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Validation for Downstream Computer Aided Manufacturing and Coordinate Metrology Processes

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By
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Validation for Downstream Computer-Aided Manufacturing and Coordinate-Metrology Processes %

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ABSTRACT

To achieve industry's 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. Today, almost all suppliers use Computer-Aided Manufacturing (CAM) and Coordinate Measuring Machine (CMM) models respectively for these tasks. In the MBE vision for model-centric data exchange, the CAD model must include product and manufacturing information (PMI) in addition to the shape geometry. Today's CAD tools can generate models with embedded PMI, with the emergence of STEP AP242, a standards-based model with embedded PMI can now be shared downstream. This project investigates the ability to utilize a STEP AP242 model with embedded PMI for CAD-to-CMM data exchange. The project examines transformational processes and identifies gaps that will impact industry's ability to achieve model-centric data interoperability cost-effectively in the pursuit of the MBE vision.

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EXECUTIVE SUMMARY

To achieve industry's 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. Today, almost all suppliers use Computer-Aided Manufacturing (CAM) and Coordinate Measuring Machine (CMM) models respectively for these tasks. Until recently data for shape has been transferred downstream via STEP AP203 but collaborators had to handle product manufacturing information (PMI, i.e. dimensions and tolerances) for metrology planning and execution via transcription from drawings.   With the recent availability of STEP AP242, the promise of direct transformation of design data to downstream consumers including PMI in a single MBD package now exists. The vision of MBE is that by using STEP AP242 for interoperability of rich design information with the manufacturing and metrology supply chain, the process would be faster, more accurate, and be less error prone.

This project was developed to investigate the interaction between STEP AP242 and CAM and CMM systems by using ACIS, the predominant modeling kernel in the manufacturing and metrology space. Algorithms were developed to transform the data but more importantly to show that validation was a critical component of success in the transformation process. In addition to examining ACIS as a vehicle for transforming design data into metrology data, the team also examined the emerging QIF standard and mapped it to STEP AP242 to determine what effort might be required to make STEP and QIF the standards of choice for this process.

The project team included interoperability experts in STEP and ACIS as well as QIF. The team developed metrics for validation of PMI data into ACIS and examined the results of the STEP to ACIS transformation and validation process. The team also examined STEP and QIF standards to determine where there was commonality, where there was overlap, and where there were gaps between the standards.

This project demonstrated the ability to transform design model data that included PMI from STEP AP242 data into extended ACIS for use by Manufacturing and Metrology systems. It confirmed that transformation of such semantically rich PMI data requires an automated method to validate that the transformed data is complete and correct for downstream use.

PROJECT TEAM

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INTRODUCTION

> ***The challenge:*** *Given industry's vision of MBE, and immerging research into model-centric data interoperability between design and manufacturing and quality inspection, shouldn't these new model-centric data interoperability processes include validation mechanisms to ensure data quality and provide a metric for measuring the evolution of these processes as they mature?*

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 an 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 from 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) model with shape geometry. This model is often provided in a standards-based model format – STEP AP203 is prevalent. However, in addition to geometry, the downstream CAM and CMM processes also require product and manufacturing information (PMI) in order to fabricate and inspect the physical part.

The vision of MBE and supply chain interoperability using an MBD-based process has great potential to improve efficiency and achieve higher product quality. In 2014 a new STEP Application Protocol (AP), AP242, was published which was developed to consolidate and replace previous APs and includes support for PMI (Reference A). STEP AP242 would seem to represent the way forward to solving this downstream interoperability problem.

As stated in Reference A, many downstream systems have proprietary direct translation capability and that some of those capabilities include PMI support, though none of these systems yet support the STEP standard. The long term desire, however, is for the CAM and CM communities to support the direct consumption of STEP AP242 and other international standards with precise geometry and semantic PMI data, a more achievable approach in the short term is to leverage the modeling kernels that are the basis for many CAM and CM systems, the ACIS and Parasolid kernels. The research conducted in Reference A clearly demonstrates that this standards-based approach to downstream interoperability is feasible.

While standards-based exchange provides significant benefit to industry, one challenge that must be addressed is verification and validation of translations, ensuring adequate product data quality. The ability to validate that model data is transformed properly during the interoperability process is important to manufacturers large and small. Without it, data consumers cannot be sure that their content is complete and accurate and the risk of potentially costly rework is a major concern. Performing such validation by hands-on inspection has been,

when 2D drawings are the method for exchange of manufacturing data in the supply chain, the purview of design checkers.   The need for confidence in the conformance of 3D model data to quality standards is well understood [13].   While validation of 3D modeling data by hands-on inspection is certainly possible, it is not desirable. The process is painstakingly slow, requires a high level of skill and attention to detail, and there is a high likelihood of error even when done by a skilled practitioner.   It is also important to note that even though the burden of validation is important for geometry interoperability, it is even more critical and more challenging when PMI interoperability is required.   As such, formal requirements for verification of model data, particularly PMI data, and validation of derivative variants of that data for collaboration purposes are now in place [14].

Automation of validation for CAD-to-CAD interoperability processes is becoming an important tool particularly for 3D model data containing PMI (Reference B and Reference C).   Validation of transformed model data in the CAM and CM context is just as important to instilling confidence in automated processes for the CAM and CM communities.

STEP is generally considered to be the method of choice for CAD-to-CAD interoperability for shape, and with the availability of semantic PMI constructs in STEP AP242, STEP shows promise as a strong candidate for interoperability between CAD and CM.   The metrology community has developed their own standard, the Quality Information Framework (QIF, Reference D), to support the unique needs of that community.   QIF contains data structures for collecting, organizing, and analyzing measurement data and metrology systems are beginning to make use of those QIF standard structures.   QIF also has its own MBD data structures for both shape (geometry) and PMI.   A case could be made for interoperability between these two complementary standards.

> **First hypothesis:** *Transformation of MBD data from CAD to CAM and CAD to CMM requires a mechanism to validate the integrity and quality of the downstream data and that validation of such data provides insight into the state of art for downstream interoperability systems.*
>
> **Second hypothesis:** *The STEP AP242 and QIF standards share common ground as far as geometry and PMI interoperability is concerned and that there is an opportunity to bridge the gap between CAD and CMM communities through interoperability between these two standards.*

This project will test these two hypotheses. The first hypothesis is that model-based data transformed from CAD-to-CAM and CAD-to-CMM via STEP AP242 and ACIS can be validated using automated methods and that there is significant value in performing such validations to evaluate the nascent capabilities for interoperability between design and downstream processes. The second hypothesis is that STEP AP242 and QIF 2.0 are aligned as far as geometric and PMI data are concerned and that harmonization these standards represent a

potential way forward for future interoperability tools and processes. The project will answer the question of the current state of evolution of early CAD-to-CMM transformation tools through demonstration and measured results. It will also answer the question of how closely aligned the two standards are that may connect CAD to CMM.   It will provide for discussion and recommendations based upon the findings and observations. Finally, the project will draw conclusions about the level of maturity of standards-based model-centric data interoperability between upstream creation and downstream consumption.

MOTIVATION FOR THE STUDY

The motivation: Demonstrate the value of validation of model-centric CAD-to-CAM and CAD-to-CMM data interoperability when using STEP AP242 with embedded PMI transformed into extended ACIS data.

The research team believes this project will assist industry in its drive to achieve the vision of the Model-Based Enterprise down into the manufacturing supply chain if the above hypotheses can be substantiated.

A 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.

When moving to a model-based paradigm, the verification process is more complex since the goal is for the model geometry and PMI to be consumed directly by downstream software systems. Verification in this context requires each and every PMI element be analyzed for syntactical and semantic accuracy including proper association of the PMI to geometric references in the 3D geometry.

In addition to verifying that PMI content has been authored correctly, each time the data is transformed – from CAD to STEP and from STEP to CAM/CMM – the data must be validated to be sure no data corruption occurred during the transformation process. Since the information content in the 3D model is no longer in the form of a visually inspect-able 2D drawing, special software algorithms are required to perform the verification and validation processes on all but the simplest models.
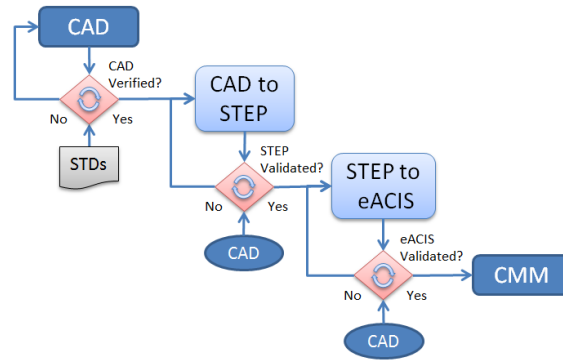
Figure 1 - Verification and validation process flow diagram

In the case of this project, we performed verification and validation following the process outlined in Figure 1. We performed verification and validation using a combination of traditional visual inspection techniques and automated techniques. In general use on more complex models, automated techniques would have been required.

The research team also believes that the developed technology and the aforementioned standards are extensible to include PMI data items beyond those used in the test models. The application can successfully exchange more complex parts than the project's demonstrated test models. The software application used in this demonstration will achieve Technology Readiness Level (TRL) 6. A list of TRL definitions is given in Appendix C. This provides motivation for commercialization of interoperability validation tools to provide standards-based 3D models with embedded PMI to the CAM and CMM industry. It is expected that CAM and CMM tools providers would be motivated to commercialize the ability to receive and utilize standards-based 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, manufacturing, inspection, and collaboration across the supply chain.

METHOD
The methodology used to test the above hypotheses is described below.

Approach Outline
To test the hypotheses, the following approach was used:

- Determine test cases for validation processing,
- Develop metrics for evaluating validation results,
- Develop prototype software for automatic validation of extended-ACIS models against original CAD data,
- Validate extended-ACIS models against source STEP model data,

- Collect and analyze metrics data to evaluate the maturity of STEP to ACIS transformation process and also to evaluate the maturity of the validation process itself,
- Determine the scope for mapping of STEP to QIF, and
- Map model-based PMI requirements from STEP to QIF and identify gaps that inhibit development of interfaces between these two standards.

Each of these elements of the approach is discussed below.

Determination of Test Cases - Models and Data Sets

In keeping with the collaborative nature of this project and its companion project (Reference A), the initial two test cases for this project were selected to be the same two models selected by that companion project team. This was a logical choice as native NX^{TM} CAD model data already existed and had been used as the source for the intermediate STEP models and the ACIS models in CAM and CM. Furthermore, all of the data - native, STEP, and ACIS - had been thoroughly analyzed by hand for completeness and correctness. These data were used to exercise the developed algorithms for automatically validating PMI-extended ACIS against native CAD models. These test cases are shown in Figures 2 and 3 below.
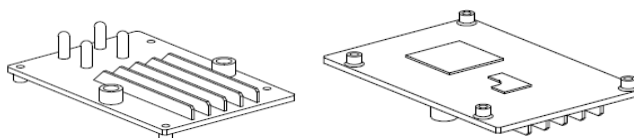
Figure 2 - Test Case #1 – Milled Part 827-9999-904
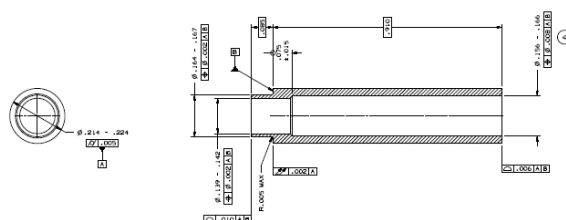
Figure 3 - Test Case #2 – Revolved Part 827-9999-903

The above two test cases were augmented by leveraging a subset of the now well-known NIST test cases and models available from References B and C. The test data were chosen from STEP files generated during several recent PDES/ProSTEP CAx test rounds. The selected STEP models were those for which semantic PMI annotation had been generated.

Definition of Validation Metrics

A mechanism was needed to quantify the extent of successful transformation of PMI annotation information from the original CAD PMI data to that same PMI data in ACIS format. The authors selected five major categories of PMI annotation data to be used as metrics for this initial validation research activity. For each of these major categories, a selected set of semantic PMI content (parameter values) would be evaluated.

The PMI annotation categories selected and the semantic parameters to be used for validating for each annotation type are shown Table 1 below:

Table 1 - PMI Annotation Categories for Validation Purposes

PMI Category	PMI Content Validated
Datum Feature Symbol (DFS)	Identifier
Datum Target Symbol (DTS)	Identifier Target type
Dimension (DIM)	Tolerance format Nominal value (with unit) Upper and lower values (with unit)
Feature Control Frame (FCF)	Type Symbol Overall tolerance Datum reference frame identifiers Modifiers
Note (NOTE)	Text
- Symbols shown in parentheses above are used in the validation results table in Appendix B to identify each PMI annotation category listed	

Development of CAM/CM (ACIS) Validation Algorithm

The plan for algorithm development was split into two phases. The first phase was to focus on the development of a prototypical capability to validate ACIS geometry. Data structures for geometry in ACIS are well known, stable, and other geometry data models can easily be mapped to ACIS. Following the development of a validation capability for geometry, the second, more challenging phase would focus on development of validation capability for PMI data. This second phase was expected to be more complex. This was due to the fact that ACIS is first and foremost a geometry model schema and that extensions to include PMI constructs are evolving. Further comments on this extended ACIS, its maturity for PMI, and the effects of that maturity on validation will be discussed in the results section.

Validation of Extended ACIS and Collection and Analysis of Validation Metrics

Validation of extended ACIS was performed by applying the developed algorithm to evaluate geometry and PMI entities in both each STEP model and its derived ACIS model. This was done for the original companion project test cases as well as selected members of the broader NIST test suite. For each test case, each entity pair was analyzed for correctness of the mapping and compared for matching values of the entity's properties. The metrics described in Table 1 were counted as either "clean" or "different" for every PMI entity pair. An entity pair was considered "clean" if the entity structure properties were preserved during transformation and if the values of those properties in the target ACIS data matched the values of the properties in the source STEP data. The results were analyzed to determine, where possible, whether any differences were a result of issues in the transformation algorithm or a result of the validation algorithm.

Scope and Mapping Process for PMI Mapping to QIF

For the STEP QIF mapping exercise, a group of STEP and QIF subject matter experts from ITI, Honeywell FM&T, Capvidia, and Metrosage, together with STEP and QIF standards experts from NIST, gathered in a workshop at the Spring 2015 PDES Offsite in Gaithersburg, MD, to form a working group responsible for the PMI mapping task. That working group collectively determined ground rules for the mapping research and outlined a reasonable scope for the mapping process. The working group agreed to leverage the STEP and ACIS mapping tables produced as part of the companion project (again Reference A) as the framework for the QIF mapping. The working group also agreed to focus attention on the subset of QIF referred to as QIF MBD – that part of the QIF standard addressing product shape and PMI content that would likely be received from upstream design-related processes.

Following the workshop, the working group held bi-weekly conference calls over the course of a 3-month period to review mapping progress, discuss issues concerning interpretation of the standards, and formulate new work items for the next two-week period. Over the course of that period the existing STEP-ACIS mapping table was extended to include QIF MBD constructs. Additionally, gaps between the standards that could not be closed were identified for later resolution.

RESULTS

Results from Mapping PMI between STEP and QIF

A broad subset of the possible categories of PMI data were mapped as part of this project. The mapping categories [STEP -> QIF] are listed below:

- % Boundary representation geometry,
- % Construction geometry, including points, planes, coordinate systems, curves, surfaces, and axes,
- % GTOLs and dimensions (including their tolerances),
- % Default or general tolerances,
- % Notes (including general and flag notes),
- % Tables,
- % Title block information,
- % Datums, including datum targets, datum tags, and datum reference frames, and
- % Saved views.

Certain categories of data were not mapped [STEP to QIF] as part of this project. Mapping of the three non-mapped data categories is a subject for future research. These categories are indicated in the list below:

- % Layers and groups,
- % Assembly structure, including component instancing, and
- % Cross-sections (and planar sketches).

The result of the mapping exercise was a table of PMI elements and their appropriate entities in STEP, ACIS, and QIF formats. For the purposes of discussion in this report, the table was broken up in to separate sections. Though focused on mapping of PMI related content in this study, the authors have included mappings for geometric shape entities for completeness.   The various mappings are listed below:

- GD&T Entities
- Linkage Entities
- PMI Features and User Defined Tolerances
- Boundary Representation Geometry Entities
- Other MBD-related Entities

All mapping tables are presented in Appendix A and discussed later in this report. An example of a portion of the GD&T mapping table is shown in Figure 4 below.

	STEP AP242	ACIS	QIF
PMI			
dimension types			
linear dimension	dimensional_location	spaxpmi_dimension (DIMSUBTYPE_LENGTH_OR_DISTANCE)	LengthCharacteristicDefinitionType
angular dimension	angular_location/angular_size	spaxpmi_dimension (DIMSUBTYPE_ANGLE)(no way to specify m	AngularCharacteristicDefinitionType
radius dimension	dimensional_size	spaxpmi_dimension (DIMSUBTYPE_RADIUS)	RadiusCharacteristicDefinitionType
diameter dimension	dimensional_size	spaxpmi_dimension(DIMSUBTYPE_DIAMETER)	DiameterCharacteristicDefinitionType
oriented dimension	oriented_dimensional_location	not covered	...
curved dimension	dimensional_location_with_path/dimensional_size_with_path	spaxpmi_dimension(DIMSUBTYPE_CURVILINEAR)	CurvedLengthCharacteristicDefinitionType
coordinate dimension		spaxpmi_dimension(DIMSUBTYPE_COORDDIM2D, DIMSUBTYPE_	LinearCoordinateCharacteristicDefinitionType
dimension tolerance principle			
independency	shape_dimension_representation.name	not covered	<>EnvelopeRequirement(FALSE)
envelope	shape_dimension_representation.name	not covered	<>EnvelopeRequirement(TRUE)
dimension values			
nominal value	measure_representation_item	dimension value	<>TargetValue
nominal value with qualifier	qualified_representation_item	not covered	<>TargetValue
nominal value with plus/minus bounds	plus_minus_tolerance	not covered	<>DefinedAsLimit(FALSE)
value range	measure_representation_item	dimtol lower limit/dimtol upper limit	<>DefinedAsLimit(TRUE)
tolerance class	limits_and_fits	not covered	
dimension modifiers			
basic/theoretical	descriptive_representation_item	dimension_type (dimtype_basic)	<>DimensionType(BASIC)
reference/auxiliary	descriptive_representation_item	dimension_type (dimtype_reference)	<>DimensionType(REFERENCE)
controlled radius	descriptive_representation_item	not covered	RadiusCharacteristicDefinitionType<>ControlledRadius(TRUE)
square	descriptive_representation_item	not covered	SquareCharacteristicDefinitionType
statistical tolerance	descriptive_representation_item	dimension_type (dimtype_tolerance)	CharacteristicDefinitionBaseType<>StatisticalCharacteristic(TRUE)
continuous feature	descriptive_representation_item	not covered	

Figure 4 - Example of PMI(GD&T)/STEP/ACIS/QIF Mapping Table

Results from Validation of Original Project Test Models

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 2. The validation shows that all dimensions, tolerances, and datum features were transformed and exchanged.

Indicated in Table 2, general notes could not be mapped to ACIS. Although manual validation showed correct PMI counts (for PMI other than general notes), further detailed examination by automated validation of the downstream models using analysis software found anomalies in the transformed data.

Table 2: 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

Table 3 shows the results of automated validation of model transformations. In the -904 model, the automated validation tool showed that though all dimensions were transformed and, for the most part, semantically correct, a rule violation occurred when the dimension tolerance zone for one dimension was considered large relative to its nominal value. The -903 model, like the -904 model, was flagged for an instance of this same rule violation. The -903 model was also flagged for failure to maintain the semantic definition of limit dimensions in four instances of that dimension type when transformed from STEP to ACIS.

Table 3: Validation of models using analysis software

Model File	DFS[1] Clean	DIM[2] Clean	FCF[3] Clean	Clean Percent
827-9999-903	2	3	6	69%
827-9999-904	3	53	13	99%

The counts shown in Table 3 refer to the number of entities that are clean (e.g., pass all syntax and semantic validity checks during analysis of STEP to ACIS transformations). The clean percent in Table 3 ignores note entity errors.

---

[1] DFS = Datum Feature Symbol
[2] DIM = Dimension
[3] FCF = Feature Control Frame

Example validation results are shown in Figure 5 (for semantic representation PMI) below. %
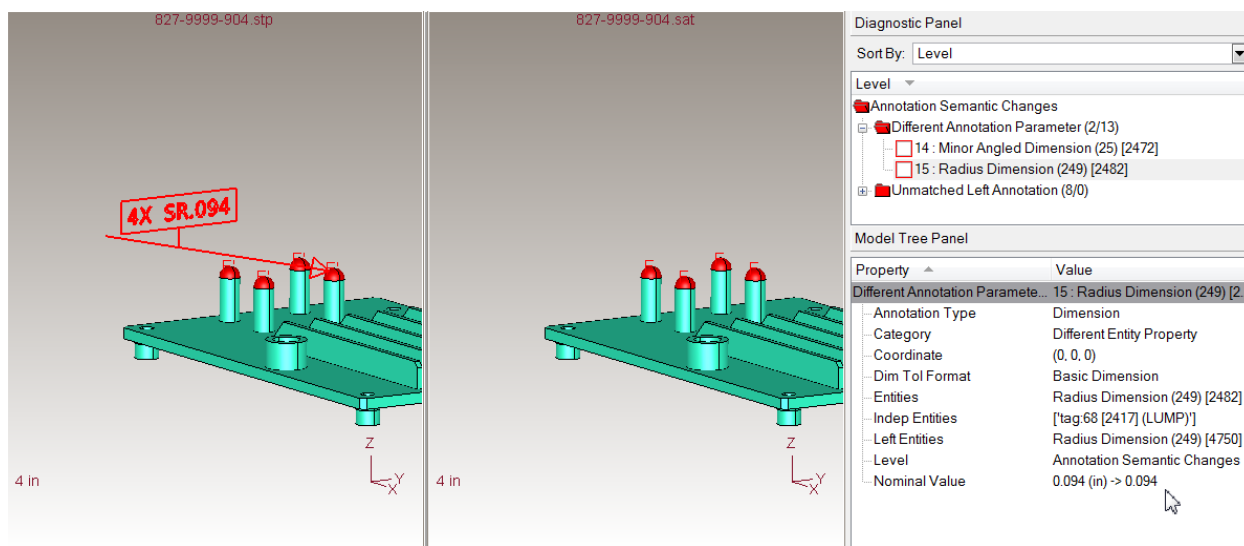
Figure 5 - Example of Validation of extended-ACIS PMI with Source STEP Model

Note that, in the example shown, though the value of the dimension was preserved during transformation, the units of the dimension value were lost. Investigation of this observed behavior suggests that adjustment to ACIS handling of units is required.

Results from Validation of Test Models from NIST Data Sets

A broader suite of models (the NIST CTCs and FTCs from Reference C and/or D were also processed to identify what additional coverage gaps might exist.   Validation of the STEP data relative to the original master CAD models was published in the above references and will not be repeated here.   Instead, the validation results described in this report are for the validation of the extended ACIS models as transformed from the STEP models. It is also important to note that the STEP files used in this study are models from the very latest PDES/ProSTEP CAx testing rounds. The results are cataloged in Appendix B.

An example of validation results is shown in Figure 6 (for PMI representation – see "model tree panel" lower left [STEP] and lower right [ACIS]).
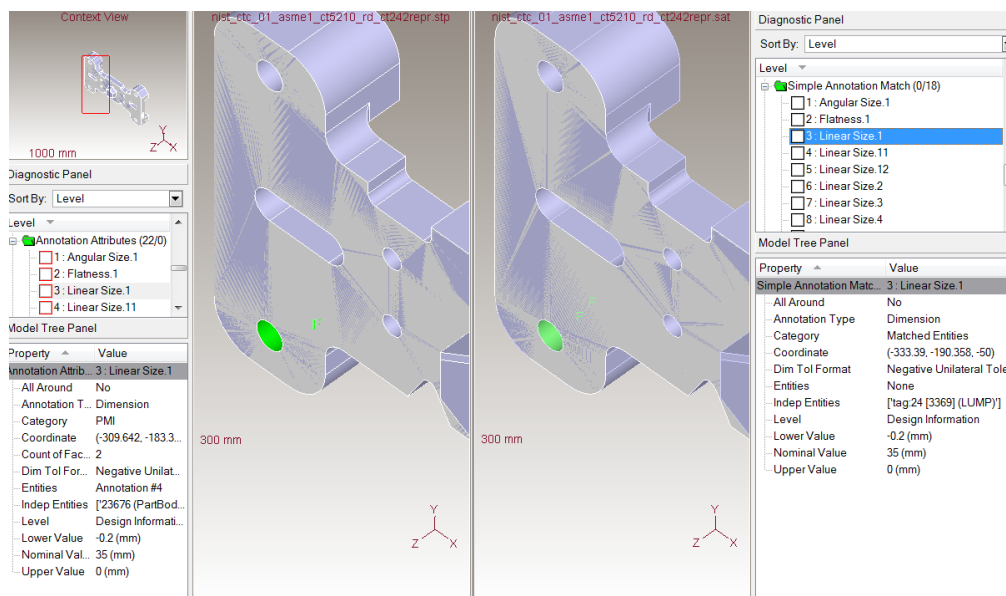
Figure 6 - Example of Successful Validation of extended-ACIS PMI representation with Source STEP Model

In this NIST CTC01 example, all semantic representation data for a linear dimension of size, including association to geometry, was successfully preserved during transformation from STEP to extended ACIS.

In a second example of validation results, shown in Figure 7 (for PMI representation – see "model tree panel" lower left [STEP] and lower right [ACIS]), the validation algorithm flags a semantic representation change due to the fact that there is no ACIS data structure for the nominal value dimension without tolerances found in the source STEP data. The current approach to work around this issue is to populate the corresponding ACIS data structure for a regular dimension with tolerances and leave the tolerance values set to zero values.
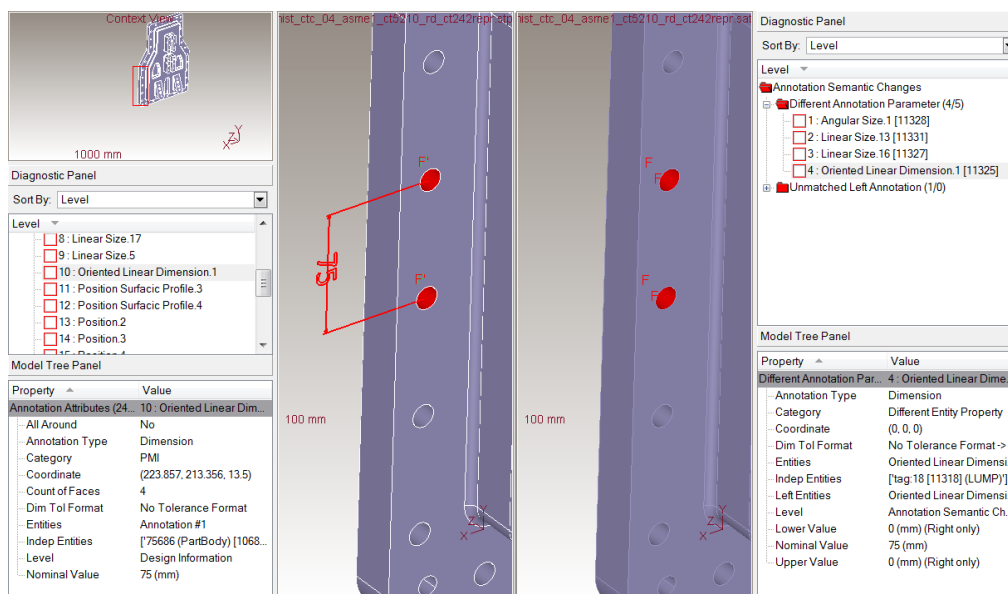
Figure 7 - Example of validation of extended-ACIS PMI representation with source STEP Model illustrating an anomaly

Additional discussion of validation results, anomalies, and likely causes will be discussed below.

DISCUSSION AND CONCLUSIONS

STEP - QIF PMI Mappings

As discussed earlier in this report, mapping between STEP and QIF resulted in some disconnects as shown in Figure 8. Some of these differences are discussed below.

- PMI
  - Dimension Types (19/21)
  - Dimension Tolerance Principle (2/2)
  - Dimension values (45/48)
  - Tolerance Types (15/18)
  - Tolerance Zone (13/18)
  - Tolerance Modifiers (17/21)
  - Unit based Tolerance (9/9)
  - Datum reference modifiers (25/32)
- Shape
  - Topology (8/8)
  - Surface Geometry (11/11)
  - Curve Geometry (10/10)

- Links
  - PMI <-> Brep (both)
  - PMI <-> Polyline presentation (both)

- Miscellaneous
  - Notes (both)
  - Flag Notes (QIF)
  - Surface Finish (QIF)
  - Tables (none)
  - Global or General Tolerances (none)
  - Views (both)

(# of STEP elements / # of QIF elements)

Figure 8 - Tally of mappings between STEP and QIF

There was generally good agreement between QIF and STEP for boundary representation shape and geometry. Two element types – mesh face and mesh loop - were supported in STEP and QIF but were absent in ACIS.

The STEP-QIF working group discussed the concept of feature at length but was not able to fully close on agreement on a reasonable mapping between the two standards. The concept of "feature" is used in many systems and standards but there is often significant variation in the meaning and usage of the term among them.   STEP has the concept of feature in AP242 (design feature) as well as AP238 (manufacturing feature), both represent a shape element that is flexibly defined by parameters which control the size or location of the shape element. QIF also has the concept of feature but that did not have direct STEP equivalent (26 QIF elements). It appeared to be a categorized shape aspect. The working group thinks these QIF features would map back and forth as shape aspects however they agreed to table the attempt to map features and recommend a separate research activity just to explore this construct.

Another area that should be studied further is that, in QIF, there are a number of user-defined tolerance entity types that were included in QIF but not included in STEP or ACIS. The working group agreed to table the attempt to map these UDTs and recommend follow-on research to explore this construct.

As shown in Figure 8, a number of ancillary MBD-related elements, also shown in Appendix A.5, are important for proper MBD usage and either do not currently have support in one or more standards. Examples of this include Notes, which are not supported in ACIS, and both Flag Notes and Surface Finish, which are not supported in STEP. In addition, there were two MBD-related elements that were not supported in any of the examined standards (e.g. Tables and Global or General Tolerances). Of the two of these, the ability to capture and map global or general tolerances was considered to be a significant impediment to MBD exchange due to its widespread use in industry.

A final observation is that, in many cases, PMI constructs could be mapped for STEP and for QIF but not for ACIS. This suggests that STEP to QIF may be a better exchange mechanism than STEP to ACIS once downstream consuming systems have developedand begun delivering QIF import capabilities.

Validation of Extended ACIS

There were a significant number of anomalies in the results for validation of the extended ACIS when performed by rigorous automated means. As mentioned above, note entities were one category of PMI that was not transferred to ACIS in all test cases. This was due to the lack of an appropriate data structure to hold them in ACIS.

It was also observed that models containing Datum Target Symbols (DTS, CTCs 02 and 05) were also not well handled during the data transfer to ACIS regardless of system. Reviewing the results in Appendices B1 and B2, the overall percent success of validation, including the note and DTS anomalies, was 59%.   If the impact of these two issues is ignored, then the overall percent success improves to 67%. It is worthwhile to note that in no exchange was the DTS type successfully exchanged, i.e. that all semantic structure information was included and the values of that semantic data were correct. The reasons for DTS failure were different. Three examples that illustrate those different failure modes are shown in Figures 9a, 9b, and 9c below for test case CTC02.

Figure 9a – Example of validation of extended-ACIS PMI representation with source STEP Model illustrating complete loss of Datum Target Symbol in the ACIS target model
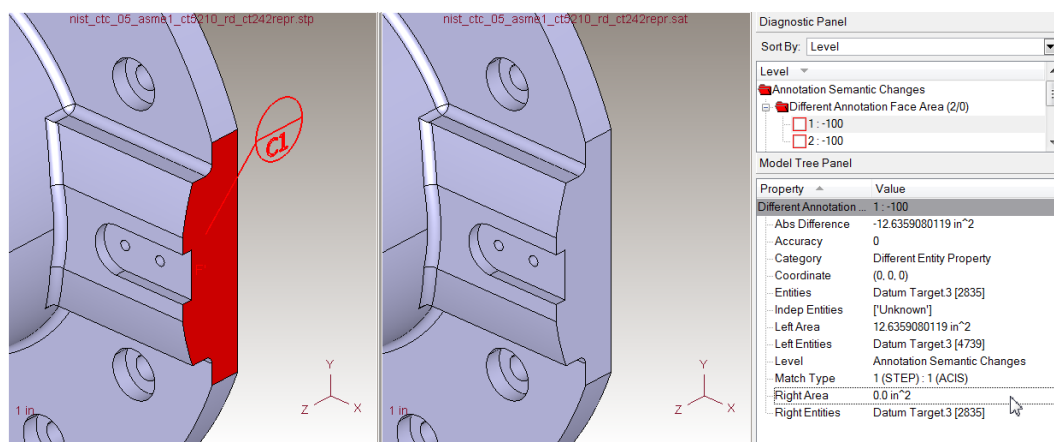
Figure 9b – Example of validation of extended-ACIS PMI representation with source STEP Model illustrating loss of Associated Geometry for a Datum Target Symbol in the target ACIS model

As shown in Figure 9a, the PMI data structure for a DTS in this particular source STEP data could not be matched to any equivalent data structure in resulting model transformed into ACIS. In a second example (Figure 9b), though the PMI data structure in the source STEP data could be matched to its equivalent data structure in resulting model transformed into ACIS, the association to the geometric surface referenced in the DTS structure was lost. Finally, in Figure 9c, the PMI data structure in the source STEP data was transferred to the resulting model in ACIS however the identifier for the DTS was changed during the exchange process. Issues with Datum Target Symbols for test case CTC05 were similar to those found in CTC02.
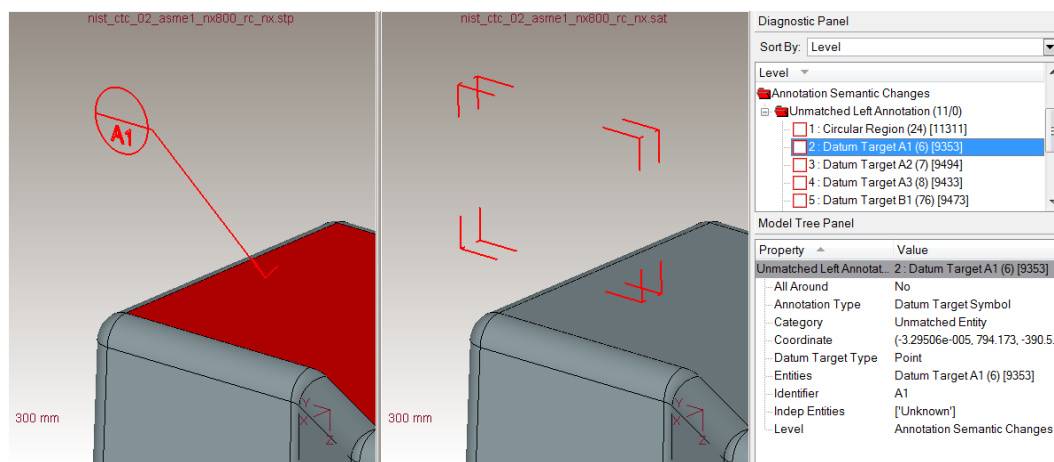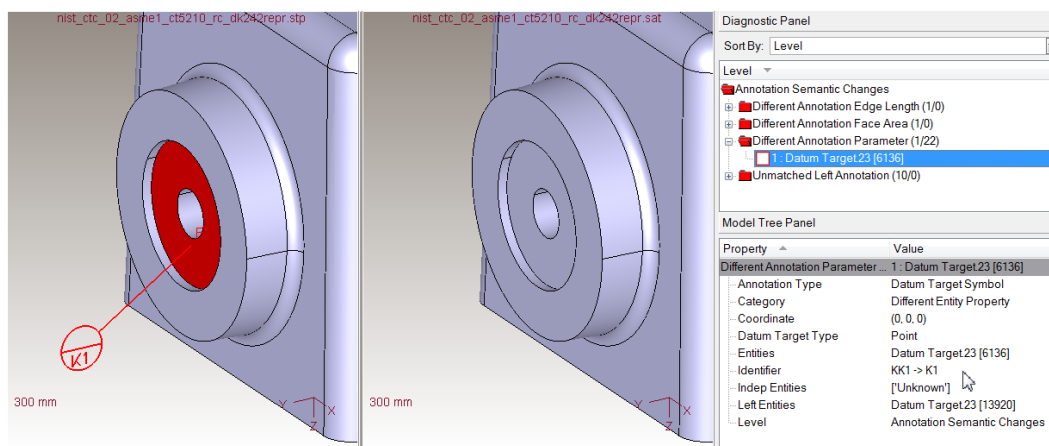
Figure 9c – Example of validation of extended-ACIS PMI representation with source STEP model illustrating an identifier change for a Datum Target Symbol in the target ACIS model

Though non-existent Note capability and widespread Datum Target Symbol failures predominated, anomalies did occur in the remaining categories. Referring to Table 4 (below), the percentage success for Datum Feature Symbols (DFS), Dimensions (DIM), and Feature Control Frames (FCF) were 72%, 64%, and 62% respectively when Notes and DTS failures were ignored.

The results for the CTC01 test case showed the most issues, and variation between systems, in dimensions.   Datum Feature Symbols and Feature Control Frames were generally stable across systems with close correlation between systems. The results for CTC3 and CTC4 test case were reasonably good for all vendors, averaging 93% and 84% success, respectively, when note failures were ignored. Dimensions were, again, the type with the most issues.

As stated earlier, the results for the CTC05 test case showed problems for Datum Target Symbols (DTS). If DTS errors and note failures are ignored, the results for CTC05 averaged 62% success.

Table 4: Validation of NIST models using analysis software

Model File	DFS[4] Clean	DIM[5] Clean	FCF[6] Clean	Percent[7] Clean (xN)	Percent[8] Clean (xNDTS)
nist_ctc_01_asme1_ct5210_rd_ct242repr.stp	2	7	6	79%	79%
nist_ctc_01_asme1_ct5210_rd_dk242repr.stp	3	6	6	79%	79%
nist_ctc_01_asme1_nx800_rd_ct242repr.stp	3	7	6	84%	84%
nist_ctc_01_asme1_nx800_rd_nx.stp	3	1	6	53%	53%
nist_ctc_01_asme1_nx800_rd_th.stp	3	9	6	95%	95%
nist_ctc_02_asme1_ct5210_rc_ct242repr.stp	0	0	0	0%	0%
nist_ctc_02_asme1_ct5210_rc_dk242repr.stp	0	0	0	0%	0%
nist_ctc_02_asme1_nx800_rc_ct242repr.stp	0	0	0	0%	0%
nist_ctc_02_asme1_nx800_rc_nx.stp	6	7	22	80%	100%
nist_ctc_02_asme1_nx800_rc_th.stp	0	0	0	0%	0%
nist_ctc_03_asme1_ct5210_rc_ct242repr.stp	6	8	13	93%	93%
nist_ctc_03_asme1_ct5210_rc_dk242repr.stp	6	8	13	93%	93%
nist_ctc_03_asme1_nx800_rc_ct242repr.stp	6	8	13	93%	93%
nist_ctc_03_asme1_nx800_rc_nx.stp	6	8	13	93%	93%
nist_ctc_03_asme1_nx800_rc_th.stp	6	9	13	97%	97%
nist_ctc_04_asme1_ct5210_rd_ct242repr.stp	8	7	5	87%	87%
nist_ctc_04_asme1_ct5210_rd_dk242repr.stp	8	9	3	83%	83%
nist_ctc_04_asme1_nx800_rd_ct242repr.stp	8	7	4	83%	83%
nist_ctc_04_asme1_nx800_rd_nx.stp	8	5	5	78%	78%
nist_ctc_04_asme1_nx800_rd_th.stp	8	7	5	87%	87%
nist_ctc_05_asme1_ct5210_rd_ct242repr.stp	4	2	6	55%	60%
nist_ctc_05_asme1_ct5210_rd_dk242repr.stp	4	3	7	64%	70%
nist_ctc_05_asme1_nx800_rd_ct242repr.stp	2	2	5	45%	50%
nist_ctc_05_asme1_nx800_rd_nx.stp	2	2	10	70%	78%
nist_ctc_05_asme1_nx800_rd_th.stp	2	2	6	45%	50%
Counts:	**107**	**178**	**186**	62%	67%
Percents:	**72%**	**64%**	**62%**		

Error conditions for Feature Control Frame included loss of geometric associativity, either loss or changes to primary datum reference frame identifiers, or loss of FCF type.   Several examples of these losses are shown in Figures 10a through 10d.

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[4] DFS = Datum Feature Symbol
[5] DIM = Dimension
[6] FCF = Feature Control Frame
[7] xN = Percent Clean excluding Note entities
[8] xNDTS = Percent Clean excluding Note and Datum Target Symbols
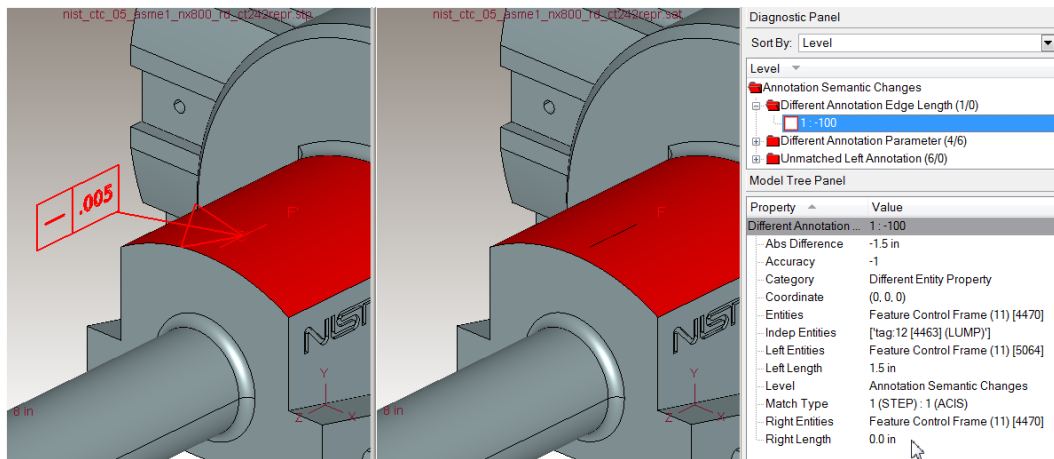
Figure 10a - Loss of Feature Control Frame associativity to associated edge geometry
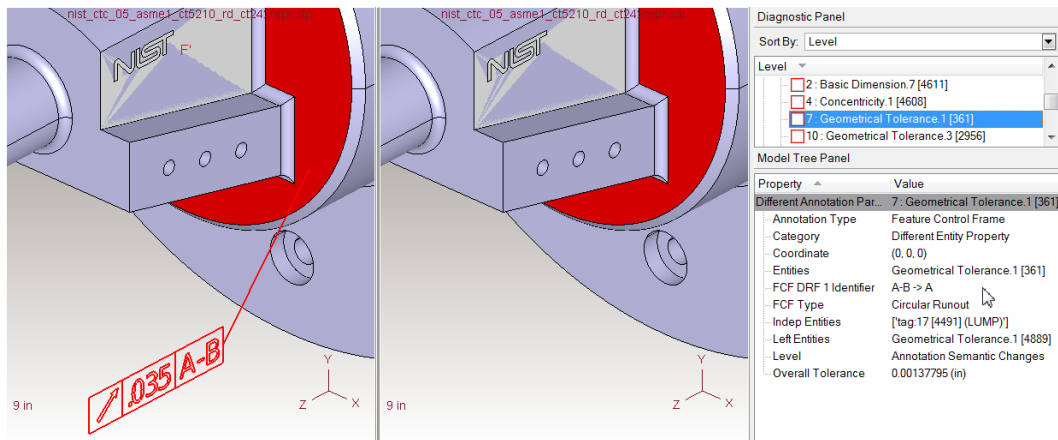
Figure 10b – Change to Feature Control Frame primary datum reference frame identifier
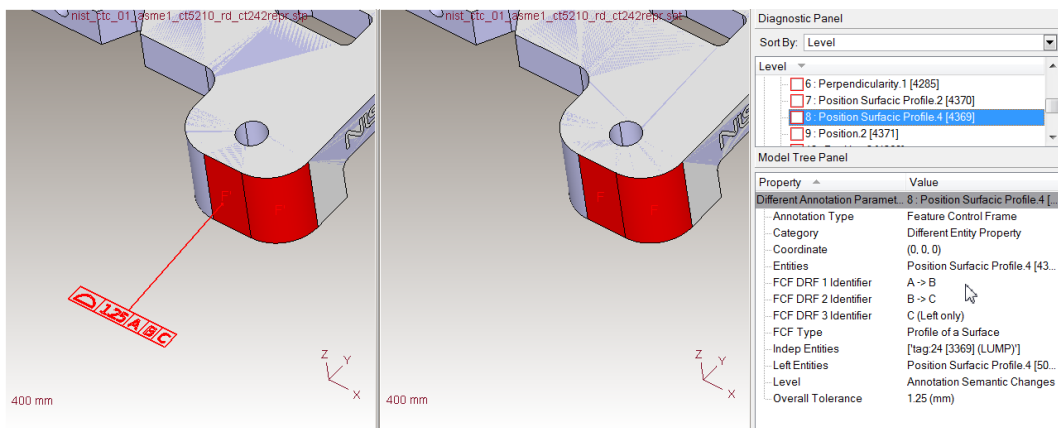
Figure 10c – Identifier of Feature Control Frame primary datum reference frame not translated

21 %
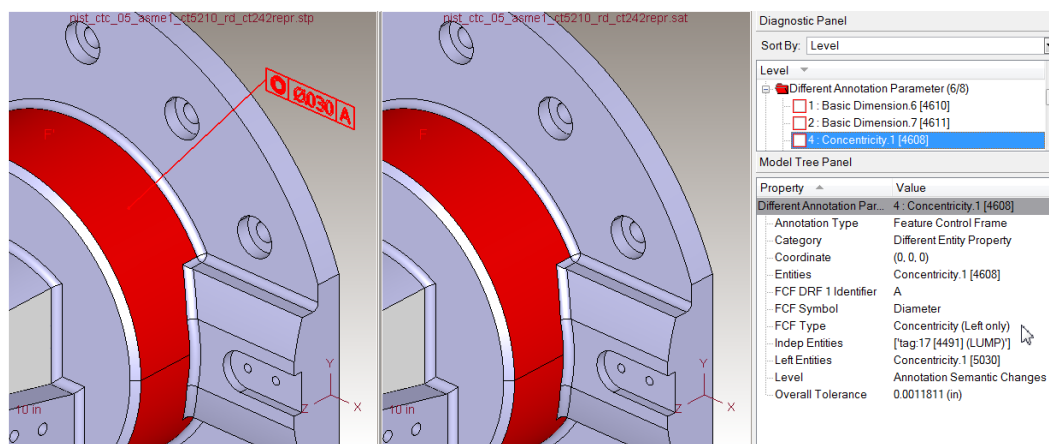
Figure 10d – Loss of Feature Control Frame type

Dimension-related errors are illustrated in Figures 11a through 11h below. In Figure 11a below, the error condition indicates that the values for the nominal and tolerance values have changed. A quick calculation shows that the difference is related to improper conversion as the values on the left differ to those on right by a factor equal to the conversion factor from degrees to radians. It is unclear without further investigation whether the effort occurs in the translation from STEP to ACIS or in the validation algorithm display.
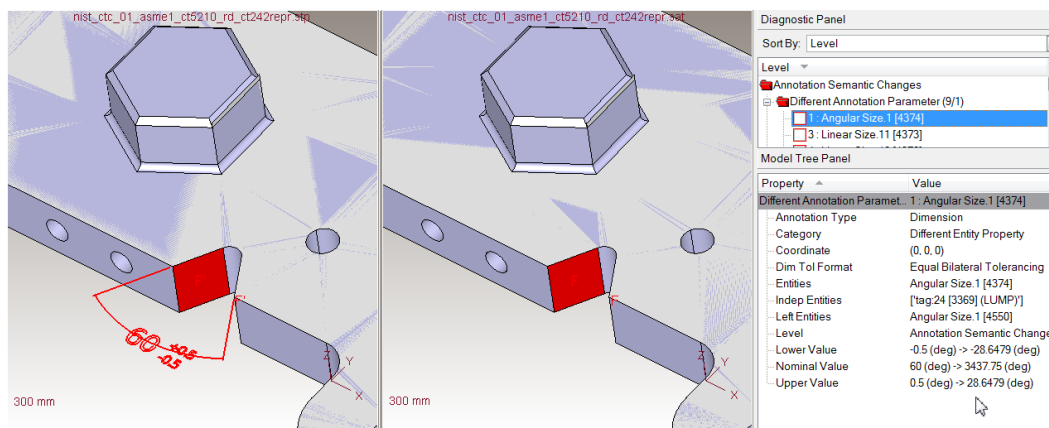
Figure 11a - Angular bilateral dimension nominal and tolerance values changed

Figure 11b illustrates a problem with extended ACIS in that there is no separate data structure for limit dimensions. To provide a workaround, dimensions of this type were recast as nominal dimensions with upper and lower tolerances when converted from STEP to ACIS. The validation algorithm needs to be adjusted to understand this workaround.   Figure 11c shows the loss of units on tolerance values. Representation of the proper units in the ACIS data is critical to reuse in the Metrology planning system. The use of not-to-scale dimensions, in Figure 11d,
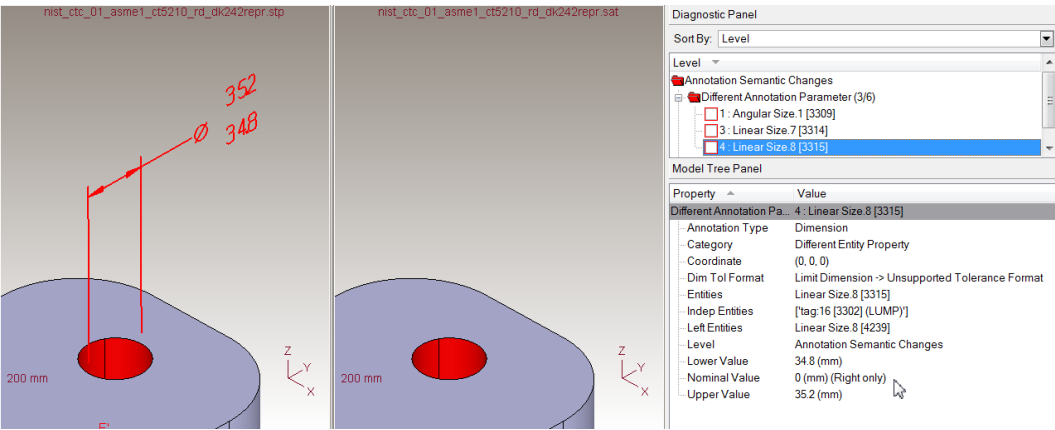
Figure 11b - Limit dimension nominal value added and set to zero
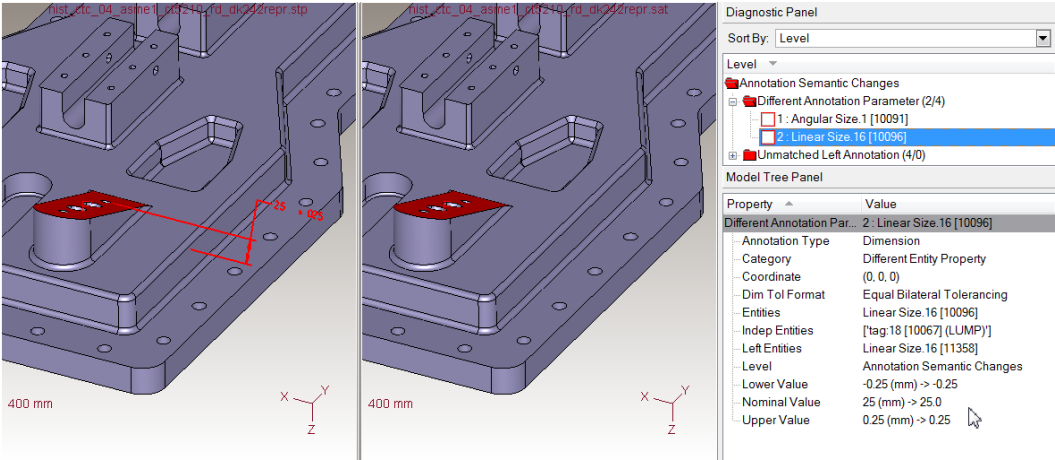
Figure 11c – Units on linear bilateral dimension nominal and tolerance values lost
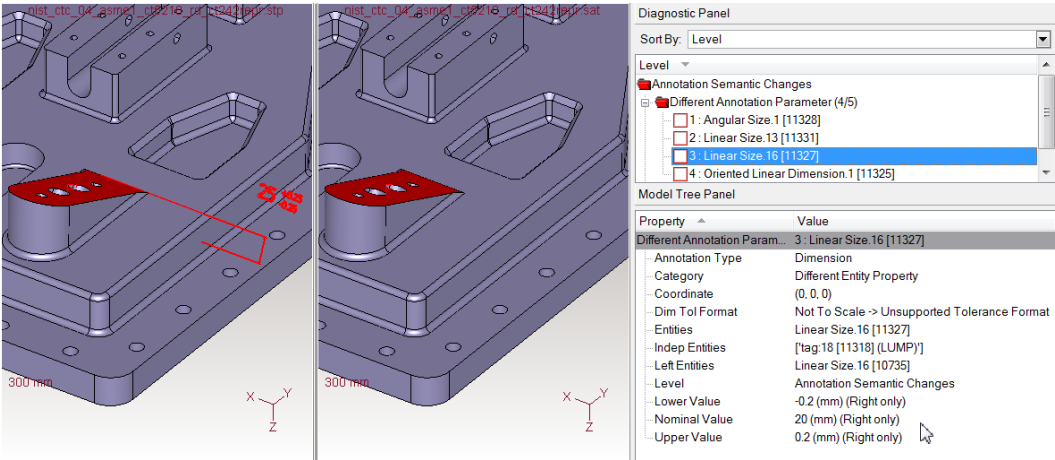
Figure 11d - Not to scale dimension nominal and tolerance values uncertain

23 %

shows a particularly challenging problem for automated systems which will need to account for such uses in 3D data. This connection between a native dimension's to-scale value and its not-to-scale value were likely lost during conversion. Further investigation is required.

In the example of Figure 11e below, a non-toleranced reference dimension has the same issue as previously discussed on page 21 for limit dimensions. The validation algorithm needs to be adjusted to understand the recasting of non-toleranced and limit dimension workaround.
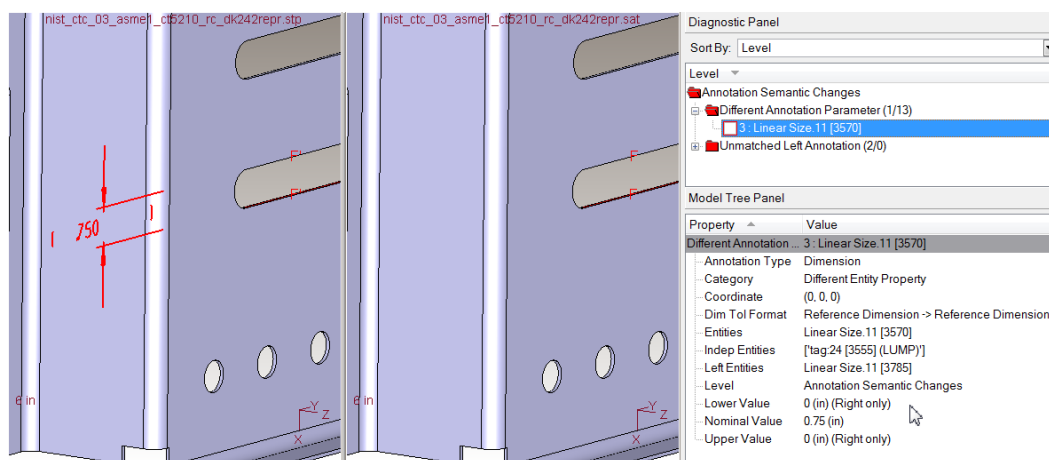
Figure 11e - Reference dimension with no tolerances gets tolerances set to zero

The final three error types will require some more detailed analysis. Each of these has been analyzed by the validation algorithm as being "unformated dimensions". This suggests that there were issues when attempting to read the STEP entity and further analysis of the entire conversion process is necessary to understand exactly where the anomaly occurred.
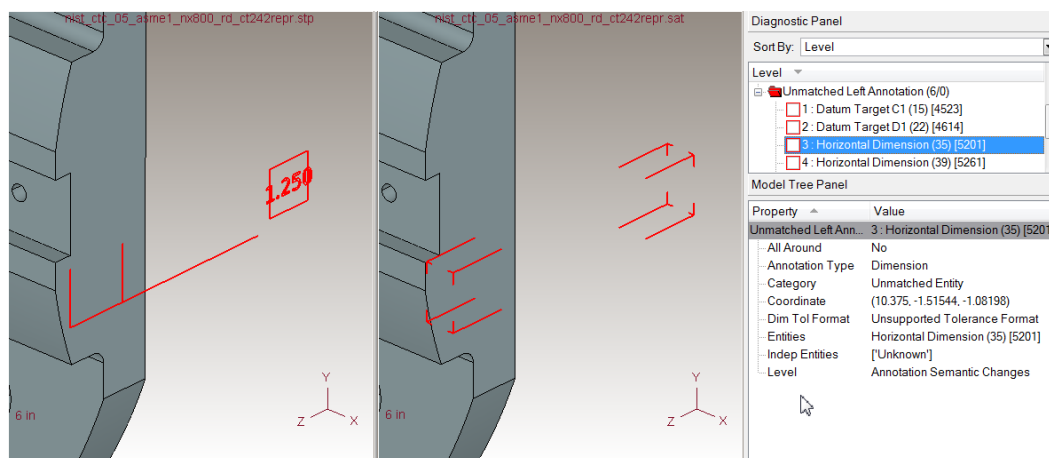
Figure 11f - Unformatted dimension with no nominal value not translated

24 %
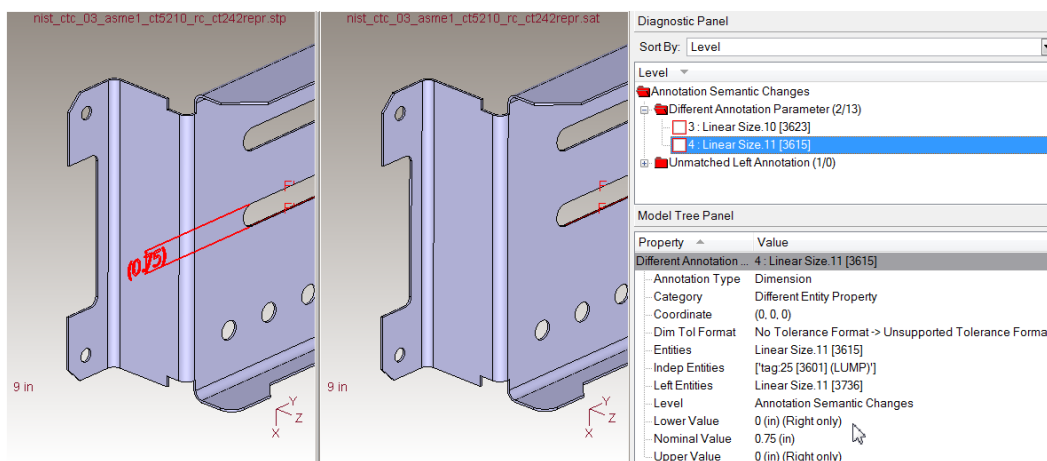
Figure 11g - Unformatted dimension with no tolerances gets tolerances set to zero
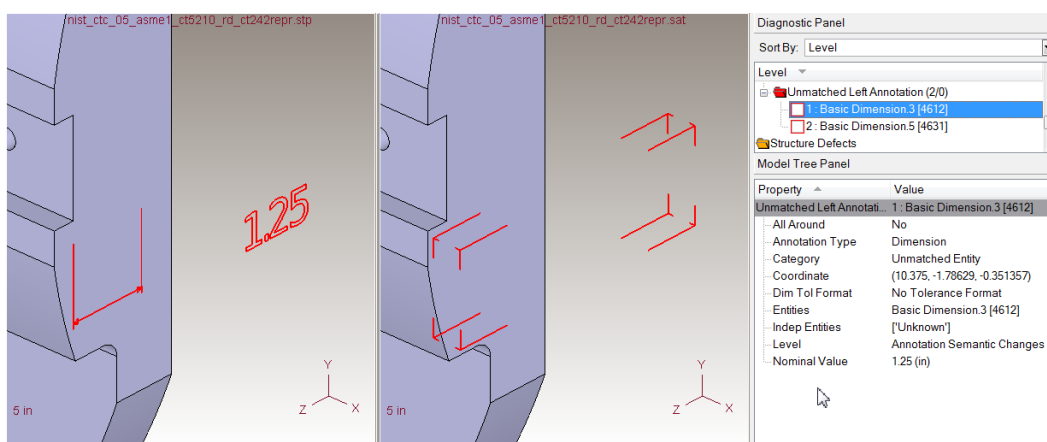
Figure 11h - Unformatted dimension with no tolerances not translated

Though some issues with PMI mapping into extended ACIS have been resolved and coverage for many typical PMI constructs are supported, other PMI mappings into extended ACIS remain unresolved due to problems in ACIS.   Those unresolved ACIS issues will likely remain open issues for consideration as further research in a future project.

Conclusions

This project sought to provide initial research necessary to understand the unique nature of CAM and CM community's needs in the area of interoperability between upstream design systems and those CAM and CM systems and how their needs map to existing standards, the development of algorithms to perform these validations of CAM and CM models, and testing these validation processes on a representative set of example CAD models that have been read by CAM and CM systems, validating these CAM and CM data models against their STEP source models for data loss during transformation.

ACIS is a typical modeling kernel in the CAM and CM space and would seem to be a good target for a transformation and validation process for passing design data downstream to these systems. The research hypothesized here suggested that using a STEP AP242 to extended ACIS translation process and following that translation with an ACIS to STEP validation would be good first step toward the promise of true MBD, i.e. the ability to share design data including PMI with downstream consumers in the manufacturing and metrology spaces. The results of this research show that there is a clear requirement for validation, as transformation of semantic data structures needed for machine consumption downstream require in-depth automated validation processes to ensure data integrity, to establish confidence in the transformed data, and to flag any losses during the transformation process.

A further conclusion, based on this research is that it is possible to use ACIS as the target for conversion of data from STEP AP242. There are, however, gaps in the process and recommended practices and algorithm refinements are required to resolve roadblocks and fully realize the potential value of MBD data in the CAM and CM domains. The mapping exercise performed between STEP AP242, ACIS, and the Metrology community's Quality Information Framework (QIF) standard suggests that transformation between STEP and QIF might be a strong contender as the mechanism of choice for exchange between design and metrology. The mappings identify data model elements, properties, and relationships which are unique to each standard and those which are equivalent between them. QIF has unique capabilities, not shared with STEP AP242, but which are necessary to properly communicate metrology data and process.

This study benefits end users, software developers, and standards experts by helping all of these groups better understand the relative strengths and weaknesses of each standard. It will also assist developers to improve translation and validation applications between the standards. And it will provide strategic direction for the standards experts as they seek to refine and further harmonize the standards, improving interoperability between the design domain and the manufacturing and metrology domains over time.

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REFERENCES *

Reference	Description
Reference A	**NIST 70NANB14H314** – Collaborative Agreement - Investigating the Impact of Standards-based Interoperability for Design to Manufacturing and Quality in the Supply Chain
Reference B	Contract Number SB1341-12-SE-0853 – NIST 3D Model-Based Engineering Product Manufacturing Information Validation and Conformance Testing Project - Phase 1
Reference C	Contract Number SB1341-14-SE-0061 – NIST 3D Model-Based Engineering Product Manufacturing Information Validation and Conformance Testing Project - Phase 2
Reference D	ISO 10303-242 "Managed Model Based 3D Engineering" [STEP AP 242]
Reference E	ANSI QIF 2.0, October 31, 2014 - http://qifstandards.org/download-qif/

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APPENDICES

Appendix A: Mapping PMI into STEP and QIF

Appendix A.1: Mapping GD&T into STEP and QIF

PMI	STEP AP242	ACIS	QIF
dimension types			
linear dimension	dimensional_location	spaxpmi_dimension	LinearCharacteristicDefinitionBaseType
radius dimension	dimensional_size.name = "radius"	spaxpmi_dimension	RadiusCharacteristicDefinitionType
spherical radius dimension	dimensional_size.name = "spherical radius"	not covered	
diameter dimension	dimensional_size.name = "diameter"	spaxpmi_dimension	DiameterCharacteristicDefinitionType
spherical diameter dimension	dimensional_size.name = "spherical diameter"	not covered	SphereFeatureDefinitionType<> Diameter [also in Spherical Segment]
oriented dimension	oriented_dimensional_location	not covered	OrientationCharacteristicDefinitionBaseType
curved dimension	dimensional_location_with_path/dimensional_size_with_path	not covered	CurvedLengthCharacteristicDefinitionType
length dimension			LengthCharacteristicDefinitionType
depth dimension	dimensional_location.name = "depth"	not covered	DepthCharacteristicDefinitionType
width dimension	dimensional_location.name = "width"	not covered	WidthCharacteristicDefinitionType
height dimension	dimensional_location.name = "height"	not covered	HeightCharacteristicDefinitionType
thickness dimension	dimension_size.name = "thickness"	not covered	ThicknessCharacteristicDefinitionType
linear coordinate dimension	dimensional_location.name = "coordinate"	spaxpmi_dimension(DIMSUBTYPE_COORDDIM2D, DIMSUBTYPE_COORDDIM3D)	LinearCoordinateCharacteristicDefinitionType
angular coordinate dimension	angular_location.name = "coordinate"	spaxpmi_dimension(DIMSUBTYPE_COORDDIM2D, DIMSUBTYPE_COORDDIM3D)	AngularCoordinateCharacteristicDefinitionType

PMI	STEP AP242	ACIS	QIF
distance between dimension	derived_shape_aspect/centre_of_symmetry	not covered	DistanceBetweenCharacteristicDefinitionType
distance from dimension	directed_dimensional_location	not covered	DistanceFromCharacteristicDefinitionType
chord dimension	dimensional_location.name = "chord"	not covered	ChordCharacteristicDefinitionType
square dimension			SquareCharacteristicDefinitionType
angular dimension	angular_location/angular_size	spaxpmi_dimension (no way to specify which angle)	AngleCharacteristicDefinitionType
angle-from dimension	not covered	not covered	AngleFromCharacteristicDefinitionType
angle-between dimension	derived_shape_aspect/centre_of_symmetry	not covered	AngleBetweenCharacteristicDefinitionType
dimension tolerance principle			
independency	shape_dimension_representation.name = "independency"	not covered	<>EnvelopeRequirement(FALSE)
envelope	shape_dimension_representation.name = "envelope"	not covered	<>EnvelopeRequirement(TRUE)
dimension values			
nominal value	measure_representation_item.name = "nominal value"	dimension value	<>TargetValue
nominal value with qualifier	qualified_representation_item/type_qualifier.name = "maximum"/"minimum"/"average"	not covered	<>TargetValue
nominal value with plus/minus bounds	plus_minus_tolerance	not covered	<>DefinedAsLimit(FALSE)
value range	measure_representation_item.name = "upper limit"/"lower limit"	dimtol lower limit/dimtol upper limit	<>DefinedAsLimit(TRUE)
tolerance class (ISO 286)	limits_and_fits	not covered	not covered
basic/theoretical	descriptive_representation_item.description = "theoretical"	dimension_type (dimtype_basic)	<>DimensionType(BASIC)
set			<>DimensionType(SET)
reference/auxiliary	descriptive_representation_item.description = "auxiliary"	dimension_type (dimtype_reference)	<>DimensionType(REFERENCE)
key characteristic			<>KeyCharacteristic
non-tolerance			<>NonTolerance
	START ITEMS FROM TABLE 8 OF AP242 RECOMMENDED PRACTICES (from ISO ?)		

30 !

PMI	STEP AP242	ACIS	QIF
controlled radius	descriptive_representation_item.description = "controlled radius"	not covered	RadiusCharacteristicDefinitionType<>ControlledRadius(TRUE)
square	descriptive_representation_item.description = "square"	not covered	SquareCharacteristicDefinitionType
statistical tolerance	descriptive_representation_item.description = "statistical tolerance"	dimension_type (dimtype_tolerance)	CharacteristicDefinitionBaseType<>StatisticalCharacteristic(TRUE)
continuous feature	descriptive_representation_item.description = "continuous feature"	not covered	UnitedFeature
two point size	descriptive_representation_item.description = "two point size" (not Y14.5)	not covered	CharacteristicDirectionalZoneLimitType<>FromPoint,<>ToPoint
local size defined by a sphere	descriptive_representation_item.description = "local size defined by sphere" (not Y14.5)	not covered	CharacteristicBaseType<>Description
least-squares association criterion	descriptive_representation_item.description = "least-squares association criterion"	not covered	XXXSubst.Feat.Algor.EnumType (LEASTSQUARES), for [Non]FeatureOfSize, Curve, Surface
maximum inscribed association criterion	descriptive_representation_item.description = "maximum inscribed association criterion"	not covered	FeatureOfSizeSubstituteFeatureAlgorithmEnumType(MAXINSCRIBED)
minimum circumscribed association criterion	descriptive_representation_item.description = "minimum circumscribed association criterion"	not covered	FeatureOfSizeSubstituteFeatureAlgorithmEnumType(MINCIRCUMSCRIBED)
circumference diameter	descriptive_representation_item.description = "circumference diameter" (not Y14.5)	not covered	CharacteristicBaseType<>Description
area diameter	descriptive_representation_item.description = "area diameter" (not Y14.5)	not covered	CharacteristicBaseType<>Description
volume diameter	descriptive_representation_item.description = "volume diameter" (not Y14.5)	not covered	CharacteristicBaseType<>Description
maximum size	descriptive_representation_item.description = "maximum size"	not covered	<>MeasurementDirectiveEnum(MAXIMUM)
minimum size	descriptive_representation_item.description = "minimum size"	not covered	<>MeasurementDirectiveEnum(MINIMUM)
average size	descriptive_representation_item.description = "average size"	not covered	<>MeasurementDirectiveEnum(AVERAGE)
median size	descriptive_representation_item.description = "median size"	not covered	CharacteristicDefinitionBaseType<>MedianFeature(TRUE)
mid-range size	descriptive_representation_item.description = "mid-range size"	not covered	CharacteristicBaseType<>Description

PMI	STEP AP242	ACIS	QIF
range of sizes	descriptive_representation_item.description = "range of sizes"	not covered	CharacteristicBaseType<>Description
any restricted portion of feature	descriptive_representation_item.description = "any restricted portion of feature"	not covered	CharacteristicBaseType<>Description
any cross section	descriptive_representation_item.description = "any cross section"	not covered	SectionModifierEnumType(ACS)
specific fixed cross section	descriptive_representation_item.description = "specific fixed cross section"	not covered	CharacteristicBaseType<>Description
common tolerance	descriptive_representation_item.description = "common tolerance"	not covered	CharacteristicDefinitionBaseType<>CommonZone(TRUE)
free-state condition	descriptive_representation_item.description = "free-state condition"	not covered	CharacteristicDefinitionBaseType<>FreeState(TRUE)
	END TABLE 8 ITEMS		
united feature	descriptive_representation_item.description = "continuous feature"	not covered	CharacteristicDefinitionBaseType<>UnitedFeature(TRUE)
dimension decimal places	value_format_type_qualifier	dimtol precision	<>SpecifiedDecimalType@decimalPlaces
datum	datum	spaxpmi_datum	DatumDefinitionType
datum feature	datum_feature	attrib_spaxpmi_datum	FeatureNominal
datum target	placed_datum_target_feature	spaxpmi_datumtgt	DatumTargetDefinitionBaseType
point	axis2_placement_3d.name = "orientation"	datum_target_type (dt_point)	DatumTargetPointDefinitionType
line	axis2_placement_3d/length_measure_with_unit.name = "target length"	datum_target_type (dt_line)	DatumTargetLineDefinitionType
circular line	axis2_placement_3d/length_measure_with_unit.name = "circle diameter"		DatumTargetCircularLineDefinitionType
rectangle	axis2_placement_3d/length_measure_with_unit.name = "target width"	datum_target_type (dt_area_rect)	DatumTargetRectangularAreaDefinitionType
circle	axis2_placement_3d/length_measure_with_unit.name = "target diameter"	datum_target_type (dt_area_circ)	DatumTargetCircularAreaDefinitionType
cylindrical area	advanced_face	datum_target_type (dt_area_face)	DatumTargetCylindricalAreaDefinitionType
sphere	advanced_face	datum_target_type (dt_area_face)	DatumTargetSphereDefinitionType
area	advanced_face	datum_target_type (dt_area_face)	DatumTargetIrregularAreaDefinitionType
movable datum target	direction	not covered	MovableDatumTargetDirectionType
tolerance	geometric_tolerance	attrib_spaxpmi_geom_tol	CharacteristicDefinitionBaseType

PMI	STEP AP242	ACIS	QIF
tolerance types			
angularity	angularity_tolerance	tol_type (toltype_angularity)	AngularityCharacteristicDefinitionType
circular runout	circular_runout_tolerance	tol_type (toltype_runout_circular)	CircularRunoutCharacteristicDefinitionType
circularity/roundness	roundness_tolerance	tol_type (toltype_circularity)	CircularityCharacteristicDefinitionType
coaxiality	coaxiality_tolerance	not covered	*ConcentricityCharacteristicDefinitionType
concentricity	concentricity_tolerance	tol_type (toltype_concentricity)	ConcentricityCharacteristicDefinitionType
cylindricity	cylindricity_tolerance	tol_type (toltype_cylindricity)	CylindricityCharacteristicDefinitionType
flatness	flatness_tolerance	tol_type (toltype_flatness)	FlatnessCharacteristicDefinitionType
parallelism	parallelism_tolerance	tol_type (toltype_parallelism)	ParallelismCharacteristicDefinitionType
perpendicularity	perpendicularity_tolerance	tol_type (toltype_perpendicularity)	PerpendicularityCharacteristicDefinitionType
position	position_tolerance	tol_type (toltype_position)	PositionCharacteristicDefinitionType
profile of a line	line_profile_tolerance	tol_type (toltype_profile_line)	LineProfileCharacteristicDefinitionType
profile of a point			PointProfileCharacteristicDefinitionType
profile of a surface	surface_profile_tolerance	tol_type (toltype_profile_surf)	SurfaceProfileCharacteristicDefinitionType
straightness	straightness_tolerance	tol_type (toltype_straightness)	StraightnessCharacteristicDefinitionType
symmetry	symmetry_tolerance	tol_type (toltype_symmetry)	SymmetryCharacteristicDefinitionType
texture			SurfaceTextureCharacteristicDefinitionType
thread			ThreadCharacteristicDefinitionType
total runout	total_runout_tolerance	tol_type (toltype_runout_total)	TotalRunoutCharacteristicDefinitionType
tolerance zone			
diameter	tolerance_zone_form.name = "cylindrical or circular"	mod_dia_type (dm_dia)	<>DiametricalZone

PMI	STEP AP242	ACIS	QIF
spherical diameter	tolerance_zone_form.name = "spherical"	mod_dia_type (dm_spherical_dia)	<>SphericalZone
within a circle	tolerance_zone_form.name = "within a circle"	not covered	CharacteristicCircularZoneLimitType
rectangular tolerance zone	tolerance_zone_form.name = "rectangular"	not covered	CharacteristicRectangularZoneLimitType
directional tolerance zone	tolerance_zone_form.name = "directional"	not covered	CharacteristicDirectionalZoneLimitType
between two concentric circles	tolerance_zone_form.name = "between two concentric circles"	not covered	ZoneRadiiType
between two equidistant curves	tolerance_zone_form.name = "between two equidistant curves"	not covered	<>UnequallyDisposedZone [also explicit in Straightness, Circularity]
within a cylinder	tolerance_zone_form.name = "within a cylinder"	not covered	CylindricityCharacteristicNominalType<>CharacteristicDirectionalZoneLimitType
between two coaxial cylinders	tolerance_zone_form.name = "between two coaxial cylinders"	not covered	ConcentricityCharacteristicNominalType<>ZoneLimit
between two equidistant surfaces	tolerance_zone_form.name = "between two equidistant surfaces"	not covered	ConcentricityNonDiametricalZoneType [implicit in SurfaceProfile & Flatness, explicit in Cylindricity]
runout	runout_zone_definition	not covered	RunoutCharacteristicNominalBaseType<>ZoneDirection
projected	projected_zone_definition	p_mag	<>ProjectedToleranceZoneValue
non-uniform	non_uniform_zone_definition	not covered	SurfaceProfileNonUniformCharacteristicDefinitionType
non-diametrical			<>NonDiametricalZone [position, straightness, concentricity]
elongated			<>ElongatedZone [in PositionDiametricalZoneType]
outer disposition			<>OuterDisposition
offest			<>OffsetZone
planar			<>PlanarZone [orientation]
tolerance modifiers (from RecPrac 6.9.3)			
any cross section	geometric_tolerance_with_modifiers.modifiers = .ANY_CROSS_SECTION.	not covered	<>IntersectionPlane
common zone	geometric_tolerance_with_modifiers.modifiers = .COMMON_ZONE.	not covered	<>CommonZone(TRUE)

PMI	STEP AP242	ACIS	QIF
each radial element	geometric_tolerance_with_modifiers.modifiers = .EACH_RADIAL_ELEMENT.	not covered	OrientationCharacteristicDefinitionBaseType<>EachRadialElement(TRUE)
free state	geometric_tolerance_with_modifiers.modifiers = .FREE_STATE.	zone_modifier_type (zm_fs)	<>FreeState(TRUE)
least material requirement	geometric_tolerance_with_modifiers.modifiers = .LEAST_MATERIAL_REQUIREMENT.	zone_modifier_type (zm_lmc)	<>MaterialCondition(LEAST)
line element	geometric_tolerance_with_modifiers.modifiers = .LINE_ELEMENT.	not covered	<>EachElement(TRUE)
major diameter (of thread)	geometric_tolerance_with_modifiers.modifiers = .MAJOR_DIAMETER.	not covered	not covered
maximum material requirement	geometric_tolerance_with_modifiers.modifiers = .MAXIMUM_MATERIAL_REQUIREMENT.	zone_modifier_type (zm_mmc)	<>MaterialCondition(MAXIMUM)
minor diameter (of thread)	geometric_tolerance_with_modifiers.modifiers = .MINOR_DIAMETER.	not covered	not covered
not convex	geometric_tolerance_with_modifiers.modifiers = .NOT_CONVEX.	not covered	FlatnessCharacteristicDefinitionType<>NotConvex(TRUE)
pitch diameter	geometric_tolerance_with_modifiers.modifiers = .PITCH_DIAMETER.	not covered	ThreadCharacteristicActualType<>PitchDiameter
reciprocity requirement	geometric_tolerance_with_modifiers.modifiers = .RECIPROCITY_REQUIREMENT.	zone_modifier_type (zm_rfs)	not covered
separate requirement	geometric_tolerance_with_modifiers.modifiers = .SEPARATE_REQUIREMENT.	not covered	<>SeparateZone(TRUE)
statistical tolerance	geometric_tolerance_with_modifiers.modifiers = .STATISTICAL_TOLERANCE.	zone_modifier_type (zm_st)	<>StatisticalCharacteristic(TRUE)
tangent plane	geometric_tolerance_with_modifiers.modifiers = .TANGENT_PLANE.	zone_modifier_type (zm_tp)	<>TangentPlane(TRUE)
collection plane			<>CollectionPlane
direction feature			<>DirectionFeature
orientation plane			<>OrientationPlane
orientation only			<>OrientationOnly(TRUE)
unequally-disposed tolerance	unequally_disposed_geometric_tolerance	p_shift	<>UnequallyDisposedZone
tolerance with maximum value	geometric_tolerance_with_maximum_tolerance	not covered	<>MaximumToleranceValue

PMI	STEP AP242	ACIS	QIF
unit-basis tolerance			
length	geometric_tolerance_with_defined_unit	runit1	ToleranceZonePerUnitLengthType
circular	geometric_tolerance_with_defined_area_unit.area_type = .CIRCULAR.	runit1	ToleranceZonePerUnitArcLength
rectangular	geometric_tolerance_with_defined_area_unit.area_type = .RECTANGULAR.	runit1,runit2	ToleranceZonePerUnitAreaType
square	geometric_tolerance_with_defined_area_unit.area_type = .SQUARE.	runit1	ToleranceZonePerUnitAreaType
per-unit-polar-area	not covered	not covered	ToleranceZonePerUnitPolarAreaType
per-unit-angle	not covered	not covered	ToleranceZonePerUnitAngleType
composite tolerance	geometric_tolerance_relationship	attrib_spaxpmi_geom_tol	CompositeSegmentDefinitionTypeBase
tolerance with datum references	geometric_tolerance_with_datum_reference	spaxpmi_drf	XXX<>DatumReferenceFrameId
datum reference	datum_reference_compartment	spaxpmi_dref	<>DatumReferenceFrame <>Datum
datum reference modifiers			
free state	simple_datum_reference_modifier.modifiers = .FREE_STATE.	not covered	<>FreeState
basic	simple_datum_reference_modifier.modifiers = .BASIC.	not covered	DatumFeatureSimulatorModifierType<>BasicSize("BASIC")
diametrical			DatumFeatureSimulatorModifierType<>DiametricalSize
linear			DatumFeatureSimulatorModifierType<>LinearSize
translation	simple_datum_reference_modifier.modifiers = .TRANSLATION.	not covered	DatumTranslationType<>DatumTranslation
least material requirement	simple_datum_reference_modifier.modifiers = .LEAST_MATERIAL_REQUIREMENT.	datum_modifier_type (datum_modifier_lmc)	<>MaterialModifier(LEAST)
maximum material requirement	simple_datum_reference_modifier.modifiers = .MAXIMUM_MATERIAL_REQUIREMENT.	datum_modifier_type (datum_modifier_mmc)	<>MaterialModifier(MAXIMUM)
regardless			<>MaterialModifier(REGARDLESS)
point	simple_datum_reference_modifier.modifiers = .POINT.	not covered	<>ReducedDatum(PT)

PMI	STEP AP242	ACIS	QIF
line	simple_datum_reference_modifier.modifiers = .LINE.	not covered	<>ReducedDatum(SL)
plane	simple_datum_reference_modifier.modifiers = .PLANE.	not covered	<>ReducedDatum(PL)
orientation	simple_datum_reference_modifier.modifiers = .ORIENTATION.	not covered	<>ConstrainOrientation(TRUE)
any cross section	simple_datum_reference_modifier.modifiers = .ANY_CROSS_SECTION.	not covered	<>SectionModifier(ACS)
any longitudinal section	simple_datum_reference_modifier.modifiers = .ANY_LONGITUDINAL_SECTION.	not covered	<>SectionModifier(ALS)
contacting feature	simple_datum_reference_modifier.modifiers = .CONTACTING_FEATURE.	not covered	<>ContactingFeature(TRUE)
distance variable	simple_datum_reference_modifier.modifiers = .DISTANCE_VARIABLE.	not covered	<>DistanceVariable(TRUE)
constrain orientation			<>ConstrainOrientation(TRUE)
constrain subsequent			<>ConstrainSubsequent(TRUE)
fixed			<>DatumFixed(TRUE)
degree of freedom constraint x	simple_datum_reference_modifier.modifiers = .DEGREE_OF_FREEDOM_CONSTRAINT_X.	not covered	DegreeOfFreedomEnumType(X)
degree of freedom constraint y	simple_datum_reference_modifier.modifiers = .DEGREE_OF_FREEDOM_CONSTRAINT_Y.	not covered	DegreeOfFreedomEnumType(Y)
degree of freedom constraint z	simple_datum_reference_modifier.modifiers = .DEGREE_OF_FREEDOM_CONSTRAINT_Z.	not covered	DegreeOfFreedomEnumType(Z)
degree of freedom constraint u	simple_datum_reference_modifier.modifiers = .DEGREE_OF_FREEDOM_CONSTRAINT_U.	not covered	DegreeOfFreedomEnumType(U)
degree of freedom constraint v	simple_datum_reference_modifier.modifiers = .DEGREE_OF_FREEDOM_CONSTRAINT_V.	not covered	DegreeOfFreedomEnumType(V)

PMI	STEP AP242	ACIS	QIF
degree of freedom constraint w	simple_datum_reference_modifier.modifiers = .DEGREE_OF_FREEDOM_CONSTRAINT_W.	not covered	DegreeOfFreedomEnumType(W)
minor diameter	simple_datum_reference_modifier.modifiers = .MINOR_DIAMETER.	not covered	DiameterModifierEnumType(LD)
major diameter	simple_datum_reference_modifier.modifiers = .MAJOR_DIAMETER.	not covered	DiameterModifierEnumType(MD)
pitch diameter	simple_datum_reference_modifier.modifiers = .PITCH_DIAMETER.	not covered	DiameterModifierEnumType(PD)
with value	datum_reference_modifier_with_value	not covered	DatumFeatureSimulatorModifierType<>LinearSize/DiametricalSize
projected			<>ProjectedDatum
common datum/multiple datum features	datum_reference_element	spaxpmi_dref	<>CompoundDatum
polyline presentation	annotation_curve_occurrence/annotation_fill_area_occurrence/annotation_symbol_occurrence/annotation_text_occurrence/tessellated_annotation_occurrence	body/wire	UserDefinedExtension

Appendix A.2: Mapping Linkages into STEP and QIF ）

linkages	STEP AP242	ACIS	QIF
PMI<->BREP	BREP<-geometric_item_specific_usage->shape_aspect<-PMI	spacollection/entity	PMI->Feature->Brep
PMI<->polyline presentation	PMI<-draughting_model_item_association->annotation_occurrence/draughting_callout	not covered	PMIDisplayType->PMI

Appendix A.3: Mapping PMI Features and User Defined Tolerances into STEP and QIF)

PMI features	STEP AP242	ACIS	QIF
arc feature	not covered		ArcFeatureXXXType
circle feature	not covered		CircleFeatureXXXType
compound feature	not covered		CompoundFeatureXXXType
pattern feature	not covered		PatternFeatureXXXType
profile group feature	not covered		ProfileGroupFeatureXXXType
runout group feature	not covered		RunoutGroupFeatureXXXType
cone feature	not covered		ConeFeatureXXXType
conical segment feature	not covered		ConicalSegmentFeatureXXXType
cuboid (box) feature	not covered		CuboidFeatureXXXType
cylinder feature	not covered		CylinderFeatureXXXType
cylindrical segment feature	not covered		CylindricalSegmentFeatureXXXType
edge point feature	not covered		EdgePointFeatureXXXType
ellipse feature	not covered		EllipseFeatureXXXType
elongated cylinder feature	not covered		ElongatedCylinderFeatureXXXType
extruded cross section feature	not covered		ExtrudedCrossSectionFeatureXXXType
line feature	not covered		LineFeatureXXXType
opposite (parallel) lines feature	not covered		OppositeLinesFeatureXXXType
opposite (parallel) planes feature	not covered		OppositePlanesFeatureXXXType
plane feature	not covered		PlaneFeatureXXXType
point feature	not covered		PointFeatureXXXType
sphere feature	not covered		SphereFeatureXXXType
spherical segment feature	not covered		SphericalSegmentFeatureXXXType

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PMI features	STEP AP242	ACIS	QIF
surface of revolution feature	not covered		SurfaceOfRevolutionFeatureXXX Type
threaded feature	not covered		ThreadedFeatureXXXType
toroidal segment feature	not covered		ToroidalSegmentFeatureXXXTyp e
torus feature	not covered		TorusFeatureXXXType
user defined tolerance	STEP AP242	ACIS	QIF
angular			UserDefinedAngularCharacteristi cDefinitionType
area			UserDefinedAreaCharacteristicD efinitionType
attribute			UserDefinedAttributeCharacterist icDefinitionType
force			UserDefinedForceCharacteristic DefinitionType
linear			UserDefinedLinearCharacteristic DefinitionType
mass			UserDefinedMassCharacteristicD efinitionType
pressure			UserDefinedPressureCharacteris ticDefinitionType
speed			UserDefinedSpeedCharacteristic DefinitionType
temperature			UserDefinedTemperatureCharact eristicDefinitionType
time			UserDefinedTimeCharacteristicD efinitionType
unit			UserDefinedUnitCharacteristicDe finitionType

Appendix A.4: Mapping of Boundary Representation (BREP) Geometry into STEP and QIF)

BREP	STEP AP242	ACIS	QIF
topology			
solid	manifold_solid_brep	body/lump	BodyType
shell	closed_shell/open_shell	shell	ShellType
face	advanced_face	face	FaceType
mesh face	tessellated_face	not covered	FaceMeshType
loop	face_bound/face_outer_bound/edge_loop/vertex_loop	loop	LoopType
mesh loop	tessellated_wire	not covered	LoopMeshType
edge	oriented_edge/edge_curve	edge/coedge	EdgeType/CoEdgeType
vertex	vertex_point/cartesian_point	vertex	VertexType
surface geometry			
cone	conical_surface	cone	Cone23Type
cylinder	cylindrical_surface	cone	Cylinder23Type
extruded surface	surface_of_linear_extrusion	spline	Extrude23Type
spline surface	b_spline_surface/b_spline_surface_with_knots/rational_b_spline_surface/uniform_surface/quasi_uniform_surface/bezier_surface	spline	Spline23Type
nurbs	b_spline_surface/b_spline_surface_with_knots/rational_b_spline_surface/uniform_surface/quasi_uniform_surface/bezier_surface	spline	Nurbs23Type
offset surface	offset_surface	off_spl_sur	Offset23Type
plane	planar_surface	plane	Plane23Type
revolved surface	surface_of_revolution	rot_spl_sur	Revolution23Type
sphere	spherical_surface	sphere	Sphere23Type
torus	toroidal_surface	torus	Torus23Type
ruled surface	b_spline_surface/b_spline_surface_with_knots/rational_b_spline_surface/uniform_surface/quasi_uniform_surface/bezier_surface	spline	Ruled23Type
curve geometry			
circle	circle	ellipse	ArcCircular13Type/ArcCircular12Type

BREP	STEP AP242	ACIS	QIF
ellipse	ellipse	ellipse	ArcConic13Type(ELLIPSE)/ArcConic12Type(ELLIPSE)
parabola	parabola	bs3_curve	ArcConic13Type(PARABOLA)/ArcConic12Type(PARABOLA)
hyperbola	hyperbola	bs3_curve	ArcConic13Type(HYPERBOLA)/ArcConic12Type(HYPERBOLA)
spline curve	b_spline_curve/b_spline_curve_with_knots/rational_b_spline_curve/uniform_curve/quasi_uniform_curve/bezier_curve	bs3_curve	Spline13Type/Spline12Type
nurbs	b_spline_curve/b_spline_curve_with_knots/rational_b_spline_curve/uniform_curve/quasi_uniform_curve/bezier_curve	bs3_curve	Nurbs13Type/Nurbs12Type
offset curve	offset_curve_3d	bs3_curve	Nurbs13Type/Nurbs12Type
line	line	straight	Segment13Type/Segment12Type
poly-line	polyline	body/wire	Polyline13Type/Polyline12Type
aggregate curve	composite_curve	body/wire	Aggregate13Type/Aggregate12Type

Appendix A.5: Mapping Other MBD-related Items into STEP and QIF

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

Appendix B: Validation Results for Test Models

Appendix B.1: Validation Differences by PMI Category for Test Models

STEP Model File	Native CAD	STEP Vendor	Date	DFS Count	DTS Count	DIM Count	FCF Count	NOTE Count	Total Count	DFS Diffs	DTS Diffs	DIM Diffs	FCF Diffs	NOTE Diffs	Total Diffs
827-9999-903.stp	NX	CoreTech	04/28/15	2		8	6	7	23			5		7	12
827-9999-904.stp	NX	CoreTech	07/10/15	3		54	13	8	78			1		8	9
nist_ctc_01_asme1_ct5210_rd_ct242repr.stp	CATIA	CoreTech	12/19/14	3		10	6	3	22	1		3		3	7
nist_ctc_01_asme1_ct5210_rd_dk242repr.stp	CATIA	Datakit	02/16/15	3		10	6	3	22			4		3	7
nist_ctc_01_asme1_nx800_rd_ct242repr.stp	NX	CoreTech	02/18/15	3		10	6	2	21			3		2	5
nist_ctc_01_asme1_nx800_rd_nx.stp	NX	SPLM	11/04/15	3		10	6	2	21			9		2	11
nist_ctc_01_asme1_nx800_rd_th.stp	NX	Theorem	11/10/15	3		10	6	2	21			1		2	3
nist_ctc_02_asme1_ct5210_rc_ct242repr.stp	CATIA	CoreTech	12/19/14	10	9	8	22	1	50	10	9	8	22	1	50
nist_ctc_02_asme1_ct5210_rc_dk242repr.stp	CATIA	Datakit	02/16/15	10	9	8	22	1	50	10	9	8	22	1	50
nist_ctc_02_asme1_nx800_rc_ct242repr.stp	NX	CoreTech	02/18/15	7	9	7	22	1	46	7	9	7	22	1	46
nist_ctc_02_asme1_nx800_rc_nx.stp	NX	SPLM	11/04/15	6	9	7	22	2	46		9			2	11
nist_ctc_02_asme1_nx800_rc_th.stp	NX	Theorem	11/10/15	10	9	7	22	1	49	10	9	7	22	1	49
nist_ctc_03_asme1_ct5210_rc_ct242repr.stp	CATIA	CoreTech	12/19/14	6		10	13	1	30			2		1	3
nist_ctc_03_asme1_ct5210_rc_dk242repr.stp	CATIA	Datakit	02/16/15	6		10	13	1	30			2		1	3
nist_ctc_03_asme1_nx800_rc_ct242repr.stp	NX	CoreTech	02/18/15	6		10	13		29			2			2
nist_ctc_03_asme1_nx800_rc_nx.stp	NX	SPLM	11/04/15	6		10	13		29			2			2
nist_ctc_03_asme1_nx800_rc_th.stp	NX	Theorem	11/10/15	6		10	13		29			1			1
nist_ctc_04_asme1_ct5210_rd_ct242repr.stp	CATIA	CoreTech	12/19/14	8		10	5	1	24			3		1	4
nist_ctc_04_asme1_ct5210_rd_dk242repr.stp	CATIA	Datakit	02/16/15	8		11	5	1	25			2	2	1	5
nist_ctc_04_asme1_nx800_rd_ct242repr.stp	NX	CoreTech	02/18/15	8		10	5		23			3	1		4
nist_ctc_04_asme1_nx800_rd_nx.stp	NX	SPLM	11/04/15	8		10	5		23			5			5
nist_ctc_04_asme1_nx800_rd_th.stp	NX	Theorem	11/10/15	8		10	5		23			3			3
nist_ctc_05_asme1_ct5210_rd_ct242repr.stp	CATIA	CoreTech	12/19/14	4	2	6	10		22		2	4	4		10
nist_ctc_05_asme1_ct5210_rd_dk242repr.stp	CATIA	Datakit	02/16/15	4	2	6	10		22		2	3	3		8
nist_ctc_05_asme1_nx800_rd_ct242repr.stp	NX	CoreTech	02/18/15	2	2	6	10		20		2	4	5		11
nist_ctc_05_asme1_nx800_rd_nx.stp	NX	SPLM	11/04/15	2	2	6	10	2	22		2	4		2	8
nist_ctc_05_asme1_nx800_rd_th.stp	NX	Theorem	11/10/15	4	2	6	10		22	2	2	4	4		12
			Counts:	149	55	280	299	39	800	38	55	100	107	39	329
			Percents:												

DFS = Datum Feature Symbol, DTS = Datum Tag Symbol, DIM = Dimension, FCF = Feature Control Frame

Appendix B.2: Percent Clean (%) by PMI Category for Test Models)

STEP Model File	Native CAD	STEP Vendor	Date	DFS Count	DTS Count	DIM Count	FCF Count	NOTE Count	Total Count	DFS Clean	DTS Clean	DIM Clean	FCF Clean	NOTE Clean	Total Clean	Clean Perc
827-9999-903.stp	NX	CoreTech	04/28/15	2		8	6	7	23	2	0	3	6	0	11	48%
827-9999-904.stp	NX	CoreTech	07/10/15	3		54	13	8	78	3	0	53	13	0	69	88%
nist_ctc_01_asme1_ct5210_rd_ct242repr.stp	CATIA	CoreTech	12/19/14	3		10	6	3	22	2	0	7	6	0	15	68%
nist_ctc_01_asme1_ct5210_rd_dk242repr.stp	CATIA	Datakit	02/16/15	3		10	6	3	22	3	0	6	6	0	15	68%
nist_ctc_01_asme1_nx800_rd_ct242repr.stp	NX	CoreTech	02/18/15	3		10	6	2	21	3	0	7	6	0	16	76%
nist_ctc_01_asme1_nx800_rd_nx.stp	NX	SPLM	11/04/15	3		10	6	2	21	3	0	1	6	0	10	48%
nist_ctc_01_asme1_nx800_rd_th.stp	NX	Theorem	11/10/15	3		10	6	2	21	3	0	9	6	0	18	86%
nist_ctc_02_asme1_ct5210_rc_ct242repr.stp	CATIA	CoreTech	12/19/14	10	9	8	22	1	50	0	0	0	0	0	0	0%
nist_ctc_02_asme1_ct5210_rc_dk242repr.stp	CATIA	Datakit	02/16/15	10	9	8	22	1	50	0	0	0	0	0	0	0%
nist_ctc_02_asme1_nx800_rc_ct242repr.stp	NX	CoreTech	02/18/15	7	9	7	22	1	46	0	0	0	0	0	0	0%
nist_ctc_02_asme1_nx800_rc_nx.stp	NX	SPLM	11/04/15	6	9	7	22	2	46	6	0	7	22	0	35	76%
nist_ctc_02_asme1_nx800_rc_th.stp	NX	Theorem	11/10/15	10	9	7	22	1	49	0	0	0	0	0	0	0%
nist_ctc_03_asme1_ct5210_rc_ct242repr.stp	CATIA	CoreTech	12/19/14	6		10	13	1	30	6	0	8	13	0	27	90%
nist_ctc_03_asme1_ct5210_rc_dk242repr.stp	CATIA	Datakit	02/16/15	6		10	13	1	30	6	0	8	13	0	27	90%
nist_ctc_03_asme1_nx800_rc_ct242repr.stp	NX	CoreTech	02/18/15	6		10	13		29	6	0	8	13	0	27	93%
nist_ctc_03_asme1_nx800_rc_nx.stp	NX	SPLM	11/04/15	6		10	13		29	6	0	8	13	0	27	93%
nist_ctc_03_asme1_nx800_rc_th.stp	NX	Theorem	11/10/15	6		10	13		29	6	0	9	13	0	28	97%
nist_ctc_04_asme1_ct5210_rd_ct242repr.stp	CATIA	CoreTech	12/19/14	8		10	5	1	24	8	0	7	5	0	20	83%
nist_ctc_04_asme1_ct5210_rd_dk242repr.stp	CATIA	Datakit	02/16/15	8		11	5	1	25	8	0	9	3	0	20	80%
nist_ctc_04_asme1_nx800_rd_ct242repr.stp	NX	CoreTech	02/18/15	8		10	5		23	8	0	7	4	0	19	83%
nist_ctc_04_asme1_nx800_rd_nx.stp	NX	SPLM	11/04/15	8		10	5		23	8	0	5	5	0	18	78%
nist_ctc_04_asme1_nx800_rd_th.stp	NX	Theorem	11/10/15	8		10	5		23	8	0	7	5	0	20	87%
nist_ctc_05_asme1_ct5210_rd_ct242repr.stp	CATIA	CoreTech	12/19/14	4	2	6	10		22	4	0	2	6	0	12	55%
nist_ctc_05_asme1_ct5210_rd_dk242repr.stp	CATIA	Datakit	02/16/15	4	2	6	10		22	4	0	3	7	0	14	64%
nist_ctc_05_asme1_nx800_rd_ct242repr.stp	NX	CoreTech	02/18/15	2	2	6	10		20	2	0	2	5	0	9	45%
nist_ctc_05_asme1_nx800_rd_nx.stp	NX	SPLM	11/04/15	2	2	6	10	2	22	2	0	2	10	0	14	64%
nist_ctc_05_asme1_nx800_rd_th.stp	NX	Theorem	11/10/15	4	2	6	10		22	2	0	2	6	0	10	45%
			Counts:	**149**	**55**	**280**	**299**	**39**	**800**	**107**	**0**	**178**	**186**	**0**	**471**	**59%**
			Percents:							**72%**	**0%**	**64%**	**62%**	**0%**	**59%**	

DFS = Datum Feature Symbol, DTS = Datum Tag Symbol, DIM = Dimension, FCF = Feature Control Frame