** a) 0.10 hours b) 0.05 hours	**0.15 hours** a) 0.10 hours b) 0.05 hours	**0.42 hours** a) 0.32 hours b) 0.10 hours	**0.50 hours** a) 0.35 hours b) 0.15 hours	**0.53 hours** a) 0.35 hours b) 0.18 hours
Total	**4.85 hours**	**4.92 hours**	**4.85 hours**	**8.16 hours**	**8.10 hours**	**7.06 hours**

Results from CMM Model Creation and Inspection

Once again, the cycle-time metrics show the difference between the current-state processes and the future-state process. Recall that the first data set (-905 and -906) started with only a full-dimension-2D drawing including all PMI. But in this case, the supplier was able to take advantage of the model that was already created for the CAM process and re-use it in the CMM process. The same occurred for the second data set (-907 and -908), which contained a 3D-shape-geometry model (STEP AP203) and a 2D drawing with the key PMI annotation. The future-state data set (-903 and -904) contained a full-definition-3D model with embedded PMI (STEP AP242). The metrics for CMM model creation are shown in Table 11.

Table 11: CMM model creation and part inspection process

CMM Metrics	**Rolled Standoff** 			**Heat Sink** 		
827-9999	**-903** 3D model with embedded PMI	**-905** 2D drawing fully annotated	**-907** 2D PMI drawing and 3D model	**-904** 3D model with embedded PMI	**-906** 2D drawing fully annotated	**-908** 2D PMI drawing and 3D model
CMM Process Preparation	Unable to perform automated inspection process due to physical size limits of the available CMM equipment. The part features were too small for the CMM probe to measure. These test parts were inspected manually.			**0.10 hours**	**0.50 hours**	**0.75 hours**
CMM Setup				**0.10 hours**	**0.75 hours**	**1.00 hour**
CMM Programming				**0.50 hours**	**4.76 hours**	**4.75 hours**
CMM Verification a) Verify information b) Verify for collisions				**0.30 hours** a) 0.15 hours b) 0.15 hours	**1.00 hours** a) 0.50 hours b) 0.50 hours	**1.00 hour** a) 0.50 hours b) 0.50 hours
Inspection a) CMM inspection b) Manual inspection	**0.50 hours** a) 0.00 hours b) 0.50 hours	**0.25 hours** a) 0.00 hours b) 0.25 hours	**0.25 hours** a) 0.00 hours b) 0.25 hours	**0.70 hours** a) 0.20 hours b) 0.50 hours	**0.40 hours** a) 0.20 hours b) 0.20 hours	**0.40 hours** a) 0.20 hours b) 0.20 hours
CMM Data Analysis				**0.50 Hours**	**0.50 hours**	**0.50 hours**
Total Time	**0.50 hours**	**0.25 hours**	**0.25 hours**	**2.20 hours**	**7.91 hours**	**8.40 hours**

Discussion and Recommendations

Model Validation and Verification

Standards-based workflow for design to manufacturing and inspection involves exchange of CAD-to-AP242-to-CAM-and-CMM models. Validation and verification of this translation process is important, especially for regulated industries. An important part of quality assurance is traceability back to the design definition. To assure compliance at any point in the manufacturing or inspection process, it is essential to have validation and verification of the models throughout the data exchange process. A draft of ASME Y14.41.1 *3D Model Data Organization Schema* [11] is currently defining Critical Metadata Elements based upon MIL-STD 31000A *Department of Defense Standard Practice: Technical Data Packages,* Appendix B MBD Model Organizational Schema.[12] Once complete, these metadata elements will need to be supported by the STEP AP242 Model-Based Definition. Similar to ensuring coverage of GD&T elements defined by AMSE Y.14.5, the 3D metadata elements being defined by ASME Y14.41.1 are necessary in the AP242 model to fully support data interoperability for 3D models with embedded PMI.

[11] American Society of Mechanical Engineers. Y14.41.1. *3D Model Data Organization Schema (in development)*. ASME.

[12] United States Department of Defense. (2013, 26 February). MIL-STD-31000A. *Department of Defense Standard Practice: Technical Data Packages*.

ACIS and Embedded PMI Gaps

The PMI-element count was used as a metric to determine that the model was imported correctly as it moved from the native-CAD model through STEP AP242, ACIS, and ultimately into the CAM and CMM models. Several iterations and changes to the CAD-model-embedded PMI were required to achieve acceptable transformation into the downstream formats for CAM and CMM. Several iterations of the application algorithms were also required to enable the transformation.

Verification and validation tools are available to identify model-based data quality issues that impact downstream reuse for tooling, simulation, and data exchange. Repair tools also offer diagnostics, translation, healing, and repair of CAD geometry for downstream model use. Types of model quality issues include:

- Geometry that impedes model translation or downstream reuse of CAD models
- Unrealistic features that require changes during CAM modeling
- Unrealistic or ambiguous PMI features that require changes during CMM modeling
- Undocumented changes caused by revisions or engineering changes
- Unintended changes caused by complex parametric relationships unknown to CAD users

Additional work is needed to overcome some deficiencies in ACIS to enable embedded-PMI-data exchange. One potential solution might involve using ACIS attributes as a mechanism to provide the missing or incomplete information. However, since this method would not be a semantic representation, an agreed upon specification between the sender and the receiver would be required to interpret the augmented data correctly.

Likewise, with the polyline presentation in STEP, ACIS wire bodies could be created and associated to the PMI data using attributes. But again, the sender and receiver would need to agree upon a common specification to successfully exchange the data and its semantic meaning. ACIS does support presentation information in a more semantic form, but this is not the preferred (or implemented) method in STEP.

CAD Process Observations

One unexpected but not un-common issue occurred. The original heat sink data set with the full dimension 2D drawing (-906), and without a 3D model, was provided to the supplier with two missing dimensions. The supplier discovered the missing dimensions while the model for the CAM and CMM processes was being created. The supplier had to request an updated drawing from the OEM for the missing dimensional information. This required an ECO, which had significant impact on cycle time and delivery schedule for the part. Figure 12 shows the missing dimensions. Only when you rely on 2D drawings for information does a missing dimension become relevant. Missing dimensions are not possible when using 3D model with embedded PMI.

There are anticipated benefits in the part validation, procurement, and receiving inspection, as well as for the ECO process. These areas would be good candidates for a future, more definitive ROI study of the digital thread.

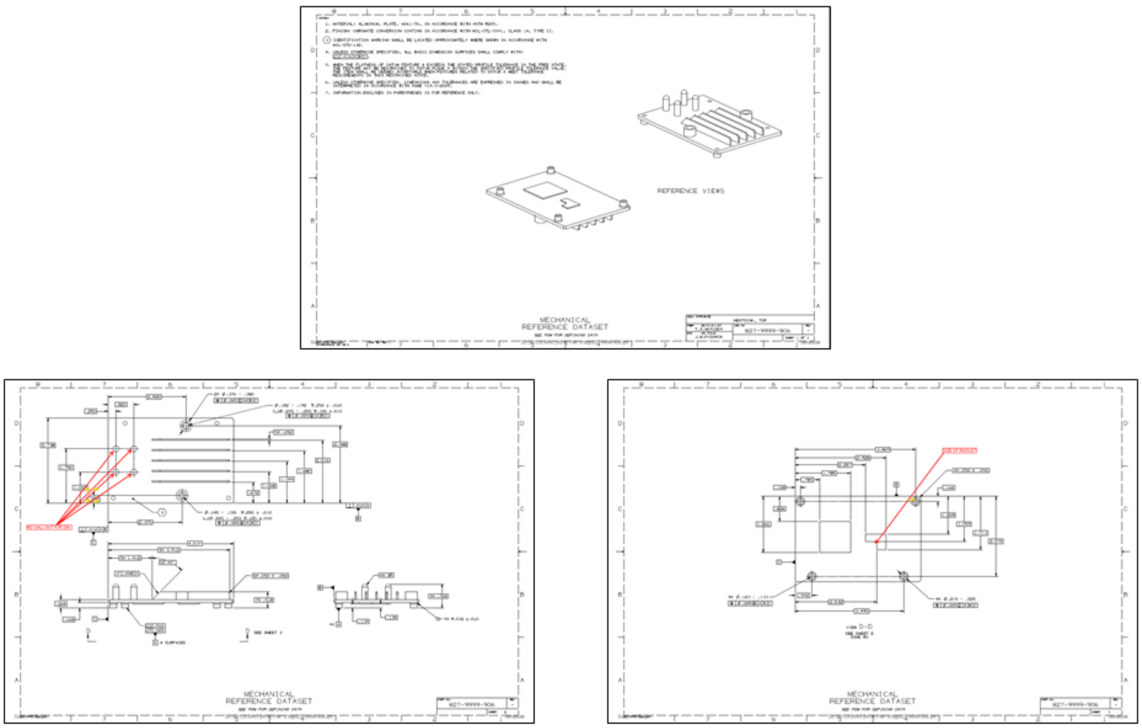


Figure 12: CAD model creation - missing dimensions

Several observations were made about the creation of the 3D CAD model with embedded PMI. During the time of CAD-model creation, some learning curve was required for the designer to become familiar with methods to both present and represent PMI annotations. User training on embedded PMI with the CAD system is absolutely necessary. There are challenges to create embedded PMI that is both human interpretable and machine readable. The inherited 3D-annotation views do not necessarily transfer to a 2D-visualization format. The 2D-GD&T presentation within the CAD software is not always easily transferred to the 3D-model representation. Critical for the support of downstream model usage is the understanding and use of a model schema that organizes data elements and standardizes how the data elements relate to one another. Edge versus face or surface selection for PMI annotation is especially important for machine-readable-downstream use. Even though human interpretation appears straight forward; there can easily be redundant association with the model that creates issues with the downstream manufacturing and inspection systems.

It was observed that for the data sets containing a 2D drawing, the drawing includes a non-semantic presentation note stating, "Unless otherwise specified, all basic dimensions (as found in the 3D model) shall comply with: |⌓|.016|A|B|C|." Only the key GD&T (PMI) items are annotated in the 2D drawing, all unspecified GD&T is implied in the note. Currently, there is no recommended practice to incorporate this UOS functionality in 3D models with embedded-PMI representation. Industry recognizes value in the cycle-time efficiency from the use of blanket tolerances. Many features share the same tolerance and if each required explicit tolerance definition it would be too time-consuming. If a blanket tolerance is not possible with embedded-PMI representation, then the time required for CAD model creation will be prohibitive for industry to move toward acceptance of full-dimension-model-based definition.

CAM Process Observations

Observations from the supplier indicate that shape-geometry imported using the STEP AP242 format was as readily imported as it was from the STEP AP203 format. The AP242 model also provided access to the semantic representation of PMI data. The ITI library used by Mastercam to support import of STEP AP242 models provides an API to set up PMI-to-geometry associations, display the associations, and allow the associations to be saved within the Mastercam file.

The supplier was able to generate toolpath data using the imported STEP files but with a slight loss of efficiency. This efficiency loss was due to the time the operator took to manually validate the CAM model to the CAD model with embedded PMI. As the confidence level in the model-based process grows, it is expected that this inefficiency with the operator will be eliminated. Model-based validation tools could help reduce the cycle-time, while ensuring data exchange continuity and model quality. There would be reduced risk of error between CAD and CAM models and there would be more opportunity to automate validation of the CAD model to the CAM model.

There were issues with the method Mastercam chose to display the PMI. For human-readable visualization the CAM model presentation looked like a “fur-ball” of information with no organization, as shown in Figure 13.

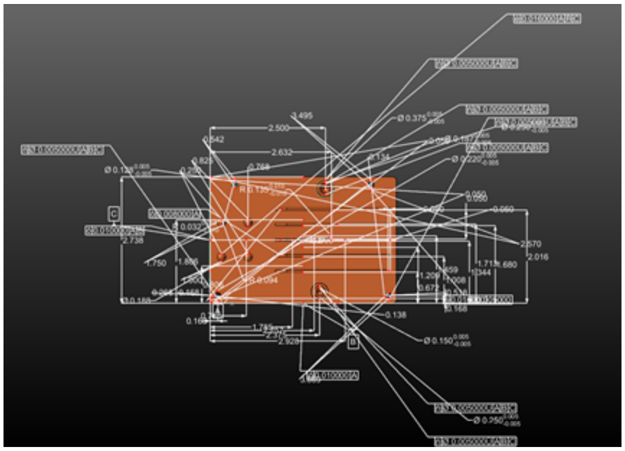
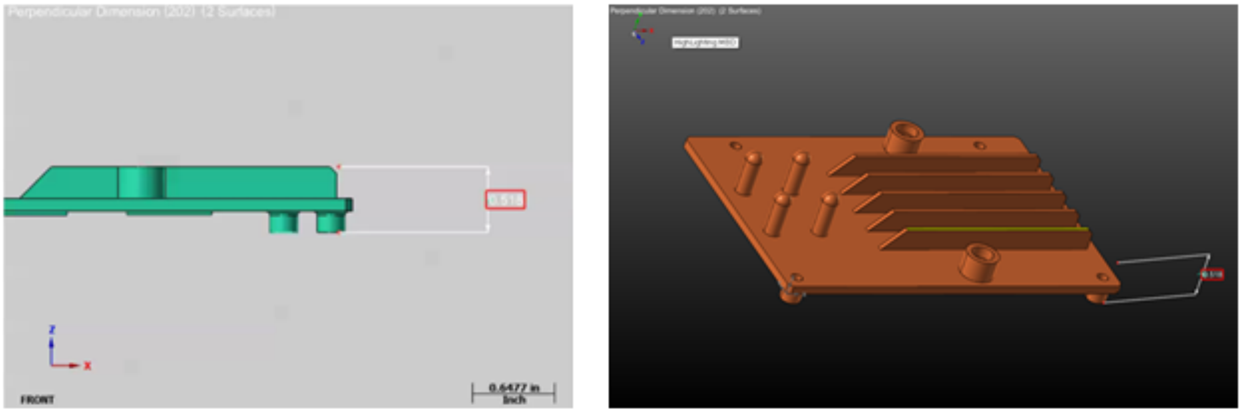


Figure 13: Dimensions imported as a "fur-ball" in CAM presentation

The imported annotations rebuilt in Mastercam using the semantic-representation data did not exactly match the original presentation data. This resulted in missing or difficult to interpret visual information.

Figure 14 is an example of presentation in the original view which did not meaningfully present in another 3D view.



Presentation is useful in original view　　Presentation is not useful in this 3D view

Figure 14: Difficult to interpret visual presentation

As shown in the results, there was no significant improvement in cycle time from the current-state to the future-state CAM model creation using embedded PMI. It actually took more cycle time to process models with the embedded PMI than it did with the 3D-shape-geometry model because the supplier spent additional time to validate the embedded information. No quality advantage was seen in the CAM model creation and part manufacture as a result of embedded PMI. It may be that no significant improvement in cycle time or quality was measured due to the simplicity of the test models. The team expects that there would be improvement in CAM model creation when applied to more complex models.

CMM Process Observations

Similar observations of the results for CMM-model creation indicate that shape-geometry is imported the same as the STEP AP203 model when using the STEP AP242 to eACIS converter. Furthermore, STEP AP242 model import using this intermediate exchange provides access to the semantic PMI data originally in the STEP file. This provides significant automation of data entry into the CMM system. The PMI data was usable for CMM programming by the MiCAT Planner application.

CMM-model creation demonstrated the most significant improvements from importing an embedded PMI model. Importing the model with embedded PMI required just 1.70 hours for CMM process preparation, set-up, programming, verification and inspection. When using the full-dimension-2D drawing the same activity required 7.40 hours and when using the 3D-shape-geometry model with a partial-dimension-2D drawing required 7.90 hours. In all, exchanging a 3Dmodel with embedded PMI demonstrates more than 4-times improvement in cycle-time over drawing-based or shape-geometry-model-based practices.

Upon delivery of the physical parts for inspection, an unexpected issue was encountered. The supplier was unable to inspect some features on the heat sink, and none of the features of the rolled standoff using the CMM process as originally planned. This issue was due to the physical-size limits of the available CMM equipment. As shown in Figure 15, the part features were too small for the CMM probe to measure even with successful model import. The manual inspection cycle-time was recorded to cover the areas not able to be measured using the CMM system. The manual-inspection metric demonstrates that even with full-model-based definition, a human-in-the-loop will sometimes still have significant process impact.

> ***The conclusion:*** *Model-centric CAD-to-CAM and CAD-to-CMM data exchange using STEP AP242 is a viable part of the MBE vision, but there are still gaps to address.*

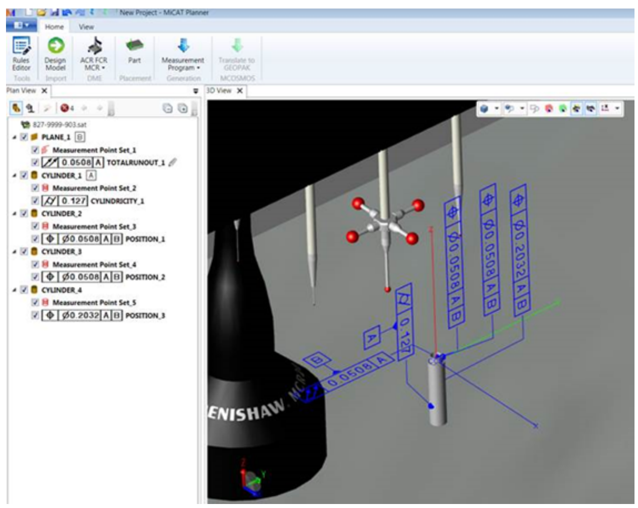


Figure 15: Physical measurement limitation even with successful model import

Conclusions

Tools

It was demonstrated that there is benefit from the CMM-system ability to interpret embedded-PMI information versus using nominal shape-geometry-model dimensions. It is anticipated that the same benefit could be gained by CAM software as well. While the basic ability to receive the embedded PMI was achieved, the CAM tools require further development to fully leverage the benefit of receiving that data.

In a number of instances, embedded PMI created by the designer does not align well to the needs of downstream-machine consumption. Since PMI-authoring capabilities of CAD systems have evolved from origins where 2D visualization of PMI was the requirement, current CAD systems allow designers to create PMI content that is, at best, partially useable for downstream consumption. Embedded-PMI rules should be implemented in CAD systems to better align model creation with the downstream-machine-interpretable expectations.

CAD-model structures are not optimized for downstream consumption. The ability to capture groupings of design features that represent geometric sets that correspond to equivalent manufacturing features is needed for downstream use and no method exists currently to achieve this functionality.

Standards

The project team recommends certain gaps be addressed by the STEP community (standards development and implementer forum). During the course of the project, it was observed that there is incomplete PMI coverage and recommended practices for the standards. Two examples illustrate the need for more coverage. There is the industry practice to use an unless-otherwise-specified tolerance callout as a general note. Although a workaround was achieved, a recommended practice is needed for this often-used callout to properly account for the required geometry associations. The second example is that surface-texture or surface-finish PMI are not yet implemented by the STEP community. A development activity to support this construct is necessary. This also necessitates a recommended practice document and the introduction of a test case into future test rounds of the STEP CAx Implementer Forum.[13]

Processes

The project demonstrated the cycle-time benefits of the future-state process. This is based upon a small-sample-size demonstration, but the authors believe the results are potentially scalable for increased model complexity and PMI-element counts. Significant reduction in cycle time for CMM model creation and characteristic analysis was observed. Cycle-time reduction was not conclusive for CAM-model creation however, and additional research is required to better understand the implications. It is recommended that additional testing of the process be completed over a broader sample size. Future research could seek out opportunities to increase the participants in the testing activity. This would result in a broader range of example data to work from and provide an opportunity to better assess the impact of variation in both design and processes.

It was clear that designer education is not aligned with requirements for downstream-PMI consumption, especially for machine-interpretable expectations. Industry needs recommended practices for proper association of PMI to geometry elements. There would also be value in a post-process to repair PMI geometry associations so they are complete and consistent. CAD systems should be augmented to provide design rules for creation of embedded PMI with downstream machine consumption in mind or, at a minimum, recommended practice documents need to be developed to guide designers as they

[13] PDES, Inc. and ProSTEP iViP. *CAx Implementor Forum.* Retrieved October, 09, 2015, from https://cax-if.org/index.html.

annotate 3D models with PMI data. Verification tools are needed to ensure that recommended practices have been followed prior to the release of models for downstream consumption.

There are anticipated benefits in the part validation, procurement, and receiving inspection, as well as for the ECO process. These areas would be good candidates for a future, more definitive ROI study of the digital thread.

The latest version of AS9102[14], the aerospace standard for reporting FAI results, suggests the potential exists to improve FAI reporting, particularly through automation. There is also potential for developing a visual presentation that ties metrology results and MBD. Lastly, there is potential mechanism to provide metrology results feedback to upstream users for analysis and prediction to better consider design decisions and manufacturing technologies for future products.

Summary

In summary, motivation exists for industry to continue its drive for the MBE vision through model-centric data interoperability for design to manufacturing and quality inspection. A number of conclusions have been drawn from the research performed under this project. An attempt has been made to organize them broadly into categories of tools, standards, and processes. Fundamentally, the project successfully demonstrated the value of standards-based CAD-to-CAM and CAD-to-CMM data interoperability when using STEP AP242 with embedded PMI. In doing so, there were many issues uncovered, some we were able to address within the project and others require further effort to overcome. Some significant gaps were identified as well. These gaps will need to be addressed through changes in the tools, standards, and processes used currently to share information from design to manufacturing and inspection across the supply chain.

[14] International Aerospace Quality Group. (2014, October 06). AS9102B. *Aerospace First Article Inspection Requirements.* SAE International.

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Appendices

Appendix A: Use Cases

Visualization and Collaboration Use Cases

Two use cases that will require significant change from current state to the future state processes following the introduction of embedded-PMI models are visualization (human-interpretable presentation) and collaboration. The need to visualize and collaborate is prevalent for both the OEM and Supplier with many of the identified use cases. For instance, it is anticipated that 3D PDF (or a similar format) will serve as a likely visualization tool to capture and display embedded information within a model. Likewise, how the OEM and supplier collaborate, whether for bidding and quoting, addressing discrepancies, or incorporating engineering changes will need to be different than how it is done today when using 2D drawings and mark-ups. These use cases are out of scope with this project.

OEM Use Cases

CAD Model Creation

This use case centers on the creation or authoring of the CAD model. Traditionally, the 3D-shape-geometry model is created without embedded PMI. Once the shape-geometry model is generated, a 2D drawing is created, and typically presented in 2D PDF format. It includes the PMI that is not part of the 3D-shape-geometry model. In the past, the 2D drawing was fully detailed and could be used by itself to manufacture the part. In more recent practice, a 3D-shape-geometry model and a 2D-partial-dimension drawing are required. The partial-dimension drawing contains only the PMI that is not embedded in the shape model. In the current-state scenarios either the full-detail drawing or the combination of the shape model and the partial-detail drawing is required for manufacturing processes. In the future-state process designers will create a 3D model with embedded PMI such that the model will completely support the manufacturing and inspection processes. This use case was used in the scope of this project.

CAD Model Validation

In this use case the current process is to manually inspect the 2D drawing and the 3D model separately when providing a producibility review or performing a check in preparation of design release into the PDM system. This relies entirely on the experience and ability of the operator to review the drawing or visually interpret the model. With embedded PMI the reviewer will need the capability to visualize and inspect the information in the 3D model. In the future, 3D models with the embedded PMI will lend themselves to more automated producibility and check (validation) tools. This automation, in turn, could enable in-process reviews to occur sooner and with more frequency than just when a designer submits work to a producibility engineer or checker near the release point for a design. This future state use case was not directly investigated as part of this project. But, during the project, metrics were captured that indicate gaps in tools and knowledge that must be overcome in order to properly embed PMI in a design model so that it is ready for consumption by downstream systems. This also amplifies the need for and importance of a model validation capability and tools.

Part Procurement (Bid Request; Supplier Portal)

The current practice is to provide the supplier with a 3D model (typically native CAD or STEP AP203 format) and a 2D drawing (PDF format) with the PMI not embedded in model. The information may be accessible through a supply chain portal at the OEM that allows the supplier to directly access both models and drawings. In the future, the 3D model with embedded PMI will be available through the same supply chain portal process. A 3D PDF (or equivalent) could also be provided for visualization as well as provide an integrated STEP file attachment for the supplier to access through the portal. This use case is out of scope for this project but should be explored in future work.

Engineering Changes (Request/Mark-up; Validation; Documentation)

Currently a change request requires the mark-up of a 2D drawing. Once the change is accepted and an ECO completed, the model and drawing updates are validated against the mark-up and the change order is provided to the supplier for implementation. This process creates opportunity for error in correctly converting the mark-up into the model. In the future, a process to address mark-up as well as convey the approved change in a full model-based approach will need to be determined. Several approaches have been demonstrated or discussed. This use case is out of scope for this project but should be addressed as industry moves to a complete model based enterprise.

Part Receiving Inspection

Today receiving inspection is completed using the 2D drawing. Parts are received from the supplier, along with the First Article Inspection Report (FAIR), which is typically provided in spreadsheet format. Receiving inspectors verify the report and check a portion of the part dimensions for consistency. In the future, when PMI is fully embedded in the 3D model, the receiving inspection process will require ability to utilize a format such as 3D PDF for visualization during part receiving inspection. This use case is out of scope for this project. There is opportunity to couple the development from this project with that of another ongoing NIST project to demonstrate the impact of model-centric data interoperability with first article inspection reporting and receiving inspection using the Quality Information Framework (QIF). [15]

Assembly Work Instructions

When a design is transformed into assembly work instructions, the 2D drawing is often used in the construction of those instructions. Assembly and manufacturing resource information associated with a particular route step is added alongside the 2D drawing for operators to follow the correct assembly process steps. In the future, a 3D visualization will replace the 2D drawing as part of the work instruction construct. This offers a more immersive experience as well as introduces other technologies to provide work instruction aids to the operators. This use case is out of scope for this project.

Technical Data Package Delivery (from OEM to Customer)

[15] NIST Collaborative Agreement: 70NANB14H256. (2015). *Validation for Downstream Computer Aided Manufacturing and Coordinate Metrology Processes*.

Today TDP delivery from an OEM to a customer is typically satisfied with 2D drawings. These may be augmented upon contract request with native CAD or STEP AP203 3D models. In the future, 3D models and 3D visualization artifacts are expected to be the primary basis for TDP delivery per MIL-STD-31000A. This use case is out of scope for this project but should be explored in related and future work.

Supplier Use Cases

Bid or Quote Process

Currently a supplier will use 2D drawings to provide a bid or quote. There is more estimation involved in the process when only a drawing is available. The opportunity to use a 3D model and associated 3D visualization file provides much more information and could even allow for some automated bidding tools. This use case is out of scope for this project, but some anecdotal insight may be provided as part of the findings.

CAM Model Creation

The CAM-programming use case focuses on the import of a STEP AP203 model for the shape-geometry. The 2D drawing is referenced for the PMI not embedded in the model. In addition, the manufacturing specifications that are referenced in the drawing are also reviewed to determine additional machine programming and secondary operations. It is difficult to envision what changes in the CAM modeling process will be introduced with the use of models with embedded PMI. There should be reduced risk of error between CAD and CAM models, and there may be improved ability to automate the validation of CAD model to CAM model. This use case is within scope of the project.

CAM Work Instruction Creation

Currently the 3D CAD model, usually in STEP AP203 format, and the manufacturing specifications referenced in the 2D drawing are used by the supplier to create part manufacturing work instructions. Starting with these artifacts, the actual instructions and graphics for each route step is created. It is anticipated that the future use case will remain similar but, it will require less reference to drawing specifications. This use case is out of scope for this project, but some anecdotal insight may be provided as part of the findings.

In-Process Part Inspection

Currently, the supplier will perform in-process inspection of a part to determine that certain dimensional aspects are correct before proceeding with the next steps of part manufacturing. This is accomplished by referencing the 2D drawing as well as the STEP AP203 model for information against which to inspect the part. Sometimes discrepancies between the CAD model and the drawing are discovered at this point. The future state with embedded PMI should offer less risk of discrepancy than might occur between the model and drawing. This use case will be out of scope for the project, but some anecdotal insight may be provided as part of the findings.

CMM Model Creation

The CMM-model use case utilizes the 2D drawing and the STEP AP203 model to create the CMM model. All the PMI is manually entered into the CMM application. The future state will directly import the embedded PMI from a STEP AP242 model, providing significant automation of data entry into the CMM system. Like the CAM programming, CMM model creation and machine programming provides a basis of measurement for the project.

CMM Inspection and First Article Inspection Report

The CMM-inspection use case involves a significantly manual process to generate the First Article Inspection Report. The anticipated future state enables a much more automated process. The inspection metrics will be captured in the project and will provide insight into the benefits possible for automating first article reporting. This use case is also explored in another NIST project involving the Quality Information Framework (QIF).[16]

Engineering Changes (Request/Mark-up; Validation; Documentation)

Today a change request requires the mark-up of a 2D drawing. Once the change is accepted and an ECO completed, the model and drawing changes are validated against the mark-up and the change order is provided to the supplier for implementation. This process creates opportunity for error in correctly converting the mark-up into the model. In the future, a method to address mark-up as well as convey the change in a model based approach will need to be determined. Several approaches have been demonstrated or discussed. This use case is out of scope for this project but should be addressed for industry to move to a complete model based enterprise.

Table 12: Product lifecycle use case metrics

Use Cases	**Metrics**				**Relative to Project Scope**
	Cycle Time	**Model Quality**	**Part Quality**	**Cost**	
at OEM					
CAD Model Creation	X	X			will be demonstrated
Model Validation (Producibility; Check; Release)	X	X		X	will be demonstrated
Part Procurement (Bid Request; Supplier Portal)	X			X	out of scope
Receiving Inspection	X		X		out of scope / possible anecdotal insight
Assembly Work Instructions					out of scope
Technical Data Package Delivery (to Customer)					out of scope
Engineering Change	X	X	X		out of scope
at Supplier					
Bid or Quote Process	X			X	out of scope / possible anecdotal insight
CAM Programming	X	X			will be demonstrated
Work Instruction Creation	X		X		may be out of scope
In-Process Inspection	X		X		out of scope / possible anecdotal insight
CMM Programming	X	X			will be demonstrated
CMM Inspection and FAI Report	X		X		will be demonstrated
Engineering Change	X	X	X		out of scope

[16] NIST Collaborative Agreement: 70NANB14H256. (2015). *Validation for Downstream Computer Aided Manufacturing and Coordinate Metrology Processes*.

Appendix B: Mapping PMI into STEP and ACIS

Appendix B.1: Mapping GD&T into STEP and ACIS

PMI	STEP AP242	ACIS
dimension types		
linear dimension	dimensional_location	spaxpmi_dimension
angular dimension	angular_location/angular_size	spaxpmi_dimension (no way to specify which angle)
radius dimension	dimensional_size.name = "radius"	spaxpmi_dimension
spherical radius dimension	dimensional_size.name = "spherical radius"	not covered
diameter dimension	dimensional_size.name = "diameter"	spaxpmi_dimension
spherical diameter dimension	dimensional_size.name = "spherical diameter"	not covered
oriented dimension	oriented_dimensional_location	not covered
curved dimension	dimensional_location_with_path / dimensional_size_with_path	not covered
dimension tolerance principle		
independency	shape_dimension_representation.name = "independency"	not covered
envelope	shape_dimension_representation.name = "envelope"	not covered
dimension values		
nominal value	measure_representation_item.name = "nominal value"	dimension value
nominal value with qualifier	qualified_representation_item	not covered
nominal value with plus / minus bounds	plus_minus_tolerance	not covered
value range	measure_representation_item.name = "upper limit" / "lower limit"	dimtol lower limit dimtol upper limit
tolerance class	limits_and_fits	not covered
dimension modifiers		
basic / theoretical	descriptive_representation_item.description = "theoretical"	dimension_type (dimtype_basic)
reference / auxiliary	descriptive_representation_item.description = "auxiliary"	dimension_type (dimtype_reference)
controlled radius	descriptive_representation_item.description = "controlled radius"	not covered
square	descriptive_representation_item.description = "square"	not covered
statistical tolerance	descriptive_representation_item.description = "statistical tolerance"	dimension_type (dimtype_tolerance)
continuous feature	descriptive_representation_item.description = "continuous feature"	not covered
two point size	descriptive_representation_item.description = "two point size"	not covered
local size defined by a sphere	descriptive_representation_item.description = "local size defined by sphere"	not covered
least-squares association criterion	descriptive_representation_item.description = "least-squares association criterion"	not covered

PMI	STEP AP242	ACIS
maximum inscribed association criterion	descriptive_representation_item.description = "maximum inscribed association criterion"	not covered
minimum inscribed association criterion	descriptive_representation_item.description = "minimum inscribed association criterion"	not covered
circumference diameter	descriptive_representation_item.description = "circumference diameter"	not covered
area diameter	descriptive_representation_item.description = "area diameter"	not covered
volume diameter	descriptive_representation_item.description = "volume diameter"	not covered
maximum size	descriptive_representation_item.description = "maximum size"	not covered
minimum size	descriptive_representation_item.description = "minimum size"	not covered
average size	descriptive_representation_item.description = "average size"	not covered
median size	descriptive_representation_item.description = "median size"	not covered
mid-range size	descriptive_representation_item.description = "mid-range size"	not covered
range of sizes	descriptive_representation_item.description = "range of sizes"	not covered
any restricted portion of feature	descriptive_representation_item.description = "any restricted portion of feature"	not covered
any cross section	descriptive_representation_item.description = "any cross section"	not covered
specific fixed cross section	descriptive_representation_item.description = "specific fixed cross section"	not covered
common tolerance	descriptive_representation_item.description = "common tolerance"	not covered
free-state condition	descriptive_representation_item.description = "free-state condition"	not covered
dimension decimal places	value_format_type_qualifier	dimtol precision
datum	datum	spaxpmi_datum
datum feature	datum_feature	attrib_spaxpmi_datum
datum target	placed_datum_target_feature	spaxpmi_datumtgt
point	axis2_placement_3d.name = "orientation"	datum_target_type (dt_point)
line	axis2_placement_3d / length_measure_with_unit.name = "target length"	datum_target_type (dt_line)
rectangle	axis2_placement_3d / length_measure_with_unit.name = "target width"	datum_target_type (dt_area_rect)
circle	axis2_placement_3d/length_measure_with_unit.name = "target diameter"	datum_target_type (dt_area_circ)
area	advanced_face	datum_target_type (dt_area_face)
movable datum target	Direction	not covered
tolerance	geometric_tolerance	attrib_spaxpmi_geom_tol
tolerance types		
angularity	angularity_tolerance	tol_type (toltype_angularity)
circular runout	circular_runout_tolerance	tol_type (toltype_runout_circular)
circularity / roundness	roundness_tolerance	tol_type (toltype_circularity)
coaxiality	coaxiality_tolerance	not covered

PMI	STEP AP242	ACIS
concentricity	concentricity_tolerance	tol_type (toltype_concentricity)
cylindricity	cylindricity_tolerance	tol_type (toltype_cylindricity)
flatness	flatness_tolerance	tol_type (toltype_flatness)
parallelism	parallelism_tolerance	tol_type (toltype_parallelism)
perpendicularity	perpendicularity_tolerance	tol_type (toltype_perpendicularity)
position	position_tolerance	tol_type (toltype_position)
profile of a line	line_profile_tolerance	tol_type (toltype_profile_line)
profile of a surface	surface_profile_tolerance	tol_type (toltype_profile_surf)
straightness	straightness_tolerance	tol_type (toltype_straightness)
symmetry	symmetry_tolerance	tol_type (toltype_symmetry)
total runout	total_runout_tolerance	tol_type (toltype_runout_total)
tolerance zone		
diameter	tolerance_zone_form.name = "cylindrical or circular"	mod_dia_type (dm_dia)
spherical diameter	tolerance_zone_form.name = "spherical"	mod_dia_type (dm_spherical_dia)
within a circle	tolerance_zone_form.name = "within a circle"	not covered
between two concentric circles	tolerance_zone_form.name = "between two concentric circles"	not covered
between two equidistant curves	tolerance_zone_form.name = "between two equidistant curves"	not covered
within a cylinder	tolerance_zone_form.name = "within a cylinder"	not covered
between two coaxial cylinders	tolerance_zone_form.name = "between two coaxial cylinders"	not covered
between two equidistant surfaces	tolerance_zone_form.name = "between two equidistant surfaces"	not covered
runout	runout_zone_definition	not covered
projected	projected_zone_definition	p_mag
non-uniform	non_uniform_zone_definition	not covered
tolerance modifiers		
any cross section	geometric_tolerance_with_modifiers.modifiers = .ANY_CROSS_SECTION.	not covered
common zone	geometric_tolerance_with_modifiers.modifiers = .COMMON_ZONE.	not covered
each radial element	geometric_tolerance_with_modifiers.modifiers = .EACH_RADIAL_ELEMENT.	not covered
free state	geometric_tolerance_with_modifiers.modifiers = .FREE_STATE.	zone_modifier_type (zm_fs)
least material requirement	geometric_tolerance_with_modifiers.modifiers = .LEAST_MATERIAL_REQUIREMENT.	zone_modifier_type (zm_lmc)
line element	geometric_tolerance_with_modifiers.modifiers = .LINE_ELEMENT.	not covered
major diameter	geometric_tolerance_with_modifiers.modifiers = .MAJOR_DIAMETER.	not covered
maximum material requirement	geometric_tolerance_with_modifiers.modifiers = .MAXIMUM_MATERIAL_REQUIREMENT.	zone_modifier_type (zm_mmc)

PMI	STEP AP242	ACIS
minor diameter	geometric_tolerance_with_modifiers.modifiers = .MINOR_DIAMETER.	not covered
not convex	geometric_tolerance_with_modifiers.modifiers = .NOT_CONVEX.	not covered
pitch diameter	geometric_tolerance_with_modifiers.modifiers = .PITCH_DIAMETER.	not covered
reciprocity requirement	geometric_tolerance_with_modifiers.modifiers = .RECIPROCITY_REQUIREMENT.	zone_modifier_type (zm_rfs)
separate requirement	geometric_tolerance_with_modifiers.modifiers = .SEPARATE_REQUIREMENT.	not covered
statistical tolerance	geometric_tolerance_with_modifiers.modifiers = .STATISTICAL_TOLERANCE.	zone_modifier_type (zm_st)
tangent plane	geometric_tolerance_with_modifiers.modifiers = .TANGENT_PLANE.	zone_modifier_type (zm_tp)
unequally-disposed tolerance	unequally_disposed_geometric_tolerance	p_shift
tolerance with maximum value	geometric_tolerance_with_maximum_tolerance	not covered
unit-basis tolerance		
length	geometric_tolerance_with_defined_unit	runit1
circular	geometric_tolerance_with_defined_area_unit.area_type = .CIRCULAR.	runit1
rectangular	geometric_tolerance_with_defined_area_unit.area_type = .RECTANGULAR.	runit1,runit2
square	geometric_tolerance_with_defined_area_unit.area_type = .SQUARE.	runit1
composite tolerance	geometric_tolerance_relationship	attrib_spaxpmi_geom_tol
tolerance with datum references	geometric_tolerance_with_datum_reference	spaxpmi_drf
datum reference	datum_reference_compartment	spaxpmi_dref
datum reference modifiers		
free state	simple_datum_reference_modifier.modifiers = .FREE_STATE.	not covered
basic	simple_datum_reference_modifier.modifiers = .BASIC.	not covered
translation	simple_datum_reference_modifier.modifiers = .TRANSLATION.	not covered
least material requirement	simple_datum_reference_modifier.modifiers = .LEAST_MATERIAL_REQUIREMENT.	datum_modifier_type (datum_modifier_lmc)
maximum material requirement	simple_datum_reference_modifier.modifiers = .MAXIMUM_MATERIAL_REQUIREMENT.	datum_modifier_type (datum_modifier_mmc)
point	simple_datum_reference_modifier.modifiers = .POINT.	not covered
line	simple_datum_reference_modifier.modifiers = .LINE.	not covered
plane	simple_datum_reference_modifier.modifiers = .PLANE.	not covered
orientation	simple_datum_reference_modifier.modifiers = .ORIENTATION.	not covered
any cross section	simple_datum_reference_modifier.modifiers = .ANY_CROSS_SECTION.	not covered
any longitudinal section	simple_datum_reference_modifier.modifiers = .ANY_LONGITUDINAL_SECTION.	not covered
contacting feature	simple_datum_reference_modifier.modifiers = .CONTACTING_FEATURE.	not covered

PMI	STEP AP242	ACIS
distance variable	simple_datum_reference_modifier.modifiers = .DISTANCE_VARIABLE.	not covered
degree of freedom constraint x	simple_datum_reference_modifier.modifiers = .DEGREE_OF_FREEDOM_CONSTRAINT_X.	not covered
degree of freedom constraint y	simple_datum_reference_modifier.modifiers = .DEGREE_OF_FREEDOM_CONSTRAINT_Y.	not covered
degree of freedom constraint z	simple_datum_reference_modifier.modifiers = .DEGREE_OF_FREEDOM_CONSTRAINT_Z.	not covered
degree of freedom constraint u	simple_datum_reference_modifier.modifiers = .DEGREE_OF_FREEDOM_CONSTRAINT_U.	not covered
degree of freedom constraint v	simple_datum_reference_modifier.modifiers = .DEGREE_OF_FREEDOM_CONSTRAINT_V.	not covered
degree of freedom constraint w	simple_datum_reference_modifier.modifiers = .DEGREE_OF_FREEDOM_CONSTRAINT_W.	not covered
minor diameter	simple_datum_reference_modifier.modifiers = .MINOR_DIAMETER.	not covered
major diameter	simple_datum_reference_modifier.modifiers = .MAJOR_DIAMETER.	not covered
pitch diameter	simple_datum_reference_modifier.modifiers = .PITCH_DIAMETER.	not covered
with value	datum_reference_modifier_with_value	not covered
common datum/multiple datum features	datum_reference_element	spaxpmi_dref
polyline presentation	annotation_curve_occurrence / annotation_fill_area_occurrence / annotation_symbol_occurrence / annotation_text_occurrence/tessellated_annotation_occurrence	body/wire
BREP		
topology		
solid	manifold_solid_brep	body/lump
shell	closed_shell / open_shell	shell
face	advanced_face	face
loop	face_bound / face_outer_bound / edge_loop / vertex_loop	loop
edge	oriented_edge / edge_curve	edge/coedge
vertex	vertex_point / cartesian_point	vertex
surface geometry		
cone	conical_surface	cone
cylinder	cylindrical_surface	cone
extruded surface	surface_of_linear_extrusion	spline
nurbs	b_spline_surface / b_spline_surface_with_knots / rational_b_spline_surface / uniform_surface / quasi_uniform_surface / bezier_surface	spline
offset surface	offset_surface	off_spl_sur
plane	planar_surface	plane
revolved surface	surface_of_revolution	rot_spl_sur
sphere	spherical_surface	sphere
torus	toroidal_surface	torus
curve geometry		

PMI	STEP AP242	ACIS
circle	circle	ellipse
ellipse	ellipse	ellipse
parabola	parabola	bs3_curve
hyperbola	hyperbola	bs3_curve
nurbs	b_spline_curve / b_spline_curve_with_knots / rational_b_spline_curve / uniform_curve / quasi_uniform_curve / bezier_curve	bs3_curve
offset curve	offset_curve_3d	bs3_curve
line	line	straight
linkages		
PMI<->BREP	BREP<-geometric_item_specific_usage->shape_aspect<-PMI	spacollection / entity
PMI<->polyline presentation	PMI<-draughting_model_item_association->annotation_occurrence / draughting_callout	not covered

Appendix B.2: Mapping Other MBD-related Items into STEP and ACIS

PMI	STEP AP242	ACIS
Notes	text_literal	not supported
Flag Notes	not supported	attrib_spaxpmi_flagnote
Surface Finish (roughness)	not supported	attrib_spaxpmi_roughness
Tables	not supported	not supported
Global or General Tolerances	not supported	not supported
Views	draughting_model / camera_model	spaxpmi_capture

Appendix C: Technology Readiness Levels (TRL)[17]

TRL 1: Lowest level of technology readiness. Scientific research begins to be translated into applied research and development (R&D). Examples might include paper studies of a technology's basic properties.

TRL 2: Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies.

TRL 3: Active R&D is initiated. This includes analytical studies and laboratory studies to physically validate the analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.

TRL 4: Basic technological components are integrated to establish that they will work together. This is relatively "low fidelity" compared with the eventual system. Examples include integration of "ad hoc" hardware in the laboratory.

TRL 5: Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so they can be tested in a simulated environment. Examples include "high-fidelity" laboratory integration of components.

TRL 6: Representative model or prototype system, which is well beyond that of TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a simulated operational environment.

TRL 7: Prototype near or at planned operational system. Represents a major step up from TRL 6 by requiring demonstration of an actual system prototype in an operational environment.

TRL 8: Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development.

TRL 9: Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation (OT&E).

[17] United States Department of Defense. (2011, April). *Technology Readiness Assessment (TRA) Guidance*. Retrieved from http://www.acq.osd.mil/chieftechnologist/publications/docs/TRA2011.pdf.