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On Migrating ISO 10303 PMI Models to a Common Core

Allison Barnard Feeney
Thomas R. Thurman

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On Migrating ISO 10303 PMI Models to a Common Core

Prepared for
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National Institute of Standards and Technology
Gaithersburg, MD 20899

By
Allison Barnard Feeney
Smart Connected Systems Division
Communications Technology Laboratory

Thomas R. Thurman
TRThurman Consulting
Marion, Iowa

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Author ORCID iDs
Allison Barnard Feeney: 0000-0002-0866-9572
Thomas R. Thurman: 0000-0002-1550-9913

Abstract

Industrial users of ISO 10303 STandard for the Exchange of Product Model Data (STEP) protocols needed the ability to exchange design product data that is in conformance with recently updated ISO geometric product specification (GPS) standards, the American Society of Mechanical Engineers (ASME) dimensioning and tolerancing standard, and recently updated digital product data definition practice standards. Updates to those standards were made to support continued migration from drawing-based product and manufacturing information (PMI) exchange to full model-based exchange, sharing and management across life-cycle viewpoints (i.e., design to fabrication to inspection). The aerospace and automotive industries created a joint project to merge ISO 10303-203: Configuration controlled 3D design (AP 203) [1] and ISO 10303-214: Core data for automotive mechanical design processes (AP 214) [2] into a new ISO 10303-242: Managed model-based 3D engineering (AP 242) [3] rather than pursue individual updates. Relevant STEP information models have been updated and new information models created to support the ASME and ISO standards, resulting in the publication of AP 242 in 2014.

Keywords

computer aided design; data exchange; data model; datum system; dimension model; dimension representation; dimensioning and tolerancing; geometric dimensioning and tolerancing; geometric tolerance; geometrical product specification; integration; product and manufacturing information; product data; profile tolerance; STEP; tolerance model; tolerance representation.

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1. Approach

Industrial users of International Organization for Standardization (ISO) 10303 STandard for the Exchange of Product Model Data (STEP) protocols needed the ability to exchange design product data that is in conformance with recently updated ISO geometric product specification (GPS) standards ISO 1101: Geometrical tolerancing – Tolerances of form, orientation, location and run-out [4], ISO 5459: Datums and datum systems [5]; ISO 14405-1: Dimensional tolerancing – Part 1: Linear sizes [6], ISO 14405-2: Dimensional tolerancing – Part 2: Dimensions other than linear sizes [7]; with American Society of Mechanical Engineers (ASME) Y14.5-2009: Dimensioning and tolerancing [8], and with recently updated Digital Product Data Definition Practices standards ISO 16792 [9] and ASME Y14.41-2012 [10]. Updates to those standards were made to support continued migration from drawing-based product and manufacturing information (PMI) exchange to full model-based exchange, sharing, and management across life-cycle viewpoints (i.e., design to fabrication to inspection). The aerospace and automotive industries created a joint project to merge ISO 10303-203 (AP 203): Configuration controlled 3D design [1] and ISO 10303-214 (AP 214): Core data for automotive mechanical design processes [2] into ISO 10303-242 (AP 242): Managed model-based 3D engineering [3] rather than pursue individual updates.

The PMI project was created to address the identified concerns. PMI project participants included industrial users of AP 203 and AP 214 as well as computer-aided design (CAD) software suppliers. Industrial participation was primarily through the long-term archival and retrieval (LOTAR) [11] project of the PDES, Inc. consortium, [12] which is comprised of global-leading aerospace companies. CAD software suppliers participated through the Computer-Aided-"x" (Design, Manufacturing, Inspection) Interoperability Forum (CAx-IF) [13], which is a software interoperability forum supporting STEP product data exchange standards. The PMI project included requirements from design product data definition practice standards and GPS standards for dimensional tolerances and for geometrical tolerances of form, orientation, location, and run-out. Requirements for datums, datum systems, datum targets, and tolerance frames were included. Existing capabilities of STEP were compared to the requirements defined by the updated documents and extensions were created as needed. The use of the EXPRESS [14] ENUMERATION, RULE, SELECT, and SUBTYPE declarations in extensions to existing constructs were included to provide upward compatibility.[1]

2. Scope and contribution

This document describes the development history and process, and it includes a description of the management data common in the distributed enterprise. It identifies EXPRESS ENTITY types that are deprecated in the second edition of ISO 10303-47 (IGR 47): Shape

[1]EXPRESS declarations in the text of this document are denoted with a bold font.

variation tolerances [15] and describes the structure of the new **datum_system** ENTITY type. Finally, it describes some of the improvements in dimensional tolerancing and in geometrical tolerancing models, and identifies future research opportunities.

3. Results

New editions of IGR 47, ISO/TS 10303-1050 (AM 1050): Dimension tolerance [16], and ISO/TS 10303-1051 (AM 1051): Geometric tolerance [17] have been created to support the additional requirements. Figure 1 illustrates the key STEP product model schemata that Dimension tolerance and Geometric tolerance application modules specialize for use across all STEP application protocols that support GPS standards.

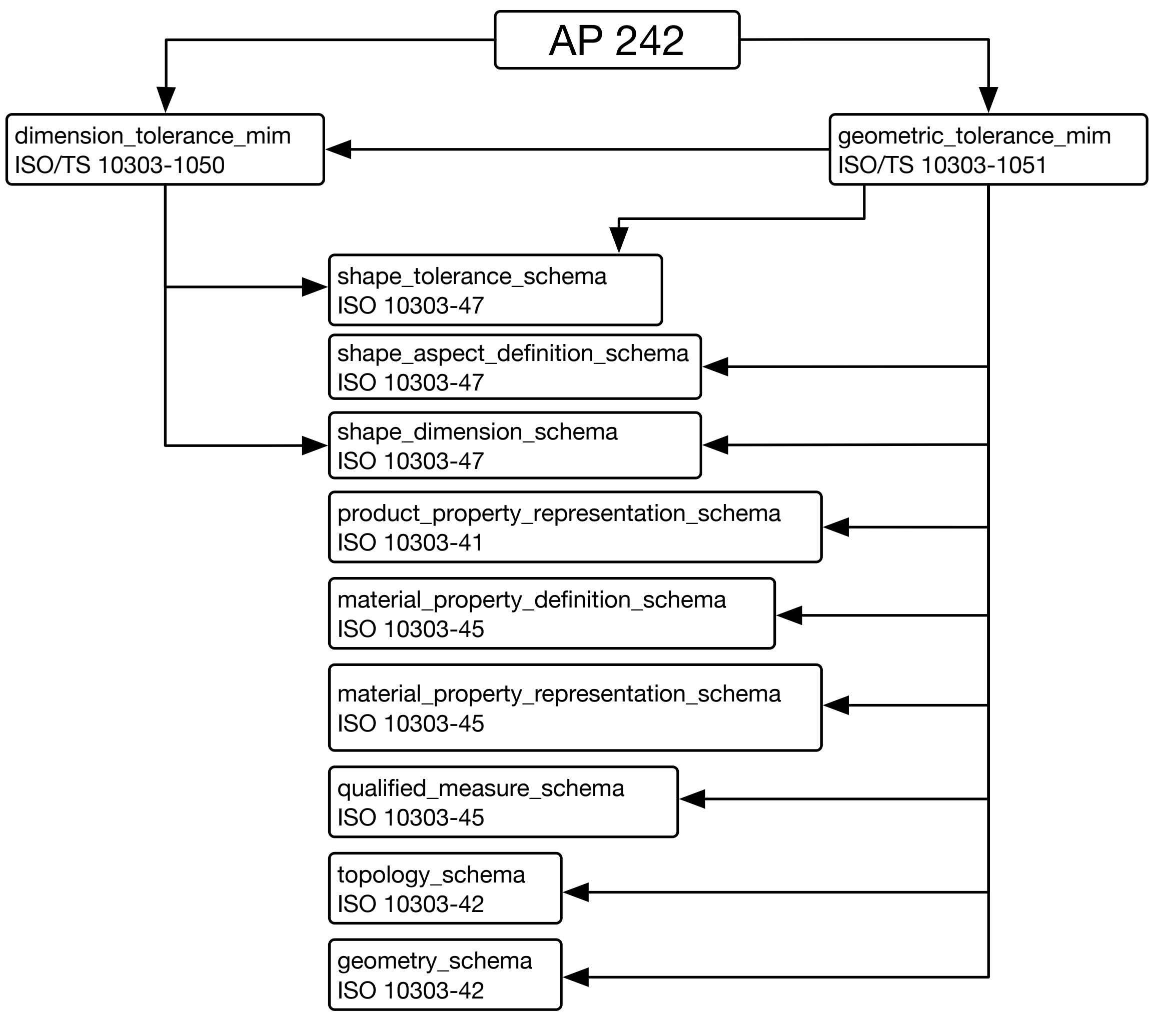

Fig. 1. Illustration of key STEP product model resource schemata specialized by Dimension tolerance and Geometric tolerance application modules.

New application modules:

- ISO/TS 10303-1816 (AM 1816) - Model-based 3d geometrical dimensioning and tolerancing representation [18],
- ISO/TS 10303-1812 (AM 1812) - Product and manufacturing annotation presentation [19],
- ISO/TS 10303-1810 (AM 1810) - Product and manufacturing information view context [20], and
- ISO/TS 10303-1811 (AM 1811) - Product and manufacturing information with nominal 3D models [21]

were created. Figure 2 illustrates the key STEP product model schemata that the new application modules specialize for use across all STEP application protocols that support GPS standards.

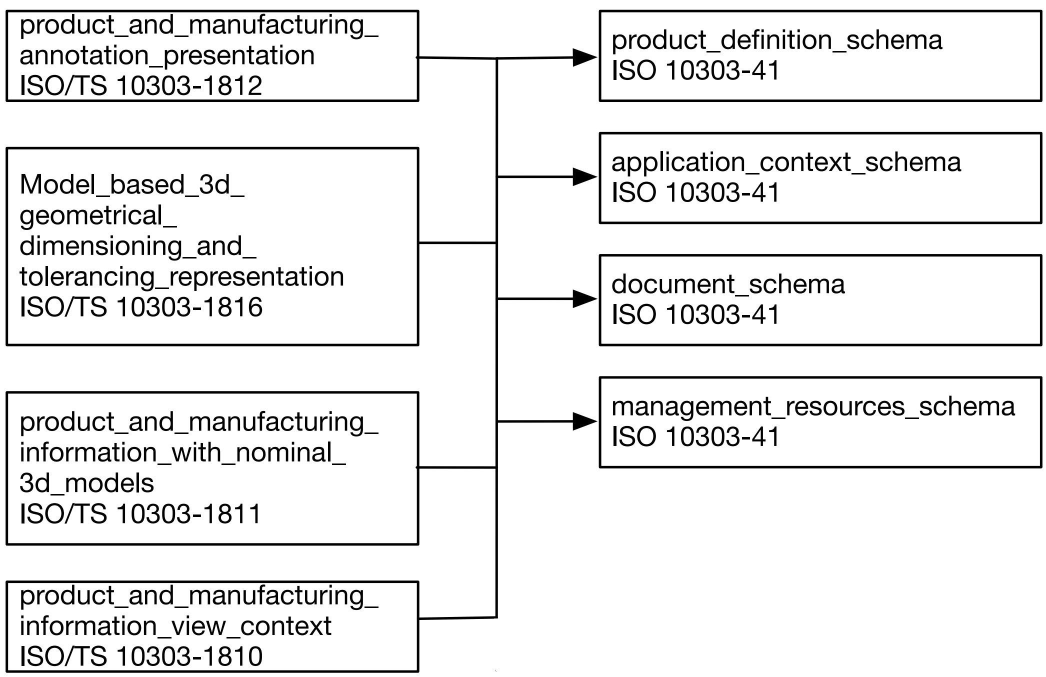

Fig. 2. An illustration of the key STEP product model schemata that the new application modules specialize.

ISO 10303-519 (AIC 519) [22] was merged into IGR 47 for model cohesion and reduced maintenance activity of the STEP product model because there were many domain-specific ENTITIES and TYPES in both standards that referenced ISO 1101. It is standard practice in the STEP PMI model to explicitly reference ASME and ISO GPS standards at the ENTITY and TYPE declarations. This practice provides a consistent, computer-interpretable means to audit STEP PMI model support of ASME and ISO GPS standards.

ISO 10303-203 (AP 203), ISO 10303-210 [23] (AP 210), ISO 10303-214 (AP 214), and ISO 10303-224 [24] (AP 224) models had several ENTITY types with similar names but different definitions. STEPmod integration required resolution of such conflicts.

Example 1. Feature_definition and Feature_occurrence from AP 214 and ISO 10303-522 (AIC 522) [25] were merged into IGR 47 for model cohesion.

Example 2. Slightly different shape_representation_with_parameters in ISO 10303-1051 and AIC 522 were harmonized and migrated to IGR 47 for model cohesion.

Asset management requirements for data sets compliant with AP 214, AP 242, and AP 210 were met. The document information models were integrated using STEPmod [26] architecture into an EXPRESS model suitable for implementation and incorporated into the AP 242 document. In most cases the upward compatibility constraint was met by extending the existing model schemata. In cases where it was infeasible to achieve upward compatibility due to structural limitations, existing structures were maintained in the information model so that existing assets would not be subject to obsolescence.

4. Architecture of PMI in STEP

STEP application protocols are viewpoint-based and require an industrial context in which to establish an information model. To provide a context, two conceptual activity models are provided. The first is of a value chain for a mechanical product; the second is a more detailed description of activities and data in the mechanical engineering and manufacturing engineering departments from the first illustration.

Figure 3 is a value chain illustration that shows the relationship of design, manufacturing engineering, and manufacturing activities in a UML activity diagram. Design engineering defines material specifications and GPS specifications. Manufacturing engineering specifies more detailed material specifications, manufacturing feature specifications, and inspection process requirements. Manufacturing receives material, processes it to create a product, and inspects the product for verification of conformance.

Figure 4 shows the relationship of a mechanical product definition flow to the key artifacts created during the flow that are required to manufacture the product. The diagram uses a generic graphical syntax in which time flows down, the boxes on the left are activities, and the boxes on the right are artifacts. The unadorned lines between the activities and artifacts are the data updates created by the activities. Arrows between activities denote sequence. The geometric design optimization activity generates an internal three-dimensional geometric model that may be represented with AP 203, AP 210, or AP 214. The detailed design activity produces a Material specification and a Design Model geometric functional specification that may be represented with AP 214 or AP 242. The Design Model geometric

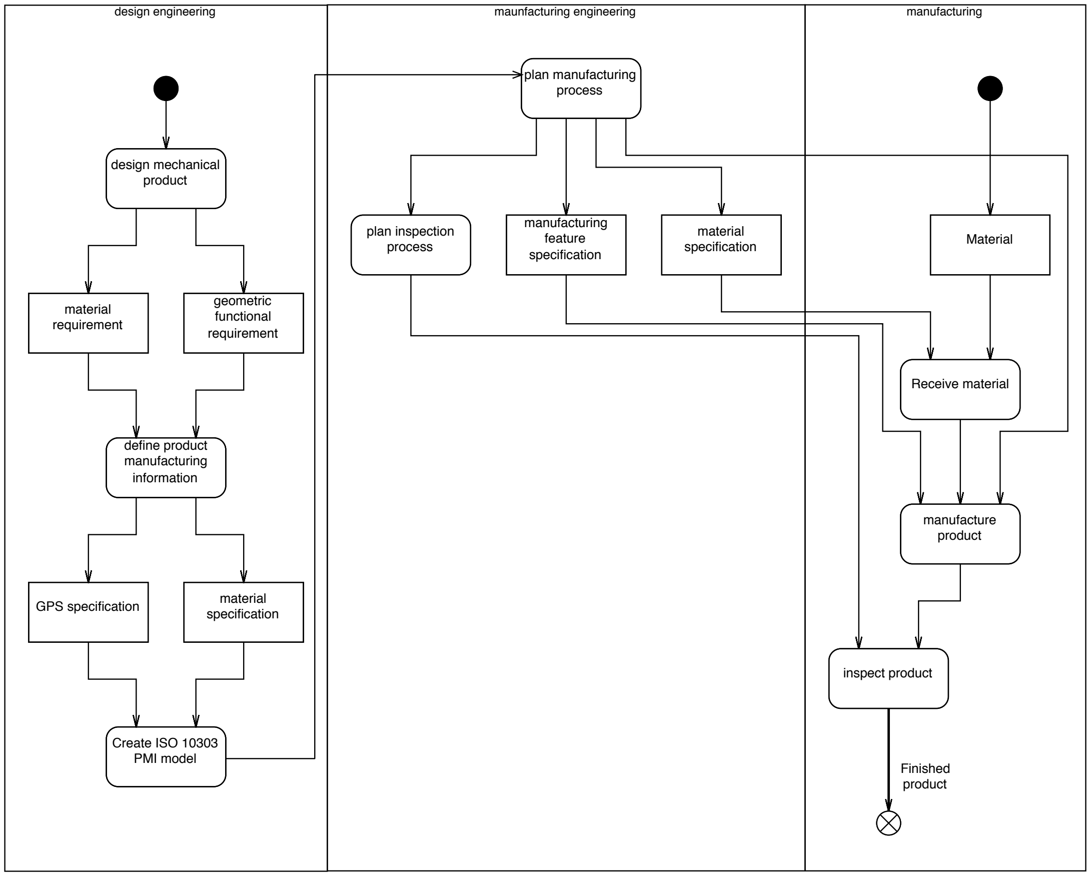

Fig. 3. A UML model of key activities in design and manufacturing for a mechanical product.

functional specification is composed of two artifacts: a Design Model Tolerance annotation that is a graphic presentation, and a Design Model Tolerance specification that is a representation. In some cases, only the Design Model Tolerance annotation is supplied. In those cases, AP 202 or AP 214 may represent the graphic representation as drawing-based data. The graphic presentation is intended for human consumption while the representation is computer interpretable. In the case of combined annotation and representation, AP 214 would be used to define the exchange data set. The manufacturing process planning activity generates Manufacturing feature definition fed to numerical control (NC) code generators computer-aided manufacturing (CAM). The Manufacturing feature definition would be an AP 242 data set. The manufacturing process planning activity generates a Manufacturing feature tolerance specification fed to measurement processes for product evaluation.

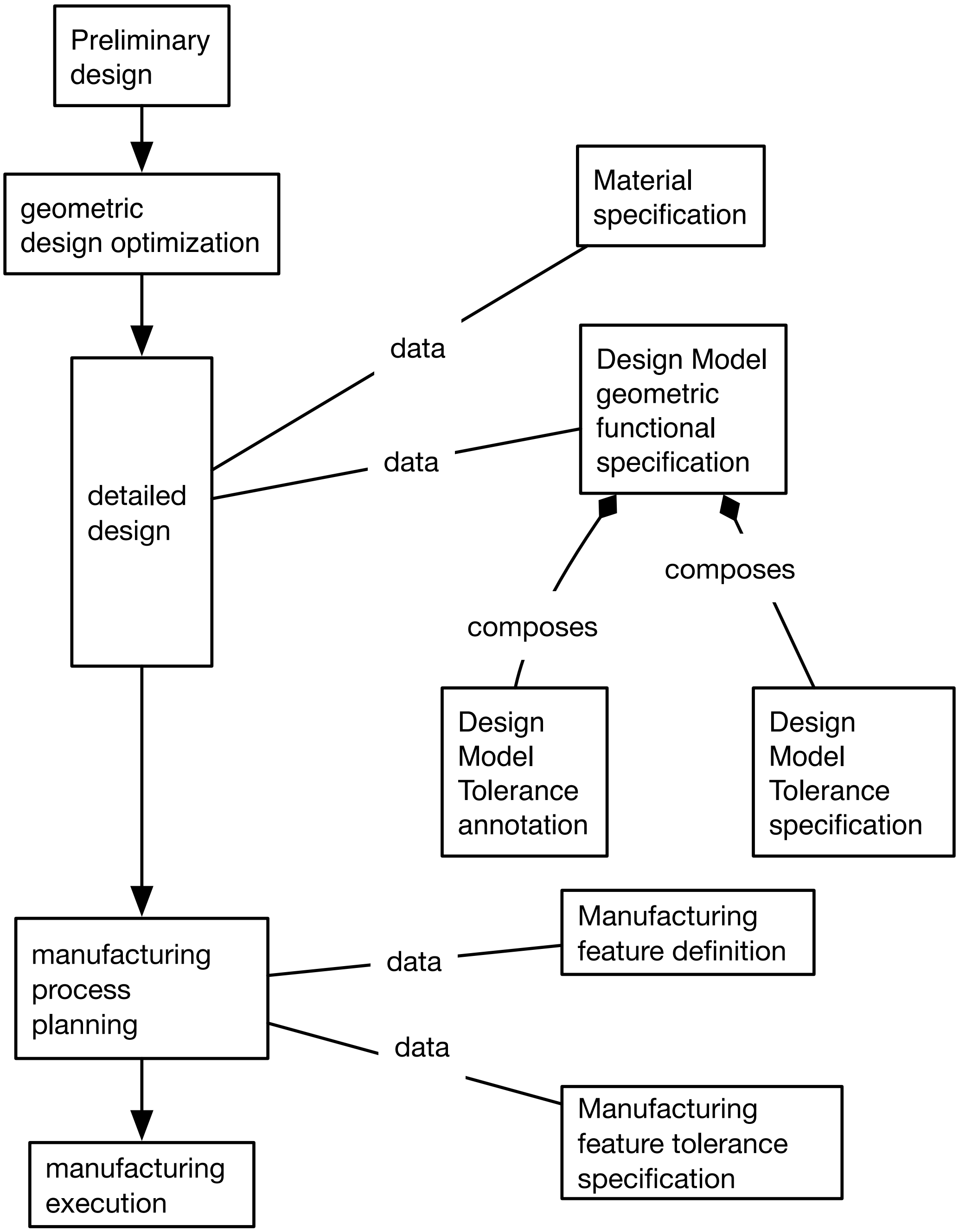

Fig. 4. Illustration of activities and data artifacts created in mechanical design and manufacturing engineering life-cycle phases.

5. PMI in STEP before AP 242

An active research and implementation program taking advantage of the integration potential of ISO 10303 in the mechanical product design to manufacturing to inspection work-

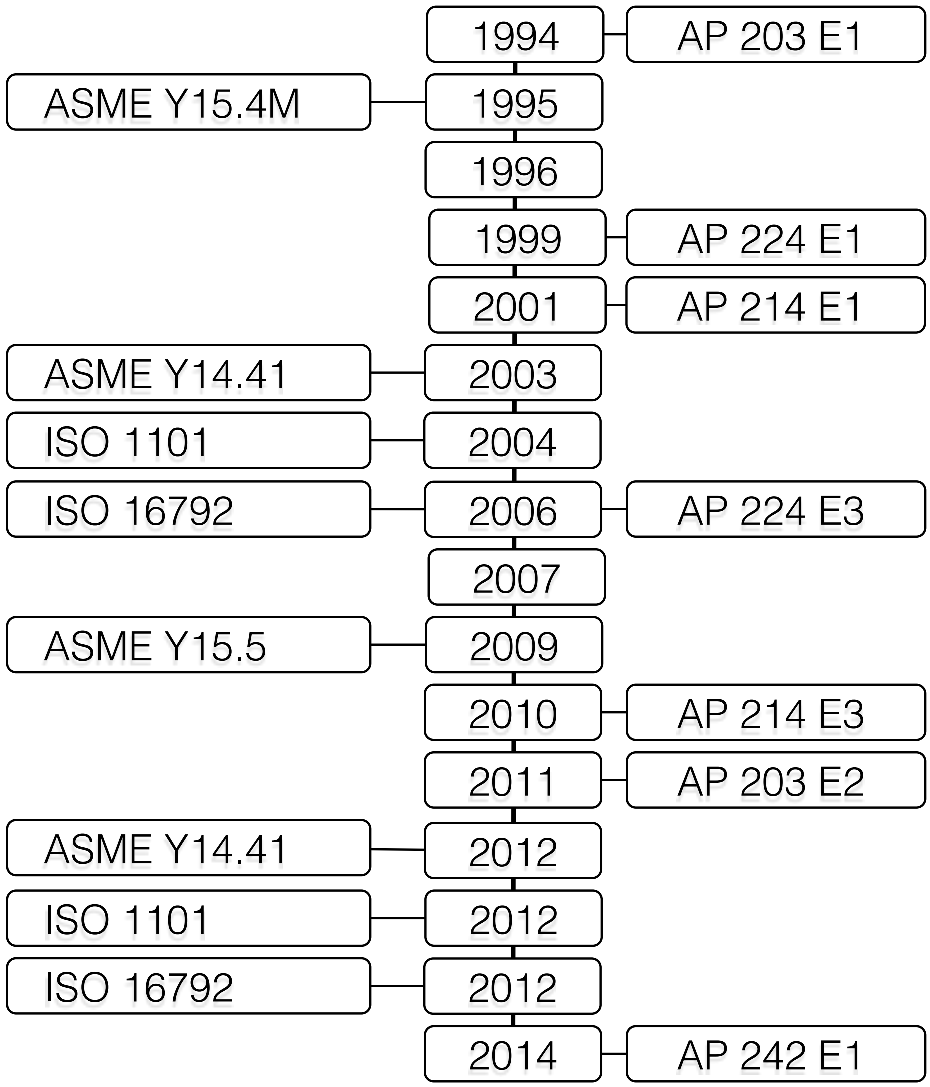

Fig. 5. Graphical timeline of PMI inclusion in STEP.

flow has resulted in requests for improvements in the dimensioning and tolerancing data models in STEP.

Figure 5 provides a graphical timeline of the inclusion of PMI in STEP parts. ISO 10303-203:1994 provided key solid modeling for unambiguous representation of piece part and assembly models in a widely accepted information model. A milestone in 1995 was the publication of ASME Y14.4M-1995 which provided one interpretation of a size tolerance, which was a key enabler for developing data exchange standards. The publication in 1999 of AP 224 provided a first edition of a standard for exchanging tolerance models and process plan models based on AP 203 and the ASME Y15.4. McCaleb [27] identified deficiencies in the datum system information model but the issues were deferred. The design and manufacturing Application Protocol (AP) projects harmonized the approach to support three-dimensional geometry with the adoption of ISO 10303-514: Advanced boundary representation (AIC 514) [28]. The first edition of AP 214 was published in 2001. The information model and document publication architecture used for STEP was revised to follow a modular approach (STEPmod) [26]. ASME Y14.41:2003 provided several improvements. These included addressing tolerancing of the design model and tolerancing of axonometric views, and offering some support for reduced dimension drawings. ISO 1101:2004 contains basic information and gives requirements for the geometrical tolerancing of workpieces; it represents the initial basis and defines the fundamentals for geometrical tolerancing. The manufacturing suite of STEP AP projects (AP 214, ISO 10303-224 (AP 224), and ISO 10303-238 (AP 238) [29]) harmonized their approach to dimensions and tolerances with AM 1050 and AM 1051 in 2005 based in part on input from ISO TC 213: Dimensional and geometrical product specifications and verification [30]. That established a solid baseline for manufacturing even as research and development of software interfaces supporting mechanical model to piece part fabrication and inspection workflow automation continued. ISO 16792:2006 specifies requirements for the preparation, revision, and presentation of digital product definition data, hereafter referred to as data sets. It supports two methods of application: model-only, and model and drawing in digital format. Its structure presents requirements common to both methods followed by clauses providing for any essential, differing requirements for each method. Additionally, its use in conjunction with computer aided design (CAD) systems could assist in the progression towards improved modeling and annotation practices for CAD and engineering disciplines, as well as serving as a guideline for IT engineers. The third edition of AP 224, published in 2006, incorporated references to externally defined gears defined in ISO 1122-1. ASME Y15.5-2009 contained many useful advances and clarifications to better empower the designer to fully and reliably express the desired functions of machine parts. As a result of their implementation experience, the CAx-IF identified issues [31] with AP 203 and AP 214 coverage of relevant ASME and ISO standards. These issues were captured in the instance [32] of bugzilla [33] devoted to ISO 10303 that is managed by ISO TC 184/SC 4. The third edition of AP 214 was published in 2010. AP 203 edition 2 was published in 2011 with significant enhancements:

- updated to use EXPRESS Edition 2, harmonized with AP 214, and extended to provide additional PDM capabilities;
- incorporated geometric dimensioning and tolerances;
- added geometric presentation structures that includes colors, layers, and groups;
- enhanced document management structures;
- added more work management capabilities;
- added geometric validation properties;
- included constructive solid geometry structures;

- incorporated 3D associative text;
- enhanced product structure capabilities, compatible with UOF specification_control (S7) and item_definition_structure (S3) from AP 214;
- added composite materials;
- added solid shape model with construction history;
- enhanced catalogue support and external references;
- reorganized application modules on presentation and drafting to fit with application interpreted construct (AIC) boundaries;
- enhanced presentation capabilities for better ISO 16792 support; and
- added support for usage of **item_identified_representation_usage** with specialized subtypes and corresponding ARM constructs for more efficient linkage between a **shape_aspect** and the corresponding geometric representation and presentation items and to establish associativity between these items.

ASME Y14.41-2012 incorporates changes based on the needs of industry and to reflect changes made to ASME Y14.5-2009: Dimensioning and Tolerancing. ISO 1101:2012 expanded upon ISO 1102:2004 by including content from ISO 1057:1992: Tolerancing of orientation and location — Projected tolerance zone. ISO 16792:2012 was an update to incorporate changes from ISO 1102:2012 and ISO 5459:2011 and to include weld and surface texture indications. During the same time period, ISO TC 10: Technical product documentation, ISO TC 213, and the ASME Y.14 standards committees continued development in support of model-based approaches to design and manufacturing. These updates removed many ambiguities in the source documents, lending credence to the idea that information models based on them should be updated. Documents supporting activities including designer-software interaction (e.g., ISO 16792 and ASME Y14.41-2012) and CAD to coordinate-measurement machine (CMM) (e.g., ISO 1101) were becoming available and provided clarification for data exchange requirements between design and manufacturing (and back to design). Horst [34] noted several requirements for design CAD PMI information models.

With the available issues and the impetus of forthcoming documents from ISO TC 10, ISO TC 213, and ASME Y.14, a project was established to update IGR 47 and relevant STEPmod application modules (AMs) and develop AP 242.

Finally, in 2014, the first edition of AP 242 was published, informed by standards identified in the timeline.

The CAx-IF published an update to the Recommended Practices for the Representation and Presentation of Product Manufacturing Information (PMI) (AP 242) [35] in 2014.

6. The taxonomy of AP 224

Figure 6 illustrates the taxonomy of resource parts used for AP 224. This is a typical taxonomy for a mechanical product design and manufacturing application protocol.

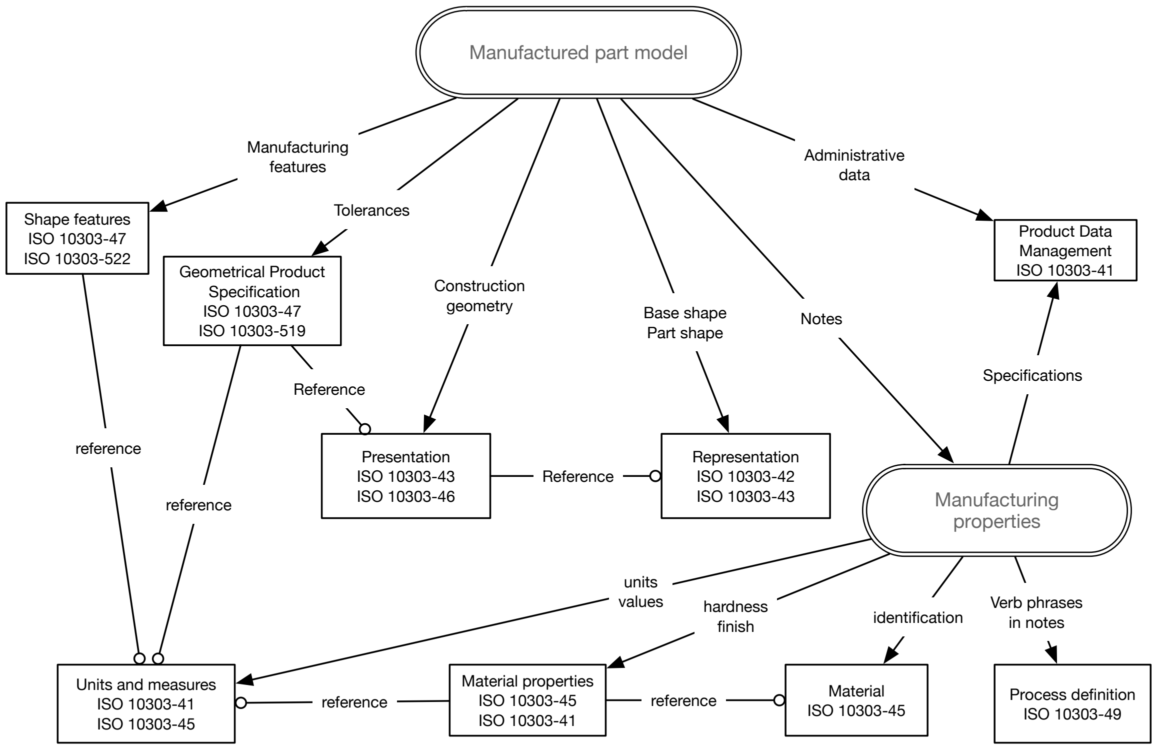

Fig. 6. Document architecture for AP 242.

A manufacturing part model is composed of:

- manufacturing features defined in IGR 47 and AIC 522;
- tolerances defined in IGR 47 and AIC 519;
- construction geometry defined in ISO 10303-43 (IGR 43) [36] and ISO 10303-46;
- a base shape defined in ISO 10303-42 (IGR 42) [37] and IGR 43;
- a part shape defined in IGR 42 and IGR 43;
- notes that define manufacturing properties; and
- administrative data defined in ISO 10303-41 (IGR 41).

A set of manufacturing properties is composed of:

- units and values defined in IGR 41 and ISO 10303-45 (IGR 45) [38];
- hardness and surface finish defined in IGR 41 and IGR 45;

- material identification defined in IGR 45; and
- verb phrases in notes defined in ISO 10303-49.

In each case, the development of the application protocol resulted in specialization of the generic concepts that was appropriate to the domain requirements listed as composing AP 224.

7. AP 242 PMI-development process model

Figure 7 illustrates high-level interaction of standard development organizations with industry. In the case of PMI, the primary committees that develop practice standards are ISO TC 10, ISO TC 213, and ASME Y14. In the case of ISO 10303, the development committee is ISO TC 184/SC 4. The practice standard committees accept issues from industry and from ISO TC 184/SC 4. ISO TC 184/SC 4 accepts issues from industrial enterprises and from implementors and receives updates from the practice standards committee, subsequently releasing a revision to ISO 10303. Enterprises incorporate the practice standards into their quality processes and accept software interfaces based upon ISO 10303 into their design and manufacturing process threads. Software implementors accept both updated practices standards and updated ISO 10303 data exchange standards, provide updated CAD software compliant to the practices standards, and provide updated interfaces compliant to the data specifications of ISO 10303.

Figure 8 is a more detailed illustration of the interaction during AP 242 development. The enterprise value chain identifies needs to the practice committees and to ISO TC 184/SC 4, and when the standards are available, provides education and updates quality processes to implement the standards in their enterprise. The practice committees accept needs from industry and publish updates to their standards. ISO TC 184/SC 4 development projects accept updates for the GPS standards, prioritize content requests from LOTAR, CAx-IF, and other stakeholders, and provide updated information models in a new release. LOTAR accepts needs from industry and government stakeholders, becomes educated on current and upcoming GPS standards, and provides consensus priority positions to funded development projects of stakeholders. The implementor group under the domain of the CAx-IF accepts content models from the practice committees, information models from ISO TC 184/SC 4, and prioritization information from LOTAR and industrial customers using user group forums and other means to collect requirements. A formal user group is also sponsored under the domain of the CAx-IF to foster closer communication. The CAx-IF develops consensus-based recommended practice documents to enhance interoperability between CAD systems and makes them publicly available. Software implementors incorporate the CAx-IF recommended practice patterns in software interfaces compliant to ISO 10303 standards. A robust interoperability testing program provides additional quality assurance.

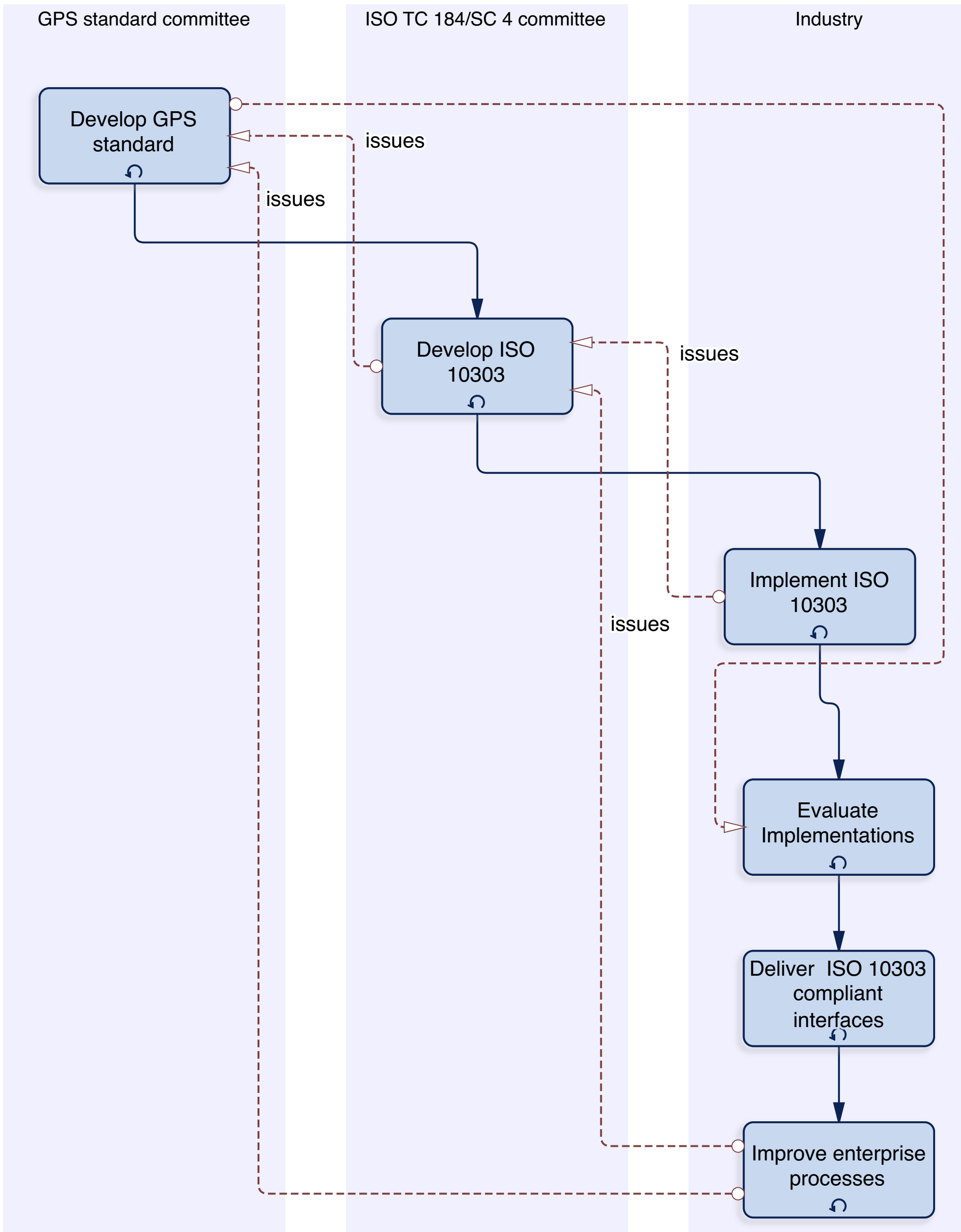

Fig. 7. Illustration of high-level SDO interactions with industry.

Figure 9 provides a high-level illustration of AP development.[2] An AP is composed of:

[2]The details of the modular development process are not discussed in this document.

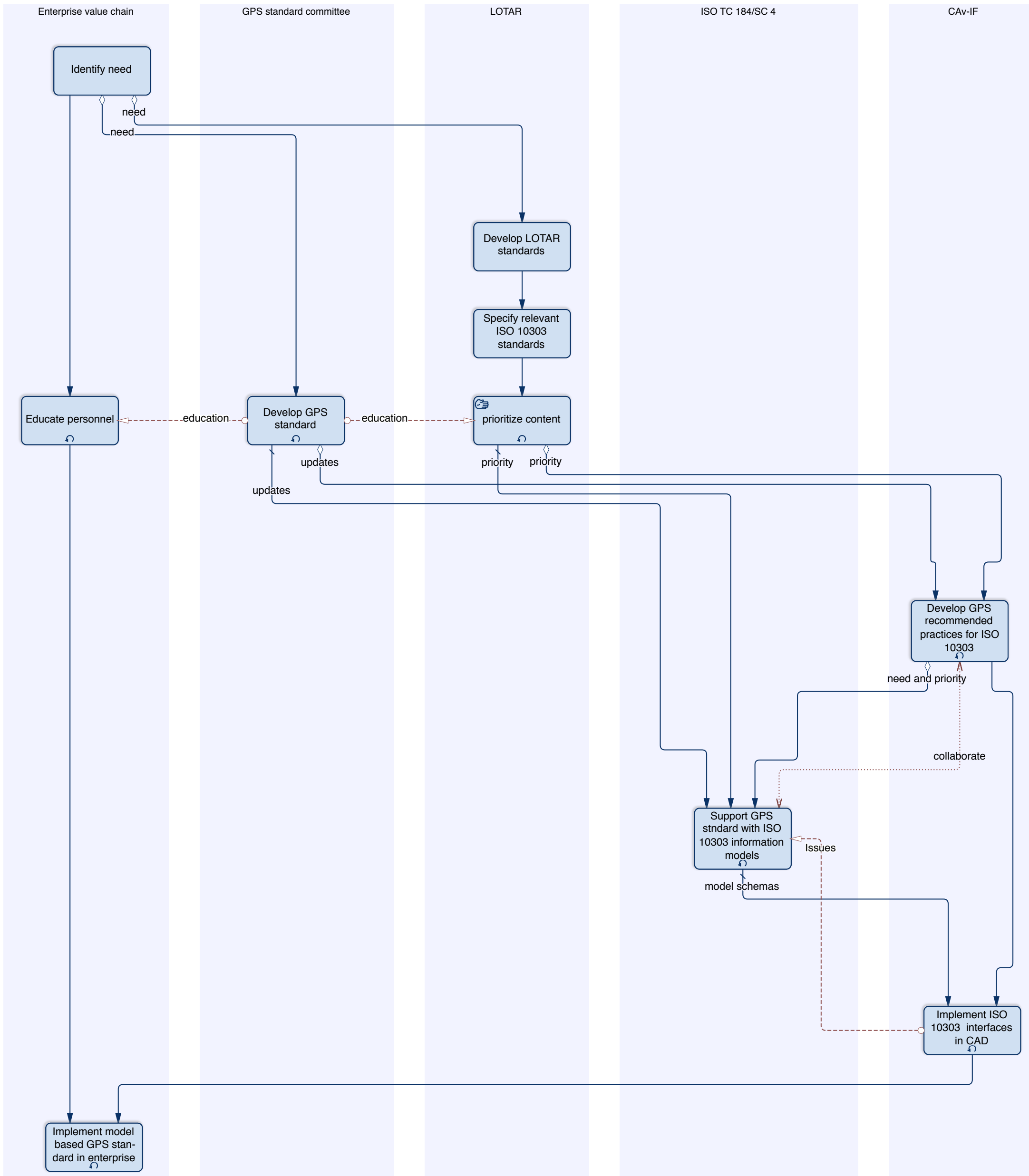

Fig. 8. Illustration of collaborative activities in developing STEP PMI models.

- activity model;
- application reference model (ARM);
- application interpreted model (AIM);
- conformance requirements; and

- mapping specification to relate the AIM model to the ARM model.

An activity model is specified from a user class viewpoint and a life-cycle stage. The ARM contains one or more domain-specific engineering languages that may be represented in narrative or in an EXPRESS information model. The AIM consists of an EXPRESS information model conformant to ISO 10303-11:1994 and contains no interfaces to other information models. The AIM is developed using the ISO TC 184/SC 4 application requirement interpretation process documented in [39] and [40] for the domain specified in the ARM. The associated consensus process for developing the STEP integrated product model is documented in [41].

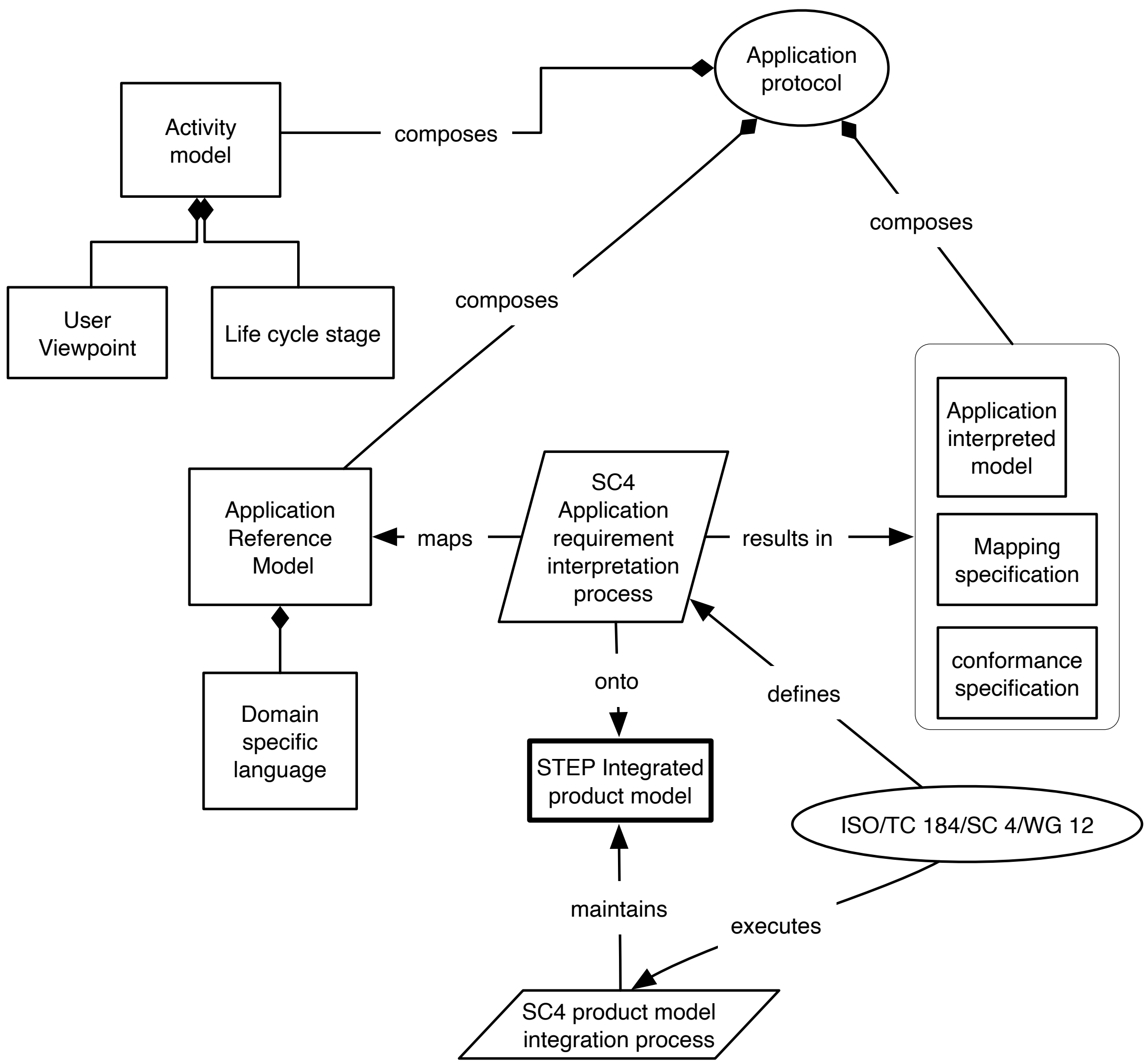

Fig. 9. Generic AP development illustration using a flowchart language.

Figure 10 illustrates the workflow utilized during development of the PMI content for AP 242.

Example 3. Material specification requirements from ISO 16792:2012 and ASME Y14.41-2012 were identified as being in the scope of IGR 45 [42]. The AP 242 ARM was updated with those requirements and the AIM was developed as a specialization of IGR 45 through the interpretation process.

Example 4. Design model geometric functional specification requirements from ISO 16792:2012, ASME Y14.41-2012, ISO 1101:2012, and ASME Y14.5-2009 were identified. Some requirements from other GPS standards were included but are not discussed in this document. Two elements of the ARM are illustrated in the diagram: Design model tolerance specification and Design model tolerance annotation.

The Design model tolerance specification requirements were identified as being in the scope of IGR 47. The AP 242 ARM was created with those requirements and the AIM was developed as a specialization of IGR 47 through the interpretation process. As part of the development process, enhancements to IGR 47 were provided using the process for developing and integrating the STEP integrated product model. The Design model tolerance annotation requirements were identified as being in the scope of ISO 10303-46. The AP 242 ARM was created with those requirements and the AIM was developed as a specialization of ISO 10303-46 through the interpretation process.

8. AP 242 PMI content model

8.1. Management data

Management data is used by design, manufacturing process planning, manufacturing execution, and quality organizations, all as a common layer for authority and identification. The management data requirements of ASME Y14.41-2012 and ISO 16792 are supported by the existing STEP product-data management (PDM) information model and by a new module, AM 1810.

Example 5. The tolerance principle to apply to a model is basic information needed by manufacturing process planning, fabrication, and inspection. However, the tolerance principle specified by ASME is different than the tolerance principle specified by ISO. The tolerance principle is applied to a model by a formal specification of the dimensioning standard that shall be used to interpret the model GPS data. The integration of the existing PDM information model and AM 1810 into AP 242 resulted in the ability to specify the dimensioning standard that applies. The AM 1811 module supports the ability to declare that the model geometry is nominal as defined in ISO 17450-1.

The AM 1050, AM 1051, and AM 1816 modules provide manufacturing technology-independent GPS information for use by design, manufacturing process planning, manufacturing execution, and inspection, all as a common layer for geometric functionality.

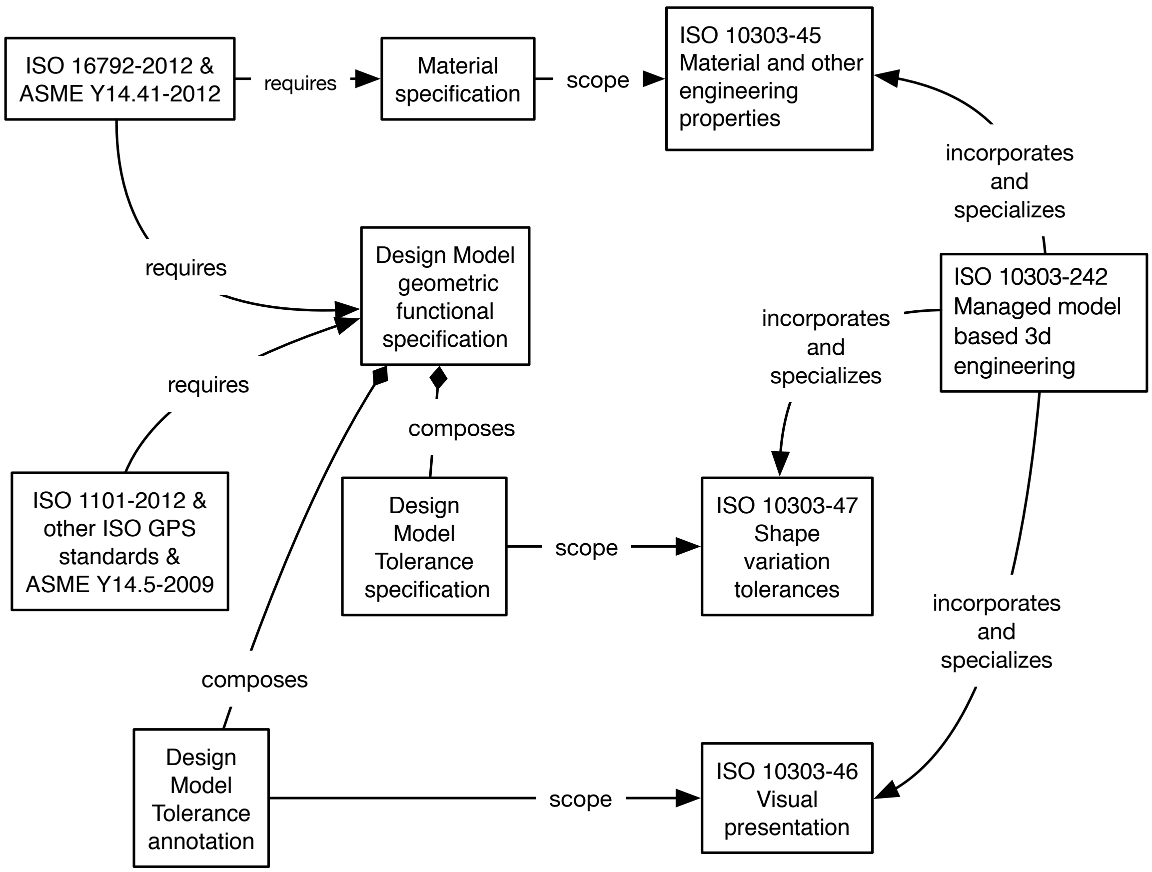

Fig. 10. The workflow for creating AP 242 PMI content from domain practice standards.

Improvements in product feature identification capability to support quality failure reporting have been provided by updates to ISO/TS 10303-1032 (AM 1032): Shape property assignment [43]. Improvements in geometric model element identification capability to support GPS requirements have been provided by updates to IGR 41.

The AM 1812 module supports annotation of nominal 3D geometric models with text and graphics that can be used by design, manufacturing process planning, and manufacturing inspection human processes.

8.2. Presentation and representation

The state of the practice that existed in the initial STEP mechanical design domain AP development was that during one activity a user interacts with a CAD system to build a geometric model based on IGR 42; during a separate activity a user interacts with a CAD system to annotate that geometric model with graphic dimensioning and tolerancing information based on ISO 10303-46 [44]; and during a third activity a user interacts with a CAD system to annotate that geometric model with semantic dimensioning and tolerancing information based on IGR 47. The separate activities led to first editions of AP 202 [45], AP 203, and AP 224 respectively. The result is that there a recognition gap [46] between the annotation and the dimensioning data sets of models created based on those separate activities. The recognition gap persists in AP 242 between requirements and notes because the requirement model in that standard does not intersect with the notes model in that standard. The conceptualization gap persists in AP 242, increasing interoperability costs between, for example, the system engineering and mechanical engineering communities. Plainly stated, the PDM, MCAD, and System Engineering Software vendors don't want to share information models.

8.3. Persistent identification

Persistent identification [47] support has been improved with the introduction of unique constraints on key GPS-related entity types: **shape_aspect**, **shape_aspect_relationship**, **dimensional_size**, **dimensional_location**, and **geometric_tolerance** in the context of a single **product_definition_shape**. When combined with the unique constraint on **geometric_item_specific_usage**, a requirement for being able to persistently associate a geometric entity (e.g., **advanced_face**) with a tolerance has been satisfied for the case of a specific combination of **product_definition_shape** and **representation** in the exchange model. The **shape_aspect** entity provides the identification of the **advanced_face** in the context of the **product_definition_shape**. Because there is a unique constraint on **product_definition_shape** for a **product_definition**, enterprises that maintain uniqueness on the tuple (enterprise id, part id, version id, **product_definition** id) are assured that the related entity types will be resolvable with a query on (enterprise id, part id, version id, **product_definition** id, **shape_aspect** id). No semantics are attached to the identifiers, and CAD software implementors are not constrained to provide human-interpretable identifiers on the related entity types.

8.4. Feature classification

As noted earlier, model feature classification is supported to some extent in AP 242. The classification of a model feature is derived from the user actions during the process of adding GPS information to the design model. The updated ASME and ISO standards require that the designer provide a feature based geometric model and define a specific class of feature, a model feature. However, the concept of feature is not a fundamental geometric construct (e.g., point, line, face) in CAD geometry, and the user must interact with the CAD system to instantiate each model feature class and specify one or more associated geometric elements for that model feature instance. STEP provides the generic **shape_aspect** ENTITY type to represent a feature, and IGR 47 provides the ability to classify a feature as a model feature. The number of model feature classes included in AP 242 is a significant improvement over earlier APs and contributes toward meeting the "tolerance feature" requirement noted in [34].

8.5. Symmetry groups, invariant classes

Some of the ASME and ISO specification operators assume the existence of a specific group of geometric properties (e.g., continuity among certain model element boundaries) of the model feature. The names of those ASME and ISO specification operators are used as names of subtypes of **shape_aspect** (e.g., **continuous_shape_aspect**) in an initial design feature classification scheme included in the second edition of IGR 47. The ISO standards include the further classification of model features of revolute class, a mathematical property of the underlying geometric model of the feature instance. Some of the ISO tolerance classes require that model features belong to one of the following invariance classes defined in ISO/TS 17450-1 [48]: complex, prismatic, revolute, helical, cylindrical, planar, and spherical. When a feature instance is assigned to a tolerance that is only permitted to be assigned to a specific revolute class, the CAD system will be required to assert that the feature instance is a member of that revolute class.

Example 6. A **roundness_tolerance** ENTITY type included in IGR 47 may only be assigned to a feature instance whose underlying geometry is a surface revolute but is not a helical shape.

The available geometric model ENTITY types in AIC 514 include some ENTITY types that map directly to a revolute class (e.g., plane, cylindrical_surface), but in the majority of cases the authoring CAD system will be responsible for ensuring that the model feature underlying geometry meets the requirements of the invoked invariance class specified by the geometric tolerance.

8.6. Datum system

The ASME standards refer to the combination of the last compartments in a tolerance frame that references datum features as a datum reference system. The ISO standards refer to that combination as a datum system if there are two or more compartments and as a single datum if there is only one compartment. An interpretation of ISO 16792 and ASME Y14.41-2012 concludes with the decision to provide an explicitly modeled **datum_system** as a new subtype of **shape_aspect** because ISO 16792 and ASME Y14.41-2012 require a model coordinate system to be associated to a datum system. ISO 5459 was chosen as the reference standard for the interpretation process for a datum system to maintain provenance.

The interpretation of ISO 5459 requirements resulted in the new ENTITY type **datum_system** which supports both the ASME and ISO definitions by supporting references of from one to three **datum_reference_compartment**s in a given order, where a **datum_reference_compartment** represents a compartment in a tolerance frame.[3] The **datum_system** ENTITY type is a subtype of **shape_aspect**, providing the capability to assign properties

[3]The details of the datum system information model differ from that proposed in [27].

to the **datum_system**. ISO 5459 also provides requirements for the datum system to be composed of datums or modified datums either singly or in a tree [49]. The root is a **datum_reference_compartment**. All intermediate nodes are **datum_reference_element** and the leaf entity types are **datum**. The **common_datum_list** satisfies the common datum requirement by providing a list of one to many **datum_reference_element**s. This structure allows us to model complex common data structures (e.g., $(A-B)xxx-(C-D)yyy$). The recursion provides the ability to nest items (e.g., $((A-B)xxx-(C-D))yyy$). A **datum_system** might have an explicitly associated model coordinate system in the related geometric model.

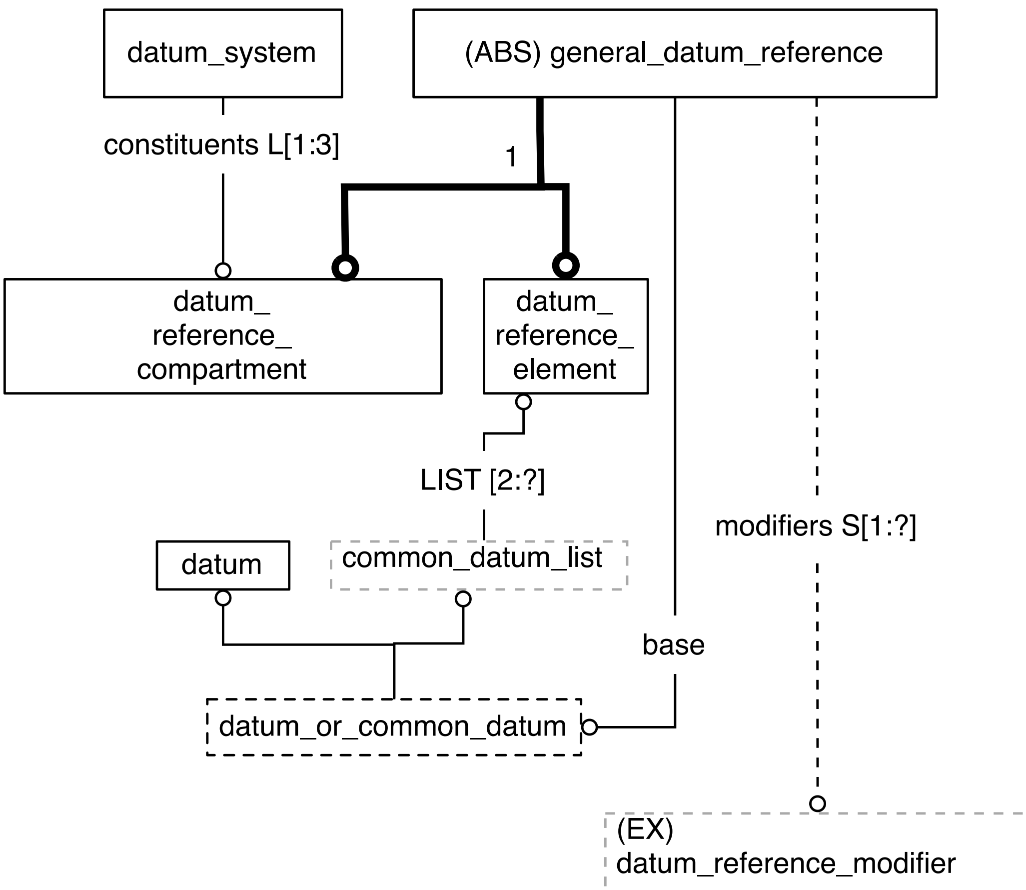

Fig. 11. An EXPRESS-G illustration of the recursive EXPRESS model for a datum system.

A tree is created by a pre-processor that traverses the recursive path illustrated in Fig. 11 from **datum_reference_compartment** to base to **datum_reference_element** that terminates on **datum** in the role of base.

The use of a list aggregate between **common_datum_list** and **datum_reference_element** imposes an ordering on the elements included in the reference compartment. At each node of the tree a set of modifiers may be applied to identify the particular operator required. The modifiers are separated into two extensible ENUMERATION types depending on whether additional values are provided. The **simple_datum_reference_modifier** is used when there is no additional value provided.

The **simple_datum_reference_modifier** includes:

- free_state,
- basic,
- translation,
- least_material_requirement,
- maximum_material_requirement,
- point,
- line,
- plane,
- orientation,
- any_cross_section,
- any_longitudinal_section,
- contacting_feature,
- distance_variable,
- degree_of_freedom_constraint_x,
- degree_of_freedom_constraint_y,
- degree_of_freedom_constraint_z,
- degree_of_freedom_constraint_u,
- degree_of_freedom_constraint_v,
- degree_of_freedom_constraint_w,
- minor_diameter,
- major_diameter, and
- pitch_diameter.

The extensible ENUMERATION type **datum_reference_modifier_type** is used when there is a value provided for the node in the tree. It provides an assertion that the shape of the associated feature used to establish a datum is circular, cylindrical, spherical, two parallel planes, or a projected length as defined in ISO 5459.

8.7. Dimensional tolerances

IGR 47 provides **dimensional_size** to represent a dimension of one feature and **dimensional_location** to represent a dimension between two features. The standard provided a mechanism to qualify the value assigned to the dimension. To support the new requirements additional mechanisms have been provided, keeping in mind the requirement for upward compatibility.

There are three mechanisms that may be used to qualify the values assigned to the **dimensional_size**. The **shape_dimension_representation**.name associated with the **dimensional_size** may be assigned a value to specify a local override of the tolerance principle applied to the design model. The Application Object Geometric_dimension in AM 1050 specifies a local override status of the default tolerance principle with the 'tolerance_principle' attribute. For qualifying the value of the dimension (e.g., maximum), the value may be represented with a **qualified_representation_item**. For cases where modifiers common to geometric tolerances are applied (e.g., statistical_tolerance, continuous) a **geometric_tolerance_with_modifiers** may be applied.

AM 1050 supports assigning radius and diameter values to features or elements of features appropriate for the following underlying geometric models: circular, cylindrical, spherical, and toroidal. For a toroid, a complete enumeration of the possible radii and diameters is included.

Example 7. The user interacted with the authoring system to place the "all over" symbol and associated elements of the symbology in an annotation plane. The user associates the elements to a point on the surface of the geometric model. The authoring system will generate the requisite instances of **product_definition_shape** and **geometric_tolerance** (referencing that **product_definition_shape**) so that the receiving system can programmatically determine that the **geometric_tolerance** applies to the entire product surface. The "all over" symbol itself is not exchanged.

8.8. Geometric tolerances

Geometric tolerances are used in the specification of a feature of the surface of a product. A geometric tolerance defines a tolerance zone, which is a region in space in which the product feature must lie. The shape of the zone depends upon the kind of tolerance and feature. When necessary, the location and orientation of the tolerance zone is specified with respect to a datum system. Improved support for tolerance zone requirements indicated in the updated ASME and ISO standards is included in the second edition of IGR 47, but tolerance zone is not discussed further in this document. The ASME term feature control frame and the ISO term tolerance frame are represented in IGR 47 by the **geometric_tolerance** ENTITY type, its subtypes, and related entities. Extensive work has been done to update the **geometric_tolerance** ENTITY type to meet the updated ASME and ISO standards while ensuring that existing assets are minimally impacted. Domain-specific subtypes of **geometric_tolerance** include:

- **angularity_tolerance**,
- **circular_runout_tolerance**,
- **coaxiality_tolerance**,
- **concentricity_tolerance**,
- **cylindricity_tolerance**,
- **flatness_tolerance**,
- **line_profile_tolerance**,
- **parallelism_tolerance**,
- **perpendicularity_tolerance**,
- **position_tolerance**,
- **roundness_tolerance**,
- **straightness_tolerance**,
- **surface_profile_tolerance**,
- **symmetry_tolerance**, and
- **total_runout_tolerance**.

The model feature that is toleranced by the **geometric_tolerance** is specified by the toleranced_shape_aspect attribute. The toleranced feature is either a **shape_aspect**, the whole **product_definition_shape**, a **dimensional_size**, or a **dimensional_location**. The ability to reference a **dimensional_size** or **dimensional_location** is provided for presentation-based use cases. The subtype **geometric_tolerance_with_datum_reference** is used when there is a requirement to reference either a **datum_system** or a set of one or more **datum_reference**. The subtype **geometric_tolerance_with_defined_unit** is used when there is a requirement to specify values with the **geometric_tolerance**. The subtype **geometric_tolerance_with_modifiers** is used when there is a requirement to specify specification operators for the **geometric_tolerance**. The subtype **unequally_disposed_geometric_tolerance** is used when there is a requirement to specify an offset tolerance zone. For purposes of reporting by a quality organization, the **geometric_tolerance** is uniquely identified within the context of a **product_definition** in the second edition of IGR 47. The attribute description is reserved for local notes associated with a tolerance frame where the information in the note does not duplicate an explicitly modeled construct. A **geometric_tolerance** and **shape_aspect**s it relates to are in the same context (e.g., **product_definition**). The entity types **component_path_shape_aspect** and **multi_level_reference_designator** are available to permit a

shape_aspect defined at a lower-level node of the product structure to be specified by a relationship at a higher-level node.

Example 8. Several **geometric_tolerance** instances are arranged in an ordered structure by application of **geometric_tolerance_relationship** to support a composite tolerance. Further specialization of the geometric tolerance is provided by an extensible ENUMERATION **geometric_tolerance_modifier**. The specializations include:

- maximum_material_requirement,
- least_material_requirement,
- reciprocity_requirement,
- any_cross_section,
- free_state,
- common_zone,
- minor_diameter,
- major_diameter,
- pitch_diameter,
- line_element,
- not_convex,
- statistical_tolerance,
- tangent_plane,
- each_radial_element, and
- separate_requirement.

The ISO and ASME standards provide a rich set of tolerance modifiers that are supported with new types in IGR 47. The use of extensible types supports future extensions to IGR 47 as the ISO and ASME standards evolve. In some cases, the ASME or ISO requirement is satisfied by the name of the entity type to which the tolerance is applied instead of by a specific ENUMERATION value.

9. Upward compatibility and deprecation

The information model created for the first edition of IGR 47 was based on industrial standards and practices that were understood to be necessarily incomplete due to the state of the art and practice. In some cases, implicit two-dimensional drawing-based concepts were included that were not appropriate for three-dimensional model-based technology. In some cases the structure of the EXPRESS schema of the first edition did not permit extensions and a parallel structure was put in place in the second edition to support continued use of current interfaces. Consequently, those first-edition ENTITY types that did not permit extensions have been deprecated in the second edition of IGR 47, and over time it is expected that interface software will migrate to the new structures. The **common_datum** has been replaced with **datum_reference_compartment** where the base is a **common_datum_list** because the **common_datum** was limited to only two **datum**, whereas the current edition of ISO 5459 requires that a common datum may be composed of more than two datum. The **datum_reference** has been replaced with a **datum_system** together with **datum_reference_compartment** and, as needed, instances of **datum_reference_element**. In the first edition of IGR 47 the datum system was not explicitly modeled; consequently there was no mechanism to associate a coordinate system with that implicit datum system. The **referenced_modified_datum** has been replaced with **datum_reference_compartment** or **datum_reference_element** because the **referenced_modified_datum** is a subtype of **datum** and the modifiers are now located on **general_datum_reference**. The **dimension_related_tolerance_zone_element** ENTITY type can only specify a **dimensional_location**. With the introduction of **dimensional_size** and **dimensional_location** into the select **geometric_tolerance_target**, **geometric_tolerance** can directly specify **dimensional_size** and **dimensional_location**, providing a replacement for **dimension_related_tolerance_zone_element**. The **modified_geometric_tolerance** only allowed for one modifier, a limit_condition, which did not meet the new requirements for extensibility; consequently **modified_geometric_tolerance** was replaced with **geometric_tolerance_with_modifiers**, which does support extensibility.

10. ISO 10303 resource declarations discussed

The resource EXPRESS ENTITY and TYPE declarations provided in this document are those published in 2014.[4] The following resources are those used by the sample PMI schema illustrated in this document.[5] Each declaration is provided with a reference to the source document.

```
ENTITY advanced_face -- defined in ISO 10303-511:2001
 SUBTYPE OF ( face_surface );
[local rules omitted for brevity]
END_ENTITY;

ENTITY angularity_tolerance -- defined in ISO 10303-47:2014
  SUBTYPE OF (geometric_tolerance_with_datum_reference);
END_ENTITY;
```

[4]Available at https://standards.iso.org/iso/10303/smrl/v6/tech/smrlv6.zip

[5]The SUBTYPE_CONSTRAINT **sads_shape_aspect_subtypes subtype constraint** is included for completeness.

```
ENTITY between_shape_aspect -- defined in ISO 10303-47:2014
  SUBTYPE OF (continuous_shape_aspect);
END_ENTITY;

ENTITY cartesian_point -- defined in ISO 10303-42:2014
  SUPERTYPE OF (ONEOF (cylindrical_point,
                       polar_point,
                       spherical_point))
  SUBTYPE OF (point);
  coordinates : LIST[1:3] OF length_measure;
END_ENTITY;

ENTITY circular_runout_tolerance -- defined in ISO 10303-47:2014
  SUBTYPE OF (geometric_tolerance_with_datum_reference);
END_ENTITY;

ENTITY coaxiality_tolerance -- defined in ISO 10303-47:2014
  SUBTYPE OF (geometric_tolerance_with_datum_reference);
END_ENTITY;

ENTITY common_datum -- defined in ISO 10303-47:2014
  SUBTYPE OF (composite_shape_aspect, datum);
WHERE
  WR1: SIZEOF
          (SELF\composite_shape_aspect.component_relationships) = 2;
  WR2: SIZEOF (QUERY
        ( sar <* SELF\composite_shape_aspect.component_relationships|
          NOT (('SHAPE_ASPECT_DEFINITION_SCHEMA.DATUM' IN
          TYPEOF (sar.related_shape_aspect)) AND
  NOT ('SHAPE_ASPECT_DEFINITION_SCHEMA.COMMON_DATUM' IN
          TYPEOF (sar.related_shape_aspect))) )) = 0;
END_ENTITY;

ENTITY component_path_shape_aspect -- defined in ISO 10303-41:2014
    SUBTYPE OF (shape_aspect);
    location : multi_or_next_assembly_usage_occurrence;
    component_shape_aspect : internal_or_reflected_shape_aspect;
  UNIQUE
    UR1 : location, component_shape_aspect;
  END_ENTITY;
```

```
ENTITY composite_shape_aspect -- defined in ISO 10303-47:2014
  SUPERTYPE OF (ONEOF (continuous_shape_aspect,
                      common_datum,
                      composite_group_shape_aspect))
  SUBTYPE OF (shape_aspect);
INVERSE
  component_relationships : SET[2:?] OF
            shape_aspect_relationship FOR relating_shape_aspect;
END_ENTITY;

ENTITY concentricity_tolerance -- defined in ISO 10303-47:2014
  SUBTYPE OF (geometric_tolerance_with_datum_reference);
END_ENTITY;

ENTITY continuous_shape_aspect -- defined in ISO 10303-47:2014
  SUPERTYPE OF ( ONEOF (between_shape_aspect,
                       all_around_shape_aspect) )
  SUBTYPE OF (composite_shape_aspect);
END_ENTITY;

ENTITY cylindricity_tolerance -- defined in ISO 10303-47:2014
  SUBTYPE OF (geometric_tolerance);
WHERE
  WR1 : NOT ('AIC_GEOMETRIC_TOLERANCES.' +
             'GEOMETRIC_TOLERANCE_WITH_DATUM_REFERENCE' IN
              TYPEOF (SELF));
END_ENTITY;

ENTITY datum -- defined in ISO 10303-47:2014
  SUBTYPE OF (shape_aspect);
  identification : identifier;
INVERSE
  established_by_relationships :
  SET[1:?] OF shape_aspect_relationship FOR related_shape_aspect;
UNIQUE
  UR1: identification,SELF\shape_aspect.of_shape;
WHERE
  WR1: ('SHAPE_ASPECT_DEFINITION_SCHEMA.COMMON_DATUM' IN TYPEOF(SELF))
   XOR ((SIZEOF(QUERY(x <* SELF\datum.established_by_relationships |
         SIZEOF(['SHAPE_ASPECT_DEFINITION_SCHEMA.DATUM_FEATURE',
                'SHAPE_ASPECT_DEFINITION_SCHEMA.DATUM_TARGET'] *
           TYPEOF(x\shape_aspect_relationship.relating_shape_aspect))
```

```
           = 1))
           >= 1));
  WR2: SIZEOF(QUERY(x <* SELF\datum.established_by_relationships |
          ('SHAPE_ASPECT_DEFINITION_SCHEMA.DATUM_FEATURE' IN
          TYPEOF(x\shape_aspect_relationship.relating_shape_aspect))))
          <= 1;
  WR3: SELF\shape_aspect.product_definitional = FALSE;
  WR4: SELF\shape_aspect.name = '';
END_ENTITY;

ENTITY datum_reference; -- defined in ISO 10303-47:2014
  precedence : INTEGER;
  referenced_datum : datum;
WHERE
  WR1: precedence > 0;
END_ENTITY;

ENTITY datum_reference_compartment -- defined in ISO 10303-47:2014
  SUBTYPE OF (general_datum_reference);
INVERSE
  owner : datum_system FOR constituents;
END_ENTITY;

ENTITY datum_reference_element -- defined in ISO 10303-47:2014
  SUBTYPE OF (general_datum_reference);
DERIVE
  owner : general_datum_reference :=
               sts_get_general_datum_reference(SELF);
WHERE
  WR1: SELF <> owner;
  WR2: EXISTS(owner);
  WR3: SELF\shape_aspect.of_shape = owner\shape_aspect.of_shape;
END_ENTITY;

ENTITY datum_system -- defined in ISO 10303-47:2014
  SUBTYPE OF (shape_aspect);
  constituents : LIST[1:3] OF UNIQUE datum_reference_compartment;
UNIQUE
  UR1: SELF\shape_aspect.of_shape,SELF\shape_aspect.name;
WHERE
  WR1: SELF\shape_aspect.product_definitional = FALSE;
END_ENTITY;
```

```
ENTITY dimension_related_tolerance_zone_element;
-- defined in ISO 10303-47:2014
  related_dimension : dimensional_location;
  related_element : tolerance_zone_definition;
END_ENTITY;
[this is part of the issue for removing the relation]

ENTITY dimensional_location -- defined in ISO 10303-47:2014
  SUPERTYPE OF (ONEOF (angular_location,
                      dimensional_location_with_path))
  SUBTYPE OF (shape_aspect_relationship);
WHERE
  WR1: SELF\shape_aspect_relationship.relating_shape_aspect
       :<>:
       SELF\shape_aspect_relationship.related_shape_aspect;
  WR2: SELF\shape_aspect_relationship.relating_shape_aspect.of_shape
       :=:
       SELF\shape_aspect_relationship.related_shape_aspect.of_shape;
END_ENTITY;

ENTITY dimensional_size -- defined in ISO 10303-47:2014
  SUPERTYPE OF (ONEOF (angular_size,
                      dimensional_size_with_path));
  applies_to : shape_aspect;
  name : label;
 DERIVE
  id : identifier := get_id_value(SELF);
UNIQUE
  UR1: id, applies_to;
WHERE
  WR1: applies_to.product_definitional = TRUE;
  WR2: SIZEOF(USEDIN(SELF, 'BASIC_ATTRIBUTE_SCHEMA.' +
              'ID_ATTRIBUTE.IDENTIFIED_ITEM')) <= 1;
END_ENTITY;

ENTITY flatness_tolerance -- defined in ISO 10303-47:2014
  SUBTYPE OF (geometric_tolerance);
WHERE
  WR1 : NOT ('AIC_GEOMETRIC_TOLERANCES.' +
        'GEOMETRIC_TOLERANCE_WITH_DATUM_REFERENCE' IN
             TYPEOF(SELF));
```

```
END_ENTITY;

ENTITY general_datum_reference -- defined in ISO 10303-47:2014
  ABSTRACT SUPERTYPE OF (ONEOF (datum_reference_compartment,
                                datum_reference_element))
  SUBTYPE OF (shape_aspect);
  base : datum_or_common_datum;
  modifiers : OPTIONAL SET[1:?] OF datum_reference_modifier;
WHERE
  WR1: SELF\shape_aspect.name = '';
  WR2: NOT EXISTS(SELF\shape_aspect.description);
  WR3: NOT EXISTS(SELF\shape_aspect.id);
  WR4: SELF\shape_aspect.product_definitional = FALSE;
  WR5: NOT('SHAPE_ASPECT_DEFINITION_SCHEMA.DATUM' IN TYPEOF(base))
       OR
  (SELF\shape_aspect.of_shape = base\shape_aspect.of_shape);
  WR6: NOT('SHAPE_ASPECT_DEFINITION_SCHEMA.COMMON_DATUM_LIST' IN
        TYPEOF(base)) OR
        (SELF\shape_aspect.of_shape = base[1]\shape_aspect.of_shape);
END_ENTITY;

ENTITY geometric_item_specific_usage
  -- defined in ISO/TS 10303-1032:2014-02
  SUBTYPE OF(item_identified_representation_usage);
    SELF\item_identified_representation_usage.definition          :
          geometric_item_specific_usage_select;
    SELF\item_identified_representation_usage.used_representation :
          shape_model;
    SELF\item_identified_representation_usage.identified_item     :
          geometric_model_item;
UNIQUE
  UR1: definition;
END_ENTITY;

ENTITY geometric_tolerance -- defined in ISO 10303-47:2014
  ABSTRACT SUPERTYPE OF (geometric_tolerance_with_datum_reference
         ANDOR
         geometric_tolerance_with_defined_unit
         ANDOR ONEOF
         (geometric_tolerance_with_modifiers,
             modified_geometric_tolerance)
         ANDOR
```

```
        unequally_disposed_geometric_tolerance
        ANDOR ONEOF (cylindricity_tolerance,
         flatness_tolerance,
         line_profile_tolerance,
         position_tolerance,
         roundness_tolerance,
         straightness_tolerance,
         surface_profile_tolerance));
  name : label;
  description : OPTIONAL text;
  magnitude : OPTIONAL length_measure_with_unit;
  toleranced_shape_aspect : geometric_tolerance_target;
DERIVE
  controlling_shape : product_definition_shape :=
  sts_get_product_definition_shape(toleranced_shape_aspect);
    id : identifier := get_id_value(SELF);
UNIQUE
  UR1: id, controlling_shape;
WHERE
  WR1: magnitude\measure_with_unit.value_component >= 0.0;
  WR2: EXISTS(controlling_shape);
  WR3: NOT
       ('PRODUCT_PROPERTY_DEFINITION_SCHEMA.SHAPE_ASPECT_RELATIONSHIP'
       IN TYPEOF(toleranced_shape_aspect))
       OR
       (toleranced_shape_aspect\shape_aspect_relationship.
           relating_shape_aspect.of_shape :=:
      toleranced_shape_aspect\shape_aspect_relationship.
           related_shape_aspect.of_shape);
  WR4: SIZEOF(USEDIN(SELF, 'BASIC_ATTRIBUTE_SCHEMA.' +
         'ID_ATTRIBUTE.IDENTIFIED_ITEM')) <= 1;
END_ENTITY;

ENTITY geometric_tolerance_relationship; -- defined in ISO 10303-47:2014
  name : label;
  description : text;
  relating_geometric_tolerance : geometric_tolerance;
  related_geometric_tolerance : geometric_tolerance;
END_ENTITY;

ENTITY geometric_tolerance_with_datum_reference -- defined in ISO 10303-47:2014
  SUPERTYPE OF (ONEOF (angularity_tolerance,
```

```
                       circular_runout_tolerance,
                       coaxiality_tolerance,
                       concentricity_tolerance,
                       parallelism_tolerance,
                       perpendicularity_tolerance,
                       symmetry_tolerance,
                       total_runout_tolerance))
  SUBTYPE OF (geometric_tolerance);
  datum_system : SET[1:?] OF datum_system_or_reference;
WHERE
  WR1: (SIZEOF(QUERY(ds <* datum_system | 'SHAPE_TOLERANCE_SCHEMA.' +
        'DATUM_SYSTEM' in TYPEOF(ds)))=0) OR (SIZEOF(datum_system)=1);
END_ENTITY;

ENTITY geometric_tolerance_with_defined_unit -- defined in ISO 10303-47:2014
  SUBTYPE OF (geometric_tolerance);
  unit_size : length_measure_with_unit;
WHERE
  WR1: ('NUMBER' IN
        TYPEOF(unit_size\measure_with_unit.value_component))
        AND
        (unit_size\measure_with_unit.value_component > 0.0);
END_ENTITY;

ENTITY geometric_tolerance_with_modifiers -- defined in ISO 10303-47:2014
  SUBTYPE OF (geometric_tolerance);
  modifiers : SET[1:?] OF geometric_tolerance_modifier;
END_ENTITY;

ENTITY id_attribute; -- defined in ISO 10303-41:2014
  attribute_value : identifier;
  identified_item : id_attribute_select;
END_ENTITY;

ENTITY item_identified_representation_usage; -- defined in ISO 10303-41:2014
  name : label;
  description : OPTIONAL text;
  definition : item_identified_representation_usage_definition;
  used_representation : representation;
  identified_item : item_identified_representation_usage_select;
 WHERE
 WR1: SELF.used_representation IN
```

```
              using_representations(SELF.identified_item);
END_ENTITY;

ENTITY line_profile_tolerance -- defined in ISO 10303-47:2014
  SUBTYPE OF (geometric_tolerance);
END_ENTITY;

ENTITY modified_geometric_tolerance -- defined in ISO 10303-47:2014
  SUBTYPE OF (geometric_tolerance);
  modifier : limit_condition;
END_ENTITY;

ENTITY multi_level_reference_designator -- defined in ISO 10303-44:2014
  SUBTYPE OF (assembly_component_usage);
  location : LIST[1:?] OF UNIQUE next_assembly_usage_occurrence;
DERIVE
  SELF\product_definition_relationship.relating_product_definition
     RENAMED
    root : product_definition :=
    location[1]\product_definition_relationship.
                   relating_product_definition;
  SELF\product_definition_relationship.
                   related_product_definition
     RENAMED
     leaf : product_definition_or_reference :=
     location[HIINDEX(location)]\product_definition_relationship.
     related_product_definition;
UNIQUE
  UR1: location;
WHERE
  WR1: unambiguously_specified_multi_level_reference_designator
          (location);
  WR2: SIZEOF(QUERY(cp <* location | NOT (
         EXISTS(cp\assembly_component_usage.reference_designator))))
         = 0;
END_ENTITY;

ENTITY parallelism_tolerance -- defined in ISO 10303-47:2014
  SUBTYPE OF (geometric_tolerance_with_datum_reference);
END_ENTITY;

ENTITY perpendicularity_tolerance -- defined in ISO 10303-47:2014
```

```
  SUBTYPE OF (geometric_tolerance_with_datum_reference);
END_ENTITY;

ENTITY polyline -- defined in ISO 10303-42:2014
  SUBTYPE OF (bounded_curve);
  points : LIST[2:?] OF cartesian_point;
END_ENTITY;

ENTITY position_tolerance -- defined in ISO 10303-47:2014
  SUBTYPE OF (geometric_tolerance);
END_ENTITY;

ENTITY product_definition; -- defined in ISO 10303-41:2014
  id : identifier;
  description : OPTIONAL text;
  formation : product_definition_formation;
  frame_of_reference : product_definition_context;
DERIVE
  name : label := get_name_value(SELF);
WHERE
  WR1: SIZEOF(USEDIN(SELF, 'BASIC_ATTRIBUTE_SCHEMA.' +
  'NAME_ATTRIBUTE.NAMED_ITEM')) <= 1;
END_ENTITY;

ENTITY product_definition_shape -- defined in ISO 10303-41:2014
  SUBTYPE OF (property_definition);
UNIQUE
  UR1: SELF\property_definition.definition;
WHERE
  WR1: SIZEOF(['PRODUCT_PROPERTY_DEFINITION_SCHEMA.
  CHARACTERIZED_PRODUCT_DEFINITION',
  'PRODUCT_PROPERTY_DEFINITION_SCHEMA.CHARACTERIZED_OBJECT'] *
  TYPEOF(SELF\property_definition.definition)) > 0;
END_ENTITY;

ENTITY qualified_representation_item -- defined in ISO 10303-45:2014
  SUBTYPE OF (representation_item);
  qualifiers    : SET [1:?] OF value_qualifier;
WHERE
  WR1: SIZEOF(QUERY(temp <* qualifiers |
        ('QUALIFIED_MEASURE_SCHEMA.PRECISION_QUALIFIER'
         IN TYPEOF(temp)) OR
```

```
        ('QUALIFIED_MEASURE_SCHEMA.MATHS_VALUE_PRECISION_QUALIFIER'
         IN TYPEOF(temp)))) < 2;
END_ENTITY;

ENTITY referenced_modified_datum -- defined in ISO 10303-47:2014
  SUBTYPE OF (datum_reference);
  modifier : limit_condition;
END_ENTITY;

ENTITY representation; -- defined in ISO 10303-43:2014
    name             : label;
    items            : SET[1:?] OF representation_item;
    context_of_items : representation_context;
DERIVE
    id               : identifier := get_id_value (SELF);
    description      : text := get_description_value (SELF);
WHERE
  WR1: SIZEOF (USEDIN (SELF, 'BASIC_ATTRIBUTE_SCHEMA.' +
 'ID_ATTRIBUTE.IDENTIFIED_ITEM'))
         <= 1;
  WR2: SIZEOF (USEDIN (SELF, 'BASIC_ATTRIBUTE_SCHEMA.' +
                            'DESCRIPTION_ATTRIBUTE.DESCRIBED_ITEM'))
         <= 1;
END_ENTITY;

ENTITY roundness_tolerance -- defined in ISO 10303-47:2014
  SUBTYPE OF (geometric_tolerance);
WHERE
  WR1 : NOT ('AIC_GEOMETRIC_TOLERANCES.' +
        'GEOMETRIC_TOLERANCE_WITH_DATUM_REFERENCE' IN TYPEOF (SELF));
END_ENTITY ;

ENTITY shape_aspect -- defined in ISO 10303-41:2014
  SUPERTYPE OF (ONEOF (shape_aspect_occurrence,
                       component_path_shape_aspect)
                ANDOR constituent_shape_aspect);
  name : label;
  description : OPTIONAL text;
  of_shape : product_definition_shape;
  product_definitional : LOGICAL;
DERIVE
  id : identifier := get_id_value(SELF);
```

```
UNIQUE
  UR1: id, of_shape;
WHERE
  WR1: SIZEOF(USEDIN(SELF, 'BASIC_ATTRIBUTE_SCHEMA.' +
  'ID_ATTRIBUTE.IDENTIFIED_ITEM')) <= 1;
END_ENTITY;

ENTITY shape_aspect_relationship; -- defined in ISO 10303-41:2014
  name : label;
  description : OPTIONAL text;
  relating_shape_aspect : shape_aspect;
  related_shape_aspect : shape_aspect;
DERIVE
  id : identifier := get_id_value(SELF);
WHERE
  WR1: SIZEOF(USEDIN(SELF, 'BASIC_ATTRIBUTE_SCHEMA.' +
  'ID_ATTRIBUTE.IDENTIFIED_ITEM')) <= 1;
END_ENTITY;

ENTITY shape_dimension_representation -- defined in ISO 10303-47:2014
  SUBTYPE OF (shape_representation);
  SELF\representation.items : SET[1:?] OF
                        shape_dimension_representation_item;
END_ENTITY;

ENTITY straightness_tolerance -- defined in ISO 10303-47:2014
  SUBTYPE OF (geometric_tolerance);
WHERE
  WR1 : NOT ('AIC_GEOMETRIC_TOLERANCES.' +
       'GEOMETRIC_TOLERANCE_WITH_DATUM_REFERENCE'
         IN TYPEOF (SELF));
END_ENTITY;

ENTITY surface_profile_tolerance -- defined in ISO 10303-47:2014
  SUBTYPE OF (geometric_tolerance);
END_ENTITY;

ENTITY symmetry_tolerance -- defined in ISO 10303-47:2014
  SUBTYPE OF (geometric_tolerance_with_datum_reference);
END_ENTITY;

ENTITY total_runout_tolerance -- defined in ISO 10303-47:2014
```

```
  SUBTYPE OF (geometric_tolerance_with_datum_reference);
END_ENTITY;

ENTITY unequally_disposed_geometric_tolerance -- defined in ISO 10303-47:2014
  SUBTYPE OF (geometric_tolerance);
  displacement : length_measure_with_unit;
WHERE
 WR1: ('NUMBER' IN
 TYPEOF(SELF\geometric_tolerance_with_defined_unit.
        unit_size\measure_with_unit.value_component))
        AND
       (SELF\geometric_tolerance_with_defined_unit.
       unit_size\measure_with_unit.value_component > 0.0);
END_ENTITY;

TYPE common_datum_list = -- defined in ISO 10303-47:2014
    LIST[2:?] OF datum_reference_element;
WHERE
  WR1: SIZEOF( QUERY(dre <* SELF |
  dre\shape_aspect.of_shape <> SELF[1]\shape_aspect.of_shape)) = 0;
END_TYPE;

TYPE datum_or_common_datum = -- defined in ISO 10303-47:2014
SELECT (
datum,
common_datum_list);
END_TYPE;

TYPE datum_reference_modifier_type = -- defined in ISO 10303-47:2014
EXTENSIBLE ENUMERATION OF
 (projected,
   distance,
   spherical,
   circular_or_cylindrical);
END_TYPE;

TYPE geometric_tolerance_modifier = -- defined in ISO 10303-47:2014
EXTENSIBLE ENUMERATION OF
(separate_requirement,
   each_radial_element,
   tangent_plane,
   statistical_tolerance,
```

```
   not_convex,
   line_element,
   pitch_diameter,
   major_diameter,
   minor_diameter,
   common_zone,
   free_state,
   any_cross_section,
   reciprocity_requirement,
   least_material_requirement,
   maximum_material_requirement);
END_TYPE;

TYPE geometric_tolerance_target = -- defined in ISO 10303-47:2014
SELECT
   (dimensional_location,
    dimensional_size,
    product_definition_shape,
    shape_aspect);
END_TYPE;

TYPE simple_datum_reference_modifier = -- defined in ISO 10303-47:2014
EXTENSIBLE ENUMERATION OF
   (free_state,
    basic,
    translation,
    least_material_requirement,
    maximum_material_requirement,
    point,
    line,
    plane,
    orientation,
    any_cross_section,
    any_longitudinal_section,
    contacting_feature,
    distance_variable,
    degree_of_freedom_constraint_x,
    degree_of_freedom_constraint_y,
    degree_of_freedom_constraint_z,
    degree_of_freedom_constraint_u,
    degree_of_freedom_constraint_v,
    degree_of_freedom_constraint_w,
```

```
    minor_diameter,
    major_diameter,
    pitch_diameter);
END_TYPE;

SUBTYPE_CONSTRAINT sads_shape_aspect_subtypes -- defined in ISO 10303-47:2014
  FOR shape_aspect;
  ONEOF (contacting_feature,
         datum,
         datum_feature,
         datum_target,
         datum_system,
         general_datum_reference);
END_SUBTYPE_CONSTRAINT;
```

11. EXPRESS root schema for PMI

In order to provide implementation schemata to the public, an AP development project must process a root schema with the short-to-long (shtolo) converter.

Example 9. An EXPRESS root schema based on Fig. 1 and Fig. 2 is this collection of declarations.[6]

```
SCHEMA Pmi_root_schema_mim;
USE FROM Dimension_tolerance_mim;
USE FROM Geometric_tolerance_mim;
USE FROM Product_and_manufacturing_annotation_presentation_mim;
USE FROM
Model_based_3d_geometrical_dimensioning_and_tolerancing_representation_mim;
USE FROM Product_and_manufacturing_information_with_nominal_3d_models_mim;
USE FROM Product_and_manufacturing_information_view_context_mim;
END_SCHEMA;
```

12. EXPRESS implementation schema for PMI

The short-to-long algorithm was executed with the declarations defined in Example 9 as input, resulting in a schema suitable for implementation in that there are no interfaces to external schemata. The schema is compliant with ISO 10303-11 edition 1, TC-2 for consistency with schemata delivered by ISO/TC 184/SC 4 for ISO 10303 application protocols.

[6] Only the first level of schema interfaces is declared in the root schema. The shtolo algorithm traverses the schema tree resolving all required dependencies.

The EXPRESS declarations included in Section 10 are compared with the results where there are significant differences. Schema name changes are ignored. The following are noted:

- **cartesian_point** does not include any subtypes in the implementation schema because they are not in scope for a cartesian coordinate system.
- **component_path_shape_aspect** is pruned because the relevant document is not referenced in the figures.[7]

13. An exchange scenario

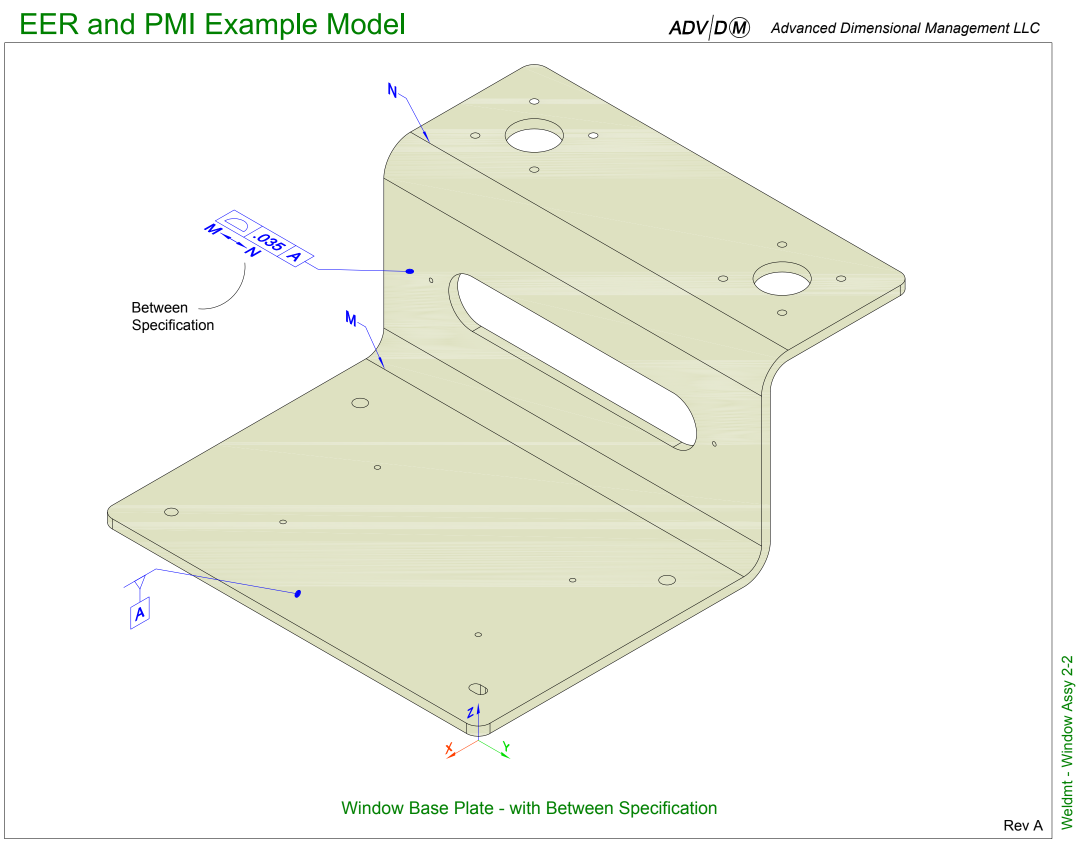

Fig. 12. This is an illustration of the linked **shape_aspect** and geometric_representation_items for the "between specification" example.

This exchange scenario involves CAD-CAD for a "between specification." Figure 12 is an illustration from a CAD system of the example. Only the instance data for the "between

[7] In an actual AP development this integration issue would be addressed during development. It is retained in this document for illustrative purposes.

specification" will be considered in this example. The datum feature and profile tolerance are excluded.

According to ASME Y14.41-2012 and ISO 16792, the activities are:

- interact with an authoring system to create a three-dimensional solid model;
- interact with that authoring system to create a model feature F1;
- interact with that authoring system to create an instance of **between_shape_aspect** which requires indicating to the CAD system the start and end of the relevant subset of the feature F1 in the geometric model coordinate system and requires interacting with the CAD system to determine the path to be traversed, resulting in one or more geometric elements to represent the path (in this example, the path is represented by a three-dimensional **polyline**);
- interact with that authoring system to create a tolerance frame and the attached $N \longleftrightarrow M$ symbol; and
- interact with the authoring system to relate that tolerance frame to that model feature by associating a leader line to the model feature between the start and end of the feature.

The pre-processor would generate **representation** instances conformant to ISO 10303-21 as a result of the first three activities listed above. Fig. 13 is the graphical output of a post-processor that is used to illustrate instance data conformant to ISO 10303-21.

The instance roles in the **representation** data set in Fig. 13 are:

- #12 is the model feature being referenced.
- #1 is the **between_shape_aspect**.
- #3 is "N" (and product_definitional is TRUE since it is on the surface).
- #5 is "M" (and product_definitional is TRUE since it is on the surface).
- #2 and #4 compose #1 with #3 and #5, respectively.
- #9 is the actual point for "N".
- #8 is the actual point for "M".
- #13 is the **polyline** that is the path between "N" and "M".
- #6, #7, and #14 bind geometric elements to persistently identifiable **shape_aspect** instances.

In this example, the actual geometric model details of instances #12 and #13 are not provided. Many other options are possible, e.g., #8 and #9 could be point_on_surface ENTITY types and the basis surface would then be provided, typically some form of face geometry.

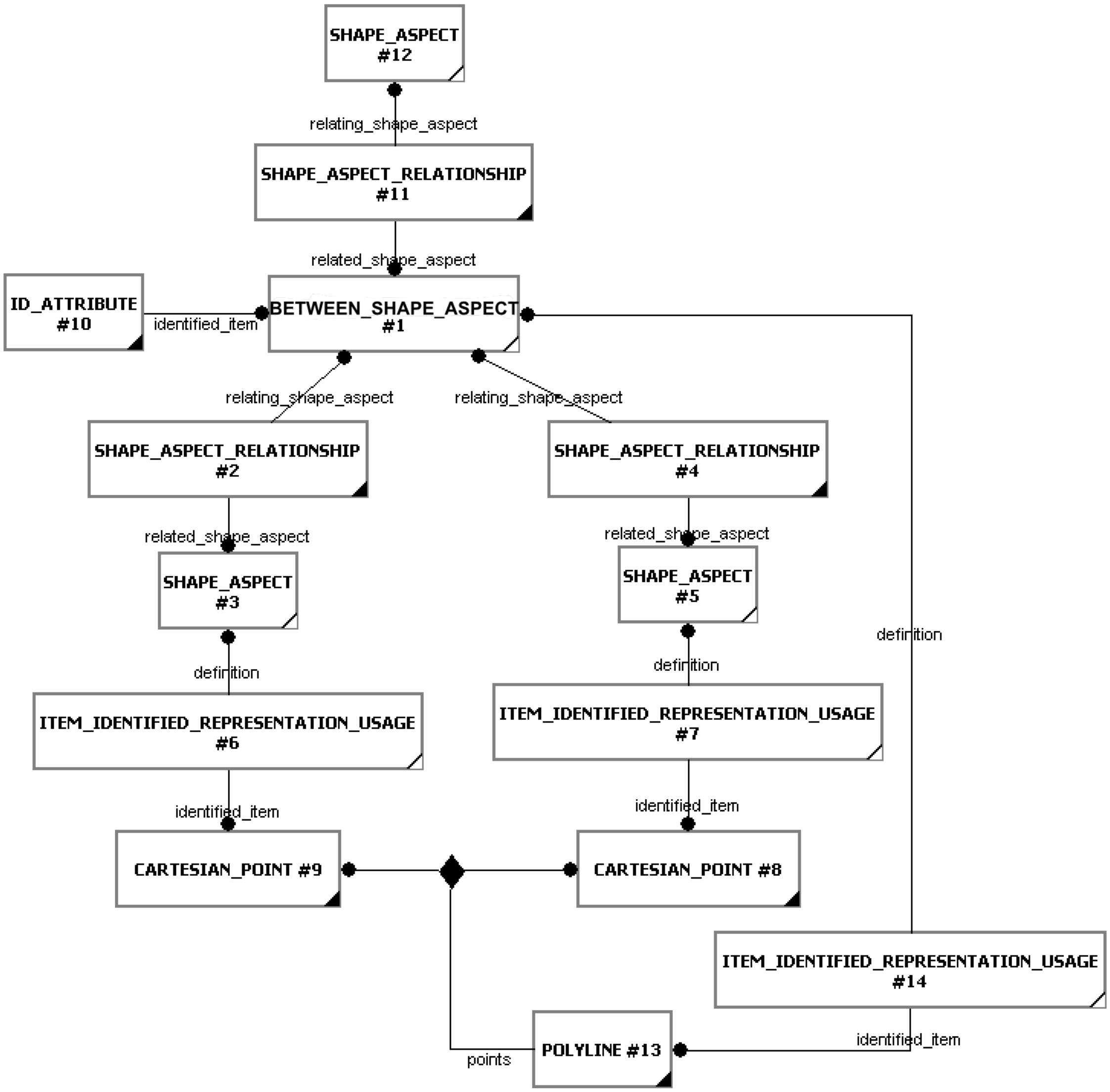

Fig. 13. This is the instantiated **between_shape_aspect** illustration.

Other structural options are possible in the geometric model, but the methodology of binding geometric elements to **shape_aspect**s using **item_identified_representation_usage** (or the subtype **geometric_item_specific_usage**) should be followed to permit persistent identification and to support the unambiguous composition of the model feature itself.

The receiving STEP interface software would extract the associated geometric data from the file into an internal CAD model, store the **between_shape_aspect** in an internal GPS model with persistent associativity to the internal CAD model, and transform the **between_shape_aspect** with the CAD system internal symbol generator into a presentation of the $N \longleftrightarrow M$ in the receiving system attached to the tolerance frame. The presentation arrangement would be controlled by ISO 16792 and ASME Y14.41-2012 but would not be an exact match of the presentation arrangement in the source system.

14. Concluding remarks

This document described the updates to the STEP PMI Information Model accomplished with the publication of AP 242. The areas of management data, presentation, **representation**, persistent identification, model feature, requirements on design model geometric properties, dimensional tolerances, datum system, geometric tolerances, **continuous_shape_aspect**, an exchange scenario, and deprecated entities in IGR 47 were addressed.

Areas to consider for follow-on projects for subsequent editions of AP 242 include additional GPS domain-specific standards related to threads, surface texture specifications, edge condition specifications, welding specifications, machining feature groups, and statistical process control specifications. Extending ISO 10303-59 [50] for new **shape_aspect**s and for revolute shapes could be considered. Planned_characteristics / Requirement_assignment to PMI data, i.e., could be extended to include **dimensional_size**, **dimensional_location**, and **geometric_tolerance** as members of assigned_requirement.item. Model critical feature characteristics (e.g., non-GPS PMI) as commonly communicated via association to numbered "balloons" on drawings is yet another area to consider.

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Appendix A. Terms, Definitions and Acronyms

Terms and Definitions

advanced_face

An advanced_face is a face defined on a surface. This face is a finite portion of the surface that has its boundaries fully defined using topological entities with associated geometric curves. The surface geometry is required to be an elementary surface, a swept surface, or a B-spline surface. [ISO 10303-511:1999]. 17

angularity_tolerance

An angularity_tolerance is a type of **geometric_tolerance_with_datum_reference**. Unless otherwise specified, the rules governing coaxiality tolerance defined in ISO 1101 or ASME Y14.5-2009 shall apply. [ISO 10303-47:2014]. 22

between_shape_aspect

A between_shape_aspect is a type of **continuous_shape_aspect** where some of the composing members are marked as forming elements of the borders of the continuous region. [ISO 10303-47:2014]. iii, 40, 41

cartesian_point

A cartesian_point is a type of point[8] defined by its coordinates in a rectangular Cartesian coordinate system, or in a parameter space. The entity is defined in a one, two, or three-dimensional space as determined by the number of coordinates in the list.[9] [10] [11] [ISO 10303-42:2014]. 39

circular_runout_tolerance

A circular_runout_tolerance is a type of **geometric_tolerance_with_datum_reference**. Unless otherwise specified, the rules governing circular run-out tolerance defined in ISO 1101 or ASME Y14.5-2009 shall apply. [ISO 10303-47:2014, definition modified]. 22

coaxiality_tolerance

A coaxiality_tolerance is a type of **geometric_tolerance_with_datum_reference**. Unless otherwise specified, the rules governing coaxiality tolerance defined in ISO 1101 or ASME Y14.5-2009 shall apply. [ISO 10303-47:2014]. 22

[8] The entity point is not discussed in this document.

[9] For PMI only two or three-dimensional points are used

[10] Depending upon the geometric_representation_context in which the point is used, the names of the coordinates may be (x,y,z), (u,v), or any other chosen values.

[11] The entity geometric_representation_context is not discussed in this document.

common_datum

A common_datum is a type of **composite_shape_aspect** and of **datum** that is established by two other **shape_aspect**s of type **datum**.[12] [ISO 10303-47:2014]. 24, 48

common_datum_list

A common_datum_list is a list of **datum_reference_element**s. Unless otherwise specified, a common_datum_list shall be used in accordance with common datum as defined in ISO 5459. [ISO 10303-47:2014]. 19, 24, 48

component_path_shape_aspect

A component_path_shape_aspect is a type of **shape_aspect** that identifies a portion of a shape of an assembly by referencing a **shape_aspect** that represents a portion of the shape of an occurrence of a part within this assembly. The referenced part and its **shape_aspect** might be defined locally or externally. [ISO 10303-41:2014]. 22, 39

composite_shape_aspect

A composite_shape_aspect is a type of **shape_aspect** that associates aspects of the product shape for a specific purpose. A composite_shape_aspect may be either an all_around_shape_aspect,[13] a **continuous_shape_aspect**, a **common_datum**, or a composite_group_shape_aspect.[14] [ISO 10303-47:2014]. 48, 49

concentricity_tolerance

A concentricity_tolerance is a type of **geometric_tolerance_with_datum_reference**. Unless otherwise specified, the rules governing concentricity tolerance defined in ISO 1101 or ASME Y14.5-2009 shall apply. [ISO 10303-47:2014]. 22

continuous_shape_aspect

A continuous_shape_aspect is a type of **composite_shape_aspect** wherein the geometric elements associated with the underlying **shape_aspect** members are touching and thus establish a continuous region. [ISO 10303-47:2014]. 18, 42, 47, 48

cylindricity_tolerance

A cylindricity_tolerance is a type of **geometric_tolerance**. Unless otherwise specified, the rules governing cylindricity tolerance defined in ISO 1101 or ASME Y14.5-2009 shall apply. [ISO 10303-47:2014]. 22

[12]The entity **common_datum** is deprecated. For new implementations it is recommended that **datum_reference_compartment** with base being a **common_datum_list** be used.

[13]The all_around_shape_aspect is not discussed in this document.

[14]The composite_group_shape_aspect is not discussed in this document.

datum

A datum is a type of **shape_aspect** used to establish an origin for theoretically exact dimensions and geometrical tolerances. This **shape_aspect** may, but need not, coincide with the boundary defining the product. A datum is established by associating to datum feature, a set of datum targets, a group of features, or one or more contacting features.[15] [ISO 10303-47:2014]. 19, 24, 48–51, 57, 58

datum_reference

A datum_reference is the specification of the use of a datum.[16] [ISO 10303-47:2014]. 22, 24, 54

datum_reference_compartment

A datum_reference_compartment is a type of **general_datum_reference** that represents the compartment of the primary, secondary, or tertiary datum in a feature control frame. [ISO 10303-47:2014]. 18, 19, 24, 48–50, 54

datum_reference_element

A datum_reference_element is a type of **general_datum_reference** that represents a single **datum** reference of a common datum with a **datum_reference_compartment**. Unless otherwise specified, the rules governing common datum defined in ISO 5459 or ASME Y14.5-2009 shall apply. [ISO 10303-47:2014]. 19, 24, 48–50, 54

datum_reference_modifier_type

A datum_reference_modifier type is either a datum_reference_modifier_with_value[17] or a **simple_datum_reference_modifier**. [ISO 10303-47:2014, modified]. 20

datum_system

A datum_system is a type of **shape_aspect** that represents the ordered collection of one to three datum reference compartments within a geometric tolerance frame. Unless otherwise specified, a datum_system shall be used in accordance to the ISO 5459 definitions or ASME Y14.5-2009 [11] or any later edition of that standard for single datum and for a datum system.[18] [ISO 10303-47:2014]. 2, 18, 19, 22, 24, 49, 50, 57

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[15] The use and application of a group of features to establish a datum is identified in ISO 5459. The group of features is established through the use of **shape_aspect_relationship** objects. The concept of a group of **shape_aspect** elements is defined in **composite_shape_aspect**.

[16] Starting with the 2014 edition of ISO 10303-47 (IGR 47), the entity datum_reference is deprecated. For new implementations it is recommended that **datum_system** together with **datum_reference_compartment** and as needed **datum_reference_element** be used.

[17] The entity datum_reference_modifier_with_value is not discussed in this document.

[18] A datum_system can be associated with a model coordinate system and can be shared by several **geometric_tolerance**s.

dimension_related_tolerance_zone_element

A dimension_related_tolerance_zone_element is an association of a tolerance zone definition with a locating dimension.[19] [ISO 10303-47:2014]. 24

dimensional_location

A dimensional_location is a type of **shape_aspect_relationship**. A dimensional_location specifies that a spatial constraint exists between two **shape_aspect** elements that are represented as a non-directed measure applied along a measurement path. A dimensional_location may be either an angular_location[20] or a dimensional_location_with_path[21].[22] [ISO 10303-47:2014]. 17, 21, 22, 24, 42, 53, 57

dimensional_size

A dimensional_size is a spatial characteristic of a **shape_aspect** that is represented by a measure. This magnitude is independent of the location of the **shape_aspect** on or within the product. A dimensional_size may be either an angular_size[23] or a dimensional_size_with_path.[24] [ISO 10303-47:2014]. 17, 21, 22, 24, 42

flatness_tolerance

A flatness_tolerance is a type of **geometric_tolerance**. Unless otherwise specified, the rules governing flatness tolerance defined in ISO 1101 or ASME Y14.5-2009 shall apply. [ISO 10303-47:2014]. 22

general_datum_reference

A general_datum_reference is a type of **shape_aspect** that represents the occurrence of a **datum** within a **datum_system**. A general_datum_reference is either a **datum_reference_compartment** or a **datum_reference_element**. [ISO 10303-47:2014]. 24, 49, 57, 58

geometric_item_specific_usage

A geometric_item_specific_usage is a type of **item_identified_representation_usage** that implements the **Application reference model (ARM)** concept of Geometric_item_specific_usage. In this specialization of **item_identified_representation_usage**,

[19] As of the 2014 edition of IGR 47, this entity is deprecated and should not be used for new implementations.
[20] The entity angular_location is not discussed in this document.
[21] The entity dimensional_location_with_path is not discussed in this document.
[22] Representation of a **shape_aspect** participating in the dimensional_location relationship implies a measuring direction for the dimensional_location through the related and relating **shape_aspect**. The meaning of the direction is specified in an application protocol.
[23] The entity angular_size is not discussed in this document.
[24] The entity dimensional_size_with_path is not discussed in this document.

the identified_item is directly included in the set of items of the used_representation. [ISO 10303-1032:2014-02]. 17, 41

geometric_tolerance

A geometric_tolerance is the specification of the allowable range within which a geometrical property of a product may deviate. [ISO 10303-47:2014, modified to remove list of subtypes]. 17, 21–24, 42, 48–53, 56, 58

geometric_tolerance_modifier

A geometric_tolerance_modifier is a collection of alternative modifier names that is used by **geometric_tolerance_with_modifiers**. [ISO 10303-47:2014, modified]. 23

geometric_tolerance_relationship

A geometric_tolerance_relationship is an association between two **geometric_tolerance**s. [ISO 10303-47:2014]. 23

geometric_tolerance_target

A geometric_tolerance_target type is a selection of items that may be a target for a geometric tolerance. [ISO 10303-47:2014, modified]. 24

geometric_tolerance_with_datum_reference

A geometric_tolerance_with_datum_reference is a type of **geometric_tolerance** that references one or more **datum**s for specifying the tolerance condition of a **shape_aspect**. [ISO 10303-47:2014]. 22, 47, 48, 53, 58

geometric_tolerance_with_defined_unit

A geometric_tolerance_with_defined_unit is a type of **geometric_tolerance** specified on a per length unit basis of the **shape_aspect**.[25] [ISO 10303-47:2014]. 22

geometric_tolerance_with_modifiers

A geometric_tolerance_with_modifiers is a type of **geometric_tolerance** that indicates additional properties of the tolerance. [ISO 10303-47:2014]. 21, 22, 24, 51, 52

item_identified_representation_usage

An item_identified_representation_usage is an identification of a single or a set or a list of **representation_item**(s) within a representation as being the element(s) that describes a particular component or part of the property that is described by the

[25] The use and application of the per unit basis are described in ISO 1101.

representation. Conversely, the product data item specified by the item_identified_-representation_usage serves as the externally visible identification of the description elements.

Example 10. In an application protocol, an instance of representation describes the shape of a product. One element of the representation - a curve - represents the boundary of a **shape_aspect**, a hole, in the product. Item_identified_representation_-usage is used to state that the curve referenced by 'identified_item' is a representation item for the **shape_aspect** referenced by 'definition' and that the whole representation is referenced by 'used_representation' to indicate the structural context for the curve. Geometric_representation_context[26] plays no role in this example. [ISO 10303-41:2014, modified]. 9, 41, 50

line_profile_tolerance

A line_profile_tolerance is a type of **geometric_tolerance**. Unless otherwise specified, the rules governing profile tolerance defined in ISO 1101 or ASME Y14.5-2009 shall apply. [ISO 10303-47:2014]. 22

modified_geometric_tolerance

A modified_geometric_tolerance is a type of **geometric_tolerance** with a material limit condition that applies to the **shape_aspect** being toleranced.[27] [ISO 10303-47:2014]. 24

multi_level_reference_designator

A multi_level_reference_designator is a type of assembly_component_usage[28] that specifies the relationship between an assembly and a constituent if the assembly is not the immediate parent for the constituent and there are several hierarchical levels between the assembly and the constituent.[29] The hierarchical levels are defined by a list of next_assembly_usage_occurrences[30] that identifies a connected path in the assembly structure.[31] [ISO 10303-44:2014, modified]. 22

[26] The entity geometric_representation_context is not discussed in this document.

[27] The entity modified_geometric_tolerance is deprecated. For new implementations it is recommended that **geometric_tolerance_with_modifiers** be used.

[28] The entity assembly_component_usage is not discussed in this document.

[29] The multi_level_reference_designator is a representation of the reference designation concept in IEC 81346.

[30] The entity next_assembly_usage_occurrence is not discussed in this document.

[31] The multi_level_reference_designator is used to identify a specific instance of a component within a multi-level assembly structure for which certain properties are to be associated.

parallelism_tolerance

A parallelism_tolerance is a type of **geometric_tolerance_with_datum_reference**. Unless otherwise specified, the rules governing parallelism tolerance defined in ISO 1101 or ASME Y14.5-2009 shall apply. [ISO 10303-47:2014]. 22

perpendicularity_tolerance

A perpendicularity_tolerance is a type of **geometric_tolerance_with_datum_reference**. Unless otherwise specified, the rules governing perpendicularity tolerance defined in ISO 1101 or ASME Y14.5-2009 shall apply. [ISO 10303-47:2014]. 22

polyline

A polyline is a type of bounded_curve[32] with (n-1) linear segments, defined by a list of n points. [ISO 10303-42:2014, simplified]. 40

position_tolerance

A position_tolerance is a type of **geometric_tolerance**. Unless otherwise specified, the rules governing position tolerance defined in ISO 1101 and ISO 5458 or ASME Y14.5-2009 shall apply. The location of the tolerance zone shall be specified with instances of **dimensional_location**. [ISO 10303-47:2014]. 22

product_definition

A product_definition is a representation of an aspect of a product, or of a class of products, for an identified life cycle stage. The life cycle stage for which a product_definition exists may be further characterized by discipline, by usage, or by both. 33

Example 11. The design of the SS Titanic and the as-built description of the SS Titanic can be represented as two instances of product_definition for the product that represents the ship itself.

The product_definition entity data type may represent particular products that are the members of an identified class of products.

Example 12. Each individual lifeboat on the SS Titanic can be represented by an instance of product_definition, in which the associated product represents the class of products whose members are the lifeboats.[34]

[32] The entity bounded_curve is not discussed in this document.

[33] The product_definition entity type supports the representation of different views of a product for different purposes. Multiple views of the same product, or class of products, are represented by different instances of product_definition for the same product_definition_formation.

[34] A product_definition can identify an occurrence of a product.

The product_definition entity data type acts as an aggregator for information about the properties of products. The usage of a product_definition in another context is specified through its participation in a product_definition_relationship[35] as the related_-product_definition in which the using context is specified by the frame_of_reference of the relating_product_definition. If a product_definition is considered in multiple contexts, the product_definition_context_association[36] shall be used to specify a collection of product_definition_contexts.[37] [ISO 10303-41:2014]. 17, 22

product_definition_shape

A product_definition_shape is a type of property_definition.[38] It identifies the shape of a characterized_object[39] or of one of the types reachable as characterized_product_-definition[40].[41] [42]

Example 13. A geometric representation of shape is not needed to assert facts such as "a shape must fit within a 5 centimeter cube". [ISO 10303-41:2014]. 17, 21, 22, 57

qualified_representation_item

A qualified_representation_item is a type of **representation_item** for which qualifiers are defined to describe its reliability and/or uncertainty. [ISO 10303-45:2014]. 21

referenced_modified_datum

A referenced_modified_datum is a type of **datum_reference** where the referenced datum may vary within the specified limits of size.[43] [ISO 10303-47:2014, modified]. 24

[35] The entity product_definition_relationship is not discussed in this document.
[36] The entity product_definition_context_association is not discussed in this document.
[37] The entity product_definition_context is not discussed in this document.
[38] The entity property_definition is not discussed in this document.
[39] The entity characterized_object is not discussed in this document.
[40] The type characterized_product_definition is not discussed in this document.
[41] A product_definition_shape need not be associated with any geometric representation.
[42] Early in the design of a product there may not be a specific idea about the shape of the product but there may be certain characteristics of the shape that are to be represented. Those product shape characteristics can be attached to the product shape using this entity.
[43] The entity referenced_modified_datum is deprecated. For new implementations it is recommended that **datum_reference_compartment** or **datum_reference_element** be used.

representation

A representation is a collection of one or more **representation_item** instances that are related in a specified **representation_context**.[44]

Example 14. Two cartesian points P and Q (described by instances of **representation_item**) are related in a context A (they are elements in the same representation in context A, or are elements in different representations that share context A). It is therefore possible to calculate the distance between these points. A third cartesian point R (also described by an instance of **representation_item**) is not related to context A. It is not possible to determine the distance between R and P, or between R and Q.

A **representation_item** can be related to a **representation_context** directly, when it occurs as an element in a representation, or indirectly, when it is referenced through any number of intervening entities, each of type **representation_item** or founded_item.

A representation relates a **representation_context** to trees of **representation_item** instances each tree being rooted in one member of the set of items. A **representation_item** or founded_item[45] is one node in the tree; a relationship between one **representation_item** or founded_item and another[46] is an edge.[47] [48]

Example 15. Consider a collection of two-dimensional **representation_item** instances used to represent the shape of a machined part. It is not a complete description of the shape, but is suitable for certain applications such as computer-aided draughting.

Two instances of representation are not related solely because the same instance of **representation_item** is referenced directly or indirectly from their sets of items.

Example 16. Consider a surface that is used in the respective representations of the shape of a casting die and of the shape of the part cast in that die. The same surface is related to two distinct instances of **representation_context** (i.e., coordinate spaces): one for the die and one for the part by the two instances of representation.

[44] The relationship of **representation_item** to **representation_context** is the basis for distinguishing which **representation_item** entities are related.

[45] The entity founded_item is not discussed in this document.

[46] The entity representation_item_relationship is not discussed in this document.

[47] Instances of representation_item_relationship do not form either nodes or edges in this tree; an instance of **representation_item** is not part of the tree solely because it is associated with an element in the tree by an instance of representation_item_relationship.

[48] A representation can be incomplete in that it need not fully model the concept that is represented, although it could be adequate for a given application.

However, the two instances of representation are not related; they simply share a common **representation_item**.

Two instances of representation are not related solely because instances of **representation_item** in their sets of items are related by an instance of representation_item_-relationship. [ISO 10303-43:2011]. 17, 40, 42, 56

representation_context

A representation_context is a context in which instances of **representation_item** are related.[49] [ISO 10303-43:2011]. 55, 56

representation_item

A representation_item is an element of **representation**. A representation_item participates in one or more instances of **representation**, or contributes to the definition of another representation_item.[50] [51]

Example 17. Consider two instances of **representation**, each having the same value for context_of_items. One is a **representation** of the shape of a cube and indirectly references a line as one of its edges. The second simply references the line as one of its items. There are not two occurrences of the line and its sub-tree of referenced instances of representation_item in the **representation_context**. Rather, the use of the line in that geometric_representation_context has been asserted twice, once in each **representation**.

[ISO 10303-43:2011, simplified]. 51, 54–56

roundness_tolerance

A roundness_tolerance is a type of **geometric_tolerance**. Unless otherwise specified, the rules governing roundness tolerance defined in ISO 1101 or ASME Y14.5-2009 shall apply. The toleranced_shape_aspect shall be of invariance class surface revolute feature but not a helical shape.[52] The actual surface shall lie in a tolerance zone limited by two co-planar and concentric circles with a difference in radii of the tolerance value. [ISO 10303-47:2014]. 18, 22

[49]Two instances of representation_context are separate and have no relationship unless a relationship is explicitly specified between them in an annotated EXPRESS schema that uses or specializes this entity data type.

[50]One representation_item contributes to the definition of a second representation_item if the first is referenced by the second.

[51]The same representation_item could be related multiple times to the same **representation_context** by being used directly or indirectly in several instances of **representation**, each referencing the same **representation_context**. This does not have the meaning that each **representation** is creating a new instance of the same representation_item in the same **representation_context**. Rather, each **representation** reasserts the use of the same instance of representation_item in the **representation_context** for different uses.

[52]In the case of a sphere, any axis through the center point of the sphere may be considered.

sads_shape_aspect_subtypes subtype constraint

The sads_shape_aspect_subtypes constraint specifies a constraint that applies to instances of subtypes of **shape_aspect**. Any instance of a **shape_aspect** shall not be an instance of more than one member of contacting_feature, **datum**, datum_feature, **datum_system**, datum_target, and **general_datum_reference**.[53] [ISO 10303-47:2014, modified]. 24

shape_aspect

A shape_aspect is an identified element of the shape of an object.

Example 18. Consider the **product_definition_shape** of a bolt. One might distinguish, as an element of this shape, the concept of the threaded portion of its shank. This portion of the shape could be specified using a **shape_aspect** entity so that other properties, such as surface finish, may be associated with it. [ISO 10303-41:2014].

iii, 9, 17, 18, 22, 23, 39–42, 48–52, 57, 58

shape_aspect_relationship

A shape_aspect_relationship is a relationship between two instances of the entity data type **shape_aspect**; it provides an identification and description of their relationship.[54] [55] [56]

Example 19. A shape_aspect_relationship might relate two instances of the entity data type **shape_aspect** whose representations are the equivalent surfaces of a mold and a molded product. The shape of the mold is not spatially related to the molded product. [ISO 10303-41:2014]. 17, 49, 50

shape_dimension_representation

A shape_dimension_representation is a type of shape_representation. A shape_dimension_representation is a representation of either **dimensional_location** or dimensional_size. It is a representation that explicitly describes a dimension of a **shape_aspect** with either a value or a range of values and needed specification modifiers. Unless otherwise specified the values and specification modifiers shall be used in accordance with ISO/TS 17450-2, ISO 14405-1, and ISO 14405-2.

Example 20. A cylindrical **shape_aspect** is prescribed to have a diameter of 10 centimeters. This specification, "10cm diameter", is a shape_dimension_repre-

[53] The entities contacting_feature, datum_feature, and datum_target are not discussed in this document.

[54] If one **shape_aspect** is part of another, this entity could be used to associate the two **shape_aspect**s.

[55] No actual physical relationship is established between related instances of the entity data type **shape_aspect**.

[56] Relationships represented using this entity may be parent child-relationships.

sentation that defines a size characteristic of the **shape_aspect** without requiring a geometric representation. [ISO 10303-47:2014]. 21

simple_datum_reference_modifier

A simple_datum_reference_modifier is an extensible collection of alternative modifier symbols, each of which can be associated to the **datum** letter by a member of **general_datum_reference**. [ISO 10303-47:2014, modified]. 20, 49

straightness_tolerance

A straightness_tolerance is a type of **geometric_tolerance** that applies either to the intersection curves between the surface and the planes parallel to the reference plane, or to the extracted median curve. Unless otherwise specified, the rules governing straightness tolerance defined in ISO 1101 or ASME Y14.5-2009 shall apply. [ISO 10303-47:2014]. 22

surface_profile_tolerance

A surface_profile_tolerance is a type of **geometric_tolerance** that applies to a surface. Unless otherwise specified, the rules governing profile any surface tolerance defined in ISO 1101 or ASME Y14.5-2009 shall apply. [ISO 10303-47:2014]. 22

symmetry_tolerance

A symmetry_tolerance is a type of **geometric_tolerance_with_datum_reference**. Unless otherwise specified, the rules governing symmetry tolerance defined in ISO 1101 or ASME Y14.5-2009 shall apply. [ISO 10303-47:2014]. 22

total_runout_tolerance

A total_runout_tolerance is a type of **geometric_tolerance_with_datum_reference**. Unless otherwise specified the rules governing total run-out tolerance defined in ISO 1101 or ASME Y14.5-2009 shall apply. The set of referenced **datum**s shall contain one revolute surface feature. [ISO 10303-47:2014]. 22

unequally_disposed_geometric_tolerance

A unequally_disposed_geometric_tolerance is a type of **geometric_tolerance** whose tolerance zone is offset from the default value. Unless otherwise specified an unequally_disposed_geometric_tolerance shall be used in accordance with unequally disposed tolerance zone as defined in ISO 1101 or ASME Y14.5-2009. [ISO 10303-47:2014]. 22

Acronyms

3D

three-dimensional. 42, 44

AIC

application interpreted construct. 9

AIC 514

ISO/TS 10303-514. 8, 18

AIC 519

ISO/TS 10303-519. 3, 10

AIC 522

ISO/TS 10303-522. 4, 10

AM

Application Module. 9

AM 1032

ISO/TS 10303-1032. 16

AM 1050

ISO/TS 10303-1050. 2, 8, 15, 21

AM 1051

ISO/TS 10303-1051. 2, 8, 15

AM 1810

ISO/TS 10303-1810. 3, 15

AM 1811

ISO/TS 10303-1811. 3, 15

AM 1812

ISO/TS 10303-1812. 3, 16

AM 1816

ISO/TS 10303-1816. 3, 15

AP
: Application Protocol. 7, 8, 38, 39

AP 202
: ISO 10303-202. 5, 17

AP 203
: ISO 10303-203. 1, 4, 7, 8, 17, 44

AP 210
: ISO 10303-210. 4

AP 214
: ISO 10303-214. 1, 4, 5, 8, 9, 44

AP 224
: ISO 10303-224. 4, 7, 8, 10, 11, 17

AP 238
: ISO 10303-238. 8

AP 242
: ISO 10303-242. iii, 1, 4, 5, 9–11, 14–17, 42, 63

ARM
: Application reference model. 50

ASME
: American Society of Mechanical Engineers. 1, 8, 9, 44

CAD
: computer-aided design. 1, 9, 17

CAM
: computer-aided manufacturing. 5

CAx
: computer-aided technologies. 43

CAx-IF

Computer-Aided-”x” (Design, Manufacturing, Inspection) Interoperability Forum. iv, 1, 8, 9, 11

CMM

coordinate-measurement machine. 9

GPS

geometric product specification. 1, 42

IGR 41

ISO 10303-41. 10, 16

IGR 42

ISO 10303-42. 10, 16

IGR 43

ISO 10303-43. 10

IGR 45

ISO 10303-45. 10, 11, 15

IGR 47

ISO 10303-47. 1–4, 9, 10, 15, 17, 18, 21–24, 42, 49, 50

ISO

International Organization for Standardization. 1

LOTAR

long-term archival and retrieval. 1, 43

MCAD

mechanical computer-aided design. 17

NC

numerical control. 5

PDM

product-data management. 15, 17

PMI

product and manufacturing information. 1, 9

STEP

STandard for the Exchange of Product Model Data. 1, 7, 8, 44

UML

Unified Modeling Language. iii, 4, 5

Appendix B. Supplemental Materials

The Pmi_root_schema (mim.exp) is available at [51]. The elaborated (long-form) schema (mim_lf.exp) for the Pmi_root_schema example is available at [52].

A complete list of the items addressed by the development of the first edition of AP 242 is available at [53], organized by ISO 10303 document.