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AN EXPOSITION OF RECENTLY STANDARDIZED CLASSIFICATIONS OF INFORMATION FOR ORGANIZING MODEL-BASED DEFINITIONS

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ABSTRACT

ASME has published a new standard (ASME Y14.47) on model-based definition (MBD) organization practices. It is part of ASME's series of standards on engineering product definition and related documentation practices. ASME Y14.47 introduces novel MBD-element classifications, which are based on industrial recommended practices in organizing and managing three-dimensional geometric models and related information of products. Such classifications form the technical basis for developing information models (e.g., as XML schema definitions) to enable interoperability among engineering information systems in model-based enterprises (MBEs). This paper provides an exposition of these classifications, while emphasizing the need and use of such standardized classifications in modern MBEs.

1 INTRODUCTION

The American Society of Mechanical Engineers (ASME) publishes a series of standards on engineering product definition and related documentation practices (e.g., Y14.5 [1], Y14.37 [2], Y14.41 [3]). The newest standard in the Y14 series is Y14.47 [4], which sets requirements for model-organization practices. ASME Y14.47-2019 introduces several classifications that are based on industry practices of organizing and managing product definitions in three-dimensional (3D) geometric models and related information. The new classifications form the technical basis for developing information models (e.g., XML Schema Definitions (XSD)) to enable interoperability among engineering information systems in model-based enterprises (MBEs).

ASME Y14.47-2019 grew out of United States Department of Defense (DoD) procedures and standards for documenting technical data packages (TDPs) – most recently Revision A of MIL-STD-31000 [5]. MIL-STD-31000 defines requirements for delivering data in a TDP. Appendix B of MIL-STD-31000 Revision A defined a model-organization schema for model-based definition (MBD). The schema was DoD focused and, therefore, limited in its applicability. The DoD approached ASME to request that they define a national standard based on Appendix B. In late 2018 and early 2019, Revision B of MIL-STD-31000 and the first edition ASME Y14.47-2019 were published – completing the transition of Appendix B to a national standard and removing Appendix B from MIL-STD-31000.

The main contributions of ASME Y14.47 are model-based practices for organizing product-definition information and classifications of model elements in MBDs. The standard is the first ASME standard to meet the industrial need to share incomplete information in an organized manner in the context of MBDs. The standard is also the first to address presentation states of MBDs for better visualization. The ASME Y14.47 standard establishes a common method for industry to access MBD data in a data set.

Composing model elements into MBDs for representing products and classifying the elements of the compositions enables quickly finding information contained in MBDs. The classifications also, to some degree, indicate how the information can be used. Providing metadata about the location and potential usage of information helps form digital threads [6]. A digital

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thread is a connected information flow that integrates phases of the product lifecycle.

To be effective, the digital thread needs well-structured digital models and data to exist across the lifecycle. Unfortunately, much of industry still communicates product specifications to supply chains using two-dimensional (2D) graphic drawing sheets. Drawings are not efficient communication mechanisms for manufacturing and other downstream phases of the lifecycle. Drawings are not consumable directly in to computer-aided processes. Drawings require humans to interpret information and, in worst cases, make assumptions about the product that is being realized. Despite an abundance of guidance materials for industry[1], making a "good" drawing still requires the work of an artisan more than an engineer. In an MBE, where models replace the paper-based communication mechanisms, more rigor is required to organize and classify information for consumption.

A recent economic study found that there is a $57.4 Billion annual opportunity available to industry through deploying novel smart-manufacturing technologies [7]. Managing digital-data streams through models accounts for $8.9 Billion of the annual opportunity, while enabling seamless transmission of digital information accounts for another $10.3 Billion. These opportunities provide evidence that there is a significant benefit available to industry in digitally transforming its operations through the ubiquitous use of MBDs across all phases of the product lifecycle. However, industry needs the MBDs to be effective in communicating at least the same information as the paper-based counterparts. Information in MBDs needs to be organized and defined explicitly for efficient use by both humans and machines. ASME Y14.47-2019 [4] is starting industry down the path of addressing the practice of organizing elements of MBDs.

The remainder of the paper is organized as follows. Section 2 provides a brief introduction to the concepts of *presentation* and *representation* information. Section 3 through Section 6 introduce the classification categories defined in ASME Y14.47-2019. The paper concludes with a summary and remarks in Section 7.

2 PRESENTATION AND REPRESENTATION

Information modelers in the engineering domain use the terms *presentation* and *representation* to describe information intended for human consumption and machine consumption, respectively. ASME Y14.47-2019 [4, p. 4] defines *presentation* and *representation* as:

"*presentation:* the manner in which information is displayed for use by a human."

"*representation:* the manner in which information is stored for interpretation by a machine."

For example, the specification of a "hole" feature is depicted in three different ways in Figure 1. In Figure 1(a), the specification of product and manufacturing information (PMI) for the hole is presented with a set of symbols displayed in a 2D paper-based drawing. In Figure 1(b), the hole's PMI, also known as geometric dimensions and tolerances (GD&T) in ASME standards, is presented in an MBD. In Figure 1(c), the Extensible Markup Language (XML)-based representation information associated with the PMI for the hole is defined in Portable Document Format (PDF) [8] with an embedded Product Representation Compact (PRC) [9] model – colloquially known as a 3D PDF.

In the context of engineering, presentation information includes a varying set of symbols and line art to communicate specifications, requirements, and meaning to humans. For example, Figure 2 shows an excerpt from ASME Y14.5-2018 [1] where the *least material condition (LMC)* modifier is applied with a position tolerance to a boss and hole. The specification of LMC modifies the position tolerance to apply at the feature-size limit where there is the least amount of material in the part. This means the hole-tolerance zone at LMC is smaller than the hole-tolerance zone at maximum material condition (MMC). Therefore, the symbol for position tolerance has different meanings depending on the context of the material condition of the part.

In addition, representation information conforms to information models or data dictionaries specific to an application domain. The technologies (e.g., XML, JavaScript Object Notation (JSON), EXPRESS) and the data schema vary between systems (e.g., computer-aided design (CAD) formats, data standards, software) . For example, PMI represented in a 3D PDF uses XML to capture information and names the entity for position tolerance as `GTOLTYPE_POSITION` (See Figure 1(c)). Whereas, STandard for the Exchange of Product Model Data (STEP) Application Protocol (AP) 242 [10] uses EXPRESS to capture information and names the entity for position tolerance as `position_tolerance` [11, p. 37].

There is no standard definition of presentation and representation information for product definitions used across the entire product lifecycle. Also representation, in most engineering contexts, applies only to the machine-readable syntactic structure of a product. Neither presentation nor representation information, as defined today, captures the semantic – the "means this" – definition of a product (see Figures 1 and 2). There are efforts to standardize the interfaces of the different viewpoints across the product lifecycle; for example, design, process planning and execution, and quality and inspection [12]. Standardizing both presentation and representation information in a way that allows each viewpoint of the lifecycle to interoperate would ensure the appropriate, viewpoint-specific, information is readily available in consumable forms [13]. We are aware of no current standards efforts to capture semantic information in MBDs.

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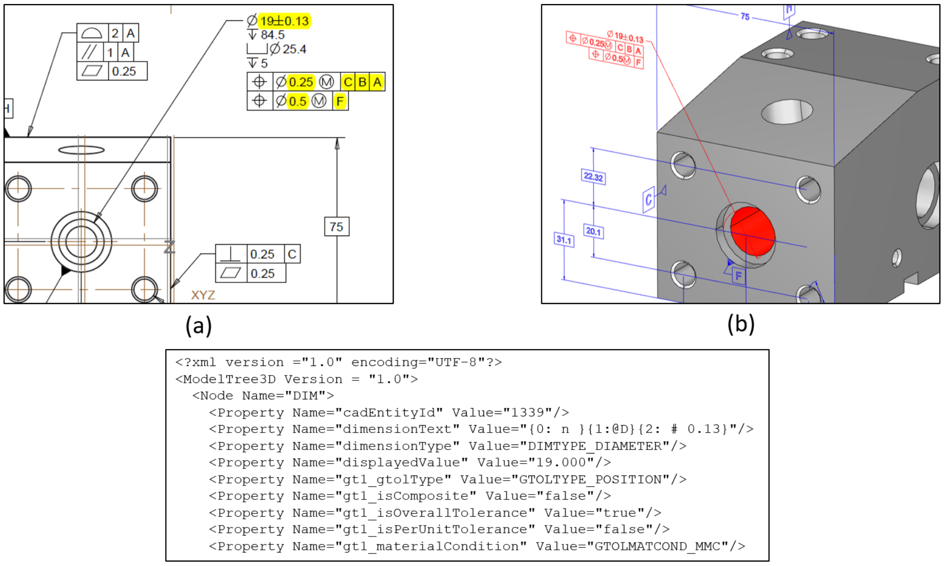
[1] A quick Amazon.com book search of "engineering drawings" returns over 20,000 results. While the Amazon.com search is not a scientific study, it is a quick and good demonstration of the substantial amount of materials available on the topic of engineering drawings.



(a)

(b)

```
<?xml version ="1.0" encoding="UTF-8"?>
<ModelTree3D Version = "1.0">
  <Node Name="DIM">
    <Property Name="cadEntityId" Value="1339"/>
    <Property Name="dimensionText" Value="{0: n }{1:@D}{2: # 0.13}"/>
    <Property Name="dimensionType" Value="DIMTYPE_DIAMETER"/>
    <Property Name="displayedValue" Value="19.000"/>
    <Property Name="gt1_gtolType" Value="GTOLTYPE_POSITION"/>
    <Property Name="gt1_isComposite" Value="false"/>
    <Property Name="gt1_isOverallTolerance" Value="true"/>
    <Property Name="gt1_isPerUnitTolerance" Value="false"/>
    <Property Name="gt1_materialCondition" Value="GTOLMATCOND_MMC"/>
```

(c)

FIGURE 1: The specification of a "hole" feature is depicted in three ways. In (a), the specification of PMI for the hole is presented with a set of symbols displayed in a drawing. In (b), the PMI for the hole is presented in an MBD generated with a CAD system. In (c), the XML-based representation information is associated with PMI for the hole in an MBD stored in a 3D PDF. (from Hedberg et al. [14]).

3 CLASSIFICATION OF ANNOTATIONS AND ATTRIBUTES

Presentation and representation are general terms used to describe the intended interaction with different types of information in an MBD. However, a main concern for ASME Y14.47 is organizing MBDs to account for the dimensions, tolerances, notes, text, and symbols that specify a product. ASME Y14.47-2019 classifies dimensions, tolerances, notes, text, and symbols in an MBD as either *annotation* or *attributes*, depending on how the elements are displayed and stored. Formally, ASME Y14.47-2019 [4, p. 3] defines annotation as, "visible dimensions, tolerances, notes, text, or symbols," and attribute as, "a dimension, tolerance, note, text, or symbol required to complete the product definition or feature of the product that is not visible but available upon interrogation of the annotated model." *Annotated model* is a controlled term in ASME Y14.47-2019 to describe a specific type of model containing geometry, annotation, and attributes to define a product.

While a note, text, or symbol element may be an attribute, most likely there will be related annotation for those elements because they will need to be displayed to the user. ASME Y14.47-2019 allows a dimension or tolerance element to be either an annotation, an attribute, or both. A dimension or tolerance should always be an attribute and include related annotation if needed. Embracing our American roots, "no presentation without representation!"

Including dimension and tolerance elements in MBDs as attributes will allow downstream systems (e.g., computer-aided manufacturing (CAM), computer-aided inspection (CAI)) to read the dimensions and tolerances directly, which speeds up processes and reduces opportunities for error. Regardless, when annotations and attributes both exist for dimensions, tolerances, notes, text, and symbols, the annotations and attributes should be linked to ensure consistency in the product specification. Annotation should be derived from attributes. For example, a CAD system could use the dimension and tolerance attributes in the XML shown in Figure 1(c) to produce the corresponding annotations shown in Figure 1(b).

An additional benefit of linking annotation and attributes together is they can also be linked to the geometry in the MBD to provide further value through the CAD system's user interface. For example, in Figure 1(b) the geometric feature is highlighted in the CAD system when the related group of dimension and tolerance annotations are selected. This associative cross-highlighting, or visual response, enables the MBD consumer to quickly identify what MBD elements are related. ASME Y14.41-2019 [3, p. 14] provides a series of requirements for defining an associative digital relationship between elements, which that standard calls *associativity*.

4 CLASSIFICATION OF PRESENTATION STATES

Presentations states are elements of the MBD intended for human consumption. ASME Y14.47-2019 [4, p. 4] defines presentation state as, "a retrievable collection or set of model display elements arranged for formal display to the viewer." Presentation

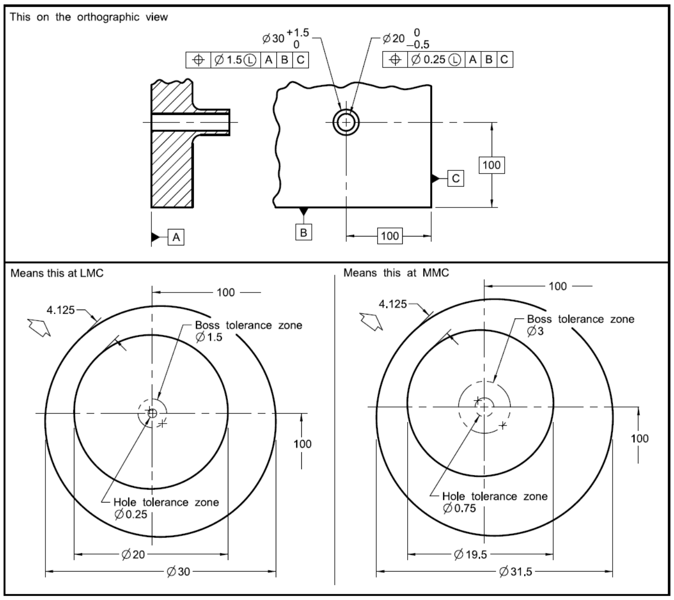
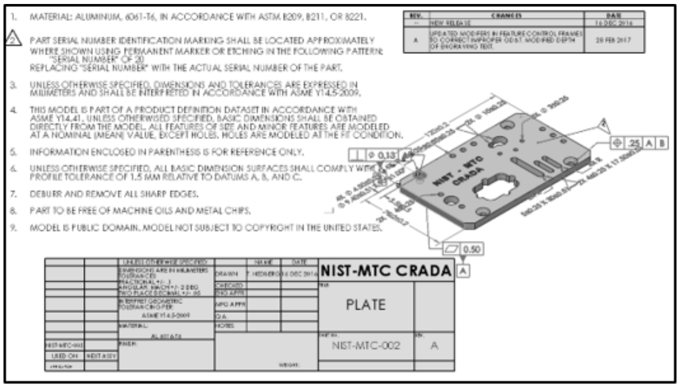


FIGURE 2: An overview of the LMC modifier applied with a position tolerance to a boss and hole. The symbology in the top of the figure drives different meaning depending on the context of the material condition of the part (from Figure 10-14 in ASME Y14.5-2018 [1]).

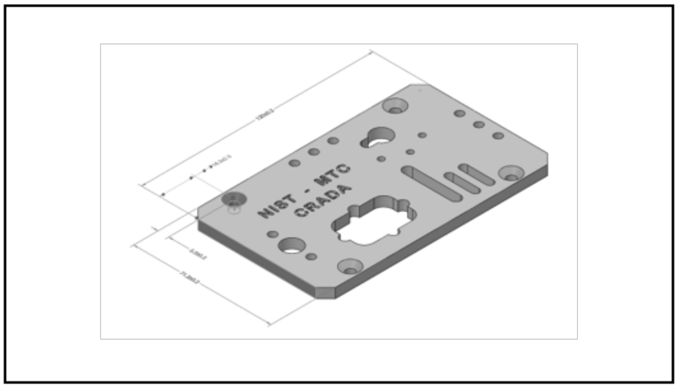
states are a useful way for the MBD author to highlight important information for the MBD consumer. In a CAD system, a presentation state may comprise camera view angle, geometry orientation and appearance, and the selected set of annotation to display to the user. When the MBD is an assembly, the assembly component configuration is also included in a presentation state.

ASME Y14.47-2019 requires at least one presentation state be included in an MBD. However, the composition of the presentation state and the number of additional presentations states included in the MBD is left to the decision of the MBD author. Suggested presentation states are listed in ASME Y14.47-2019. For example, a *Default Notice* presentation state is suggested to notify the MBD consumer of all the legal and regulatory requirements that must be displayed explicitly to the user. A *Site Map* presentation state is also suggested as a way to enable the MBD consumer to quickly navigate around the MBD and through any other included presentation states.

A 2D drawing has views to clearly present information. Presentation states are intended for the same purpose. CAD systems have the ability to show all the annotation information in an MBD at one time. The MBD consumer can quickly get lost if an overwhelming amount of annotation is presented at one time. Presentation states are used to avoid the “fur ball” effect [15], which is a situation when all the annotation displayed in the MBD completely obscures the geometry making the MBD look like it is growing fur. Figure 3 shows a comparison of a presentation state, Figure 3(a), showing all the PMI in an MBD and a presentation state, Figure 3(b), organized to show only the PMI associated with the definition of a hole feature. Viewing the MBD with the presentation state shown in Figure 3(b) is significantly clearer than the presentation state with all the other PMI. Thus, if the MBD consumer is interested in reviewing the shown hole-feature definition, he/she can quickly ascertain the relevant information about the feature and does not have to manually filter through all the other extraneous information.



(a) All PMI Presentation State



(b) Hole Definition Presentation State

FIGURE 3: A comparison of a presentation state (a) showing all PMI in a MBD and a presentation state (b) organized to show only PMI associated with the definition of a hole feature (diplayed MBD is a component of an assembly data set published in Hedberg et al. [16]).

5 CLASSIFICATION OF METADATA

Presentation states are intended for a human. Conversely, metadata is intended mainly for a machine. ASME Y14.47-2019 [4, p. 17-19] declares requirements for including in metadata MBDs. Using attributes is the most logical way to include metadata in a CAD system. The requirements for metadata in ASME

Y14.47-2019 are intended to ensure a common schema for representation information when exchanging MBDs.

Industry lacked common definition of metadata elements prior to the release of ASME Y14.47-2019. For example, one organization may store the value for a part number in an element named `part_number` while another organization stores the value in an element named `number_part`. A human can determine the two elements are the same information, but a machine does not have the same reasoning ability. Therefore, the machine may not know MBDs from two different organizations are related to the same part. ASME Y14.47-2019 declares requirements that organizations must map the metadata elements in the MBD to the common elements defined in metadata section of the standard, if the MBD's metadata elements do not already exist in the common form.

Further, ASME Y14.47-2019 defines three categories to further classify metadata. All the metadata in an MBD may not be intended for machine consumption. Some of the metadata may be used to populate annotation in the form of tables and notes. Therefore, some metadata may be stored as strings, while other metadata requires a specific data type. ASME Y14.47-2019 declares a required data type for each of the defined metadata elements. The three categories of metadata defined in ASME Y14.47-2019 [4, p. 19] are:

Category 1: data that shall be able to be processed via software application without human processing (i.e., representation).

Category 2: data that shall be able to be processed via software application but also be human processable (i.e., presentation and representation).

Category 3: data that shall be defined for human processing (i.e., presentation).

An example of *Category 1* metadata is an element such as a digital certificate. The *Category 1* metadata are elements that may have no meaning to a human. An example of *Category 2* metadata is an element such as a date stored in the ISO 8601 extended form date/time [17]. The *Category 2* metadata are elements that a human may be able to understand, but are mainly intended for a machine to do something with that metadata. Lastly, an example of *Category 3* metadata is an element such as a legal statement or engineering note. The *Category 3* metadata are elements that will most likely be free-form text that is stored for use in presentation information. A common practice in larger engineering organizations is to store common engineering notes in a database to ensure consistent call-out of specific information. *Category 3* is an appropriate class of metadata in the MBD to store the text coming from those databases.

6 CLASSIFICATION OF COMPLETENESS

GrabCAD[2] surveyed [18] their current user base in 2014 (at the time, over one-million users) and found 75 percent of the survey respondents had wasted time fabricating a prototype or production part using the wrong version of data. Declaring and communicating an MBD's status of completeness clearly is essential to ensuring the proper usage of an MBD. ASME Y14.47-2019 [4] defines MBD completeness as a combination of states for the categories of *maturity*, *geometry*, and *annotations and attributes*. The standard also provides a code definition for each category.

6.1 MATURITY STATE

The maturity state declares the authorized use of the MBD. ASME Y14.47-2019 uses the letter *M* as the prefix in the code definition of maturity state. The standard defines four states for maturity: (M1) conceptual, (M2) developmental, (M3) production, and (M4) archive. An MBD would receive a declared state of maturity, which would communicate clearly the intended purposes of the MBD to anyone using that MBD. For example, the maturity state could limit an MBD's use to only preliminary design discussions, testing and experimentation, or allow for delivering final products to market.

An MBD may be declared with a *M1* (conceptual) maturity state when the MBD is intended for early design exploration or some feasibilty study of a design concept. However, an MBD declared as a *M3* (production) maturity state would be required for realizing products intended to be delivered to market. The intended use of an MBD is unknown without a maturity-state declaration. For example, the MBD shown in Figure 4 is relatively simple. If a maturity-state declaration is not provided for the MBD, then it cannot be trusted for any purpose other than as a reference. As it turns out, the MBD shown in Figure 4 is declared to be in a *M3* maturity state in an example provided by ASME Y14.47-2019, which means this MBD may be used to realize products in a production environment. The maturity state is declared independent of the geometry state and the annotation and attribute state. Therefore, the maturity state may be declared *M3* (production) while having none, some, or all of the geometry, annotations, and attributes included in the MBD. This is particularly useful in cases where the MBD defines an intermediate definition of a product, such as a casting that will be processed further before being delivered to market.

6.2 GEOMETRY STATE

The geometry state declares the level of geometric detail for an MBD. ASME Y14.47-2019 uses the letter *G* as the prefix in the code definition of geometry state. The standard defines three

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[2] An online community of professional engineers, designers, manufacturers, and STEM students, `https://grabcad.com/`

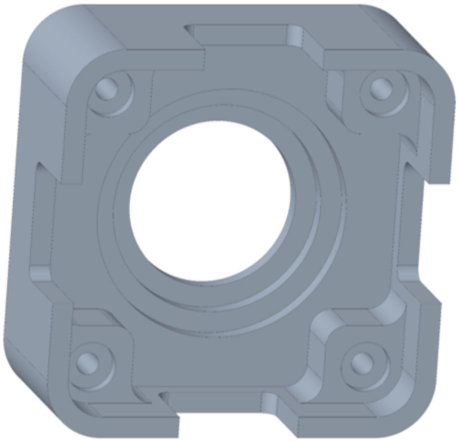


FIGURE 4: An example MBD declared to be in a *M3* maturity state (from [4, p. 7-8]).

states for geometry: (G1) none, (G2) partial, (G3) full. MBDs with a *none* geometry state could be empty CAD models that are a placeholder in some product structure or provide a definition of a coordinate system, but these MBDs have no explicit geometry defined for features. However, the *partial* and *full* geometry states have some or all of the feature geometry provided respectively in the MBD.

MBDs often exist in different levels of geometric detail for various reasons. An MBD may be defeatured to assist with better meshing for finite-element analysis (FEA) or computational fluid dynamics (CFD) analysis. An MBD may have features removed for intellectual property (IP) concerns. Regardless of the reason for the level of geometric detail, the geometric state of the MBD should be communicated to ensure transparent and explicit understanding of the geometry in the MBD. For example, the MBD shown in Figure 5 is declared to be in a *G2* geometry state in an example provided by ASME Y14.47-2019. The MBD could be a production definition for use in a casting process where the output will move to a final machining process. While the MBD does not have all the final geometry for the product, it does have the necessary information for the casting process to complete the required work. Then, the MBD shown in Figure 4, which is also declared to be in a *G3* geometry state in the ASME Y14.47-2019 example, can be used to complete the final-machining work to deliver a complete part.

6.3 ANNOTATION AND ATTRIBUTE STATE

The annotation and attribute state declares the level of specification detail for an MBD. Recall, by definition, annotation is presentation information and attribute is representation information. ASME Y14.47-2019 uses the letter *A* as the prefix in the code definition of annotation and attribute state. The standard defines three states for annotation and attribute: (A1) none, (A2) partial, (A3) full. Similar to the geometry state, an MBD may contain none, some, or all of the annotation and attributes intended to define a product.

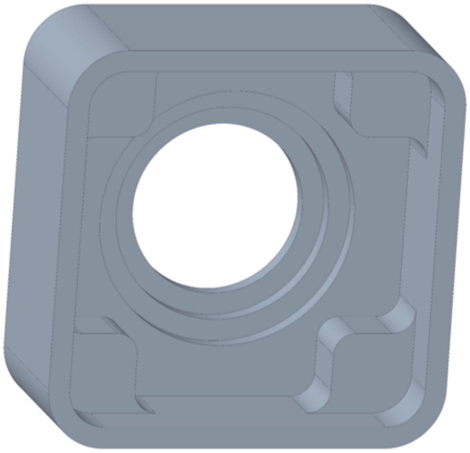
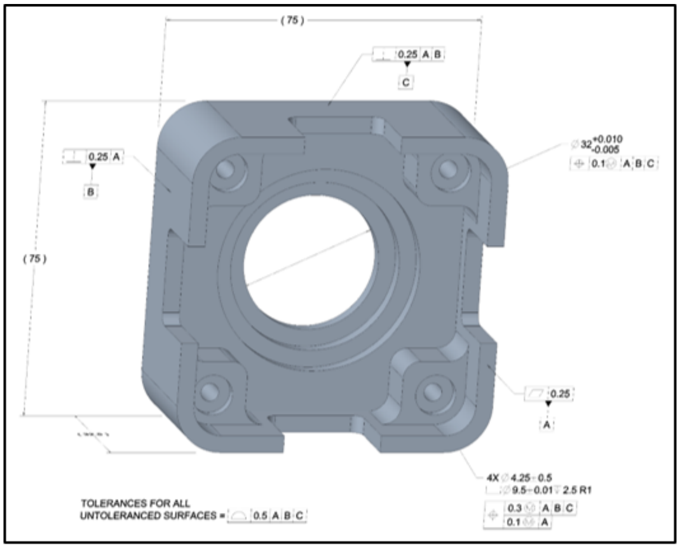


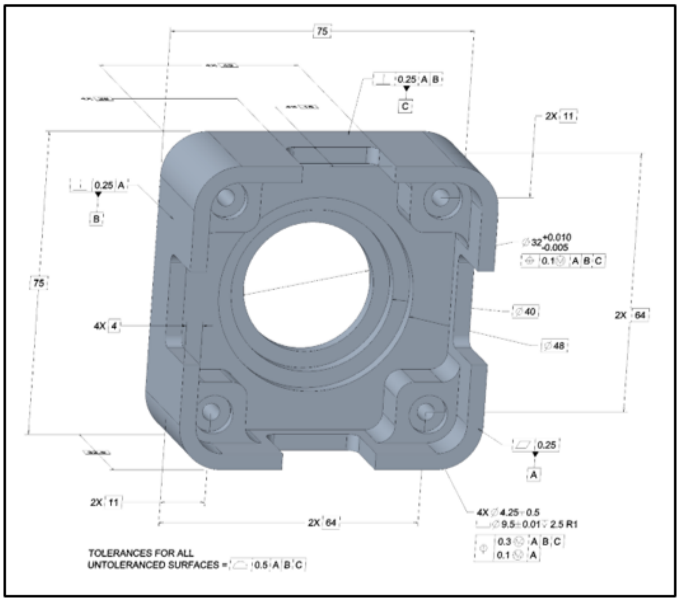
FIGURE 5: An example MBD declared to be in a *G2* geometry state (from [4, p. 8]).

When to include a specification in an MBD as an annotation, an attribute, or both is a point of debate in industry. Enterprises that deliver to the DoD will argue that the DoD wants all specifications (e.g., notes, toleranced dimensions, basic dimensions) presented as annotation, which makes the MBD appear more like a 3D drawing. In contrast, non-defense entities will often declare the geometry specifies the basic dimensions of the part and will only present toleranced dimensions as annotation. Which approach is correct? The answer is beyond the scope of this paper. However, ASME Y14.47-2019 requires an MBD to present all of the specification detail to be declared in a *A3* annotation and attribute state, “including items such as general notes and other PMI without querying the model geometry intended to be used to define the product,” [4, p. 6]. By standard definition, MBDs that do not present every dimension, note, etc. as annotations in the MBD must be declared in a *A2* annotation and attribute state.

Figure 6 shows an MBD in a *A2* annotation and attribute state and an MBD in *A3* annotation and attribute state. While the MBDs and presented information may not look drastically different, there are subtle and nuanced differences that affect the interpretation of the MBD. In the *A2* MBD, the envelope dimensions, the top-most and left-most 75 values, are surrounded by parenthesis, which means those two dimensions are defined as reference dimensions. However, in the *A3* MBD, the same envelope dimensions are bordered by a closed box, which means the two dimensions are defined as basic dimensions. The subtle difference between the two MBD has a significant impact in how tolerances are interpreted for the two dimensions.



(a) Annotation and Attribute State A2 – Partial



(b) Annotation and Attribute State A3 – Full

FIGURE 6: Example MBDs declared to be in *A2* and *A3* annotation and attribute states (from [4, p. 9]).

6.4 COMPOSING COMPLETENESS

The classification of completeness should include a declaration for each of the three state categories. The maturity state may be viewed as an overall declaration of an MBD's completeness, while the other two states make declarations about specific elements of the product specification in the MBD. For example, the geometry state and annotation and attribute state could both be declared as full, but the maturity state is declared as developmental. In this case, the MBD consumer should understand that even though a full presentation and representation of the product exists in the MBD, the MBD can not be used to deliver a final product to market because it is only declared mature enough for activities such as testing and experimentation.

Further, the completeness states should be declared using metadata included in the MBD. ASME Y14.47-2019 provides guidance for including declarations for maturity, geometry, and annotation and attributes states using metadata. Listing 1 provides an example of how the three states could be implemented as attributes using JSON. The JSON example declares the composed classification of completeness for the *M2* MBD shown in Figure 6.

LISTING 1: An example JSON implementation of completeness states as attributes in the MBD shown in Figure 6(a)

```
{
  "asme_y14.47-2019": {
    "figure_5-3": {
      "subfigure_b": {
        "CODE_MATURITY_STATE": "M3",
        "CODE_GEOMETRY_STATE": "G3",
        "CODE_ANN_ATTR_STATE": "A2"
      }
    },
    "CREATE_DATE": "2019-02-18"
  }
}
```

7 SUMMARY AND CONCLUDING REMARKS

ASME Y14.47-2019 [4] is the first ASME standard that provides valuable guidance for addressing industry's need to exchange MBDs in varying states of completeness. The standard provides a path for digitally transforming industry through the use of MBDs in place of paper. The transformed organizations form an MBE, in which MBDs proliferate through each phase of the product lifecycle to enable effective *and* efficient communication of requirements and specifications. MBE stands to enable "manufacturing as a service" [19] by supporting the composition of information services and the integration of various types of models (e.g., service, product, process, logistics) across the product lifecycle.

This paper reviewed the various types of classifications for MBD elements defined by ASME Y14.47-2019. Currently, ASME Y14.47-2019 focused mostly on presenting information to humans. The next steps of the standard should be to enable more human-to-machine and machine-to-machine communication and links. This would require more definition of representation information to make the standard more like a schema.

Further, there is a "paradox of constraints" that arises out of using more MBDs and other types of models across the product lifecycle. Careful decision making is needed in standards development to minimize over constraining the product lifecycle by forcing industry to provide explicit definitions of all information early in the lifecycle. Every decision made early in the product lifecycle becomes a constraint on the later phases of the lifecycle [20, 21]. For example, if design places specific characteristic requirements in a product definition in a way that forces a certain manufacturing process, then manufacturing is restricted to that single type of process capability. These constraints introduce significant risk to schedules and budgets. A common mistake in design is to apply too tight of tolerance requirements on a design; resulting in significant cost increases in realizing the product [22]. While explicit definition of information is required for machines to effectively process the information, the MBD author needs to determine the right balance of information needed and where in the product lifecycle that information is to be defined and/or augmented.

Therefore, three questions related to MBE and ASME Y14.47 require further study. First, where could the next evolution of the ASME Y14.47 standard start? Then, can ASME Y14.47 be harmonized with other standards to enable effective and efficient communication and flow of information in an MBE? Last, what are the benefits of an MBE enabled by ASME Y14.47?

Where could ASME Y14.47 go next? The scope of ASME Y14.47-2019 says [4, p. 1], “This Standard establishes a schema for organizing a three-dimensional (3D) model and other associated information within the context of a digital product definition data set for the purpose of conveying a product definition that enables a model-based enterprise (MBE).” However, this first edition of the standard lacks the required definition of syntactic structure to fully support an MBE. Moving forward, ASME Y14.47 could establish more requirements and rules, defined using a formal language, to include and organize representation information for all aspects of an MBD.

Industry needs ASME Y14.47 to be a fully defined schema to be useful for MBE. ASME Y14.47 could include a conceptual data model for product-specification standards. For example, Figure 7 presents an example conceptual data model for a feature control frame as defined in ASME Y14.5-2018 [1]. The example data model normalizes the definition of the representation information composed and aggregated to make up a feature control frame. Providing a standard conceptual data model would ensure developers of computer-aided systems (e.g., CAD, CAM, CAI) to define logical and functional data models that conform to the practice standards that satisfy industry’s needs. Currently, some CAD systems combine some components of a feature control frame into a single data element (e.g., tolerance value and modifier are combined into a single attribute) while other CAD systems define an individual data element for each component of a feature control frame. Not having a standard conceptual data model for elements of a product specification inhibits manufacturers’ ability to use MBDs directly in process workflows. The MBDs coming from CAD systems often need to be modified to make them usable directly in CAM or CAI systems. A schema for MBDs used as product definitions would ensure those MBDs are mappable to the types of models the manufacturing domain needs to execute its processes.

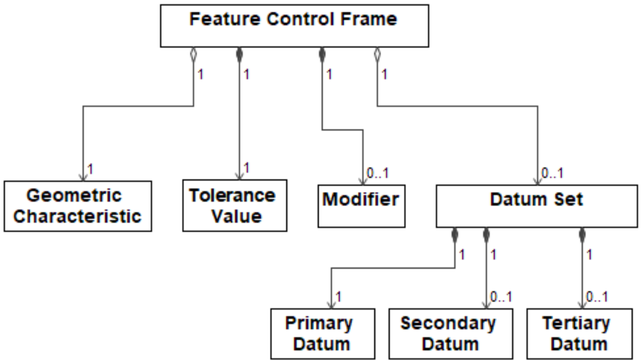


FIGURE 7: Example conceptual data model for a feature control frame as defined in ASME Y14.5-2018 [1]. Modeled using the Unified Modeling Language (UML).

Further research is needed in addition to making ASME Y14.47 a fully defined schema. However, schema does not equal semantics. In the context of manufacturing, a semantic data model is a representative abstraction, of the physical product, for expressing information in a way that humans and machines both understand the information without requiring custom rules and codes [23, 24, 25, 13]. A study is needed in to how representation information can move beyond capturing just syntactic structure. Specifically, research is needed to study how semantics can be included in representation information.

Can ASME Y14.47 be harmonized with other standards? The STEP standards have a 30-year[3] history in organizing data and information in a neutral-model format and data-exchange standards. International Standards Organization (ISO) 10303-242 [10] (AP242) and ISO 10303-239 [26] (AP239) are two STEP standards that share domains with ASME Y14.47. AP242 and AP239, when combined, aim to cover data exchanges across the entire product lifecycle. AP242 covers the data exchanges up to the realization of physical parts and AP239 covers the data exchanges required for data related to physical parts. The shared areas of interest between ASME Y14.47 and the APs are identification of part, part version, and part view; user-defined attributes; mechanical CAD structures; component instances, placement, and transformations; classification; and document management [27]. AP242 and AP239 provide requirements for organizing data included for exchange. However, there is little consensus

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[3] `https://pdesinc.org/timeline/`

on what information must be exchanged (e.g., the minimum information model [28]), which inhibits uniform implementation of the APs. Harmonizing the classifications of ASME Y14.47 with AP242 and AP239 could assist reaching consensus on the minimum information that must exist in an MBD, which would alleviate some implementation challenges of AP242 and AP239.

Further, the STEP standards generate activity models of engineering practices and workflows during the standards development process. The activity models are used for scoping the STEP standards and extracting business requirements for the neutral-model format and data-exchanges. However, the activity models are not intended for implemention by industry. Also, there is no, or minimal, verification and validation (V&V) done for conforming the STEP standards to the practice standards (e.g., ASME Y14.5, ISO geometrical product specifications). A hierarchy of roles and dependencies exist between the practice standards and the neutral-model format and data-exchange standards [29]. The ASME Y14 standards and ISO geometrical product specifications could come first and then the neutral-model format and data-exchange standards could conform to the practice standards.

ISO has a long history of organizing data and information through STEP. Industry needs consistently defined engineering practices for organizing elements of MBDs. There is an opportunity for ASME and ISO to work together to define formal links between the practice standards and the neutral-model format and data-exchange standards. ASME and ISO Technical Committees (TCs) 213 and 10 could define the engineering practices. The STEP standards, developed by ISO TC 184 Subcommittee (SC) 4 could define the data structures for the neutral-model format and data-exchange standards.

What are the benefits? Digitally transforming manufacturing requires MBDs, other type of models, and data to take the place of paper across the product lifecycle. The concepts of MBE, digital thread, and digital twin are success enablers for manufacturing, but require high-quality information models to function properly. Using well-defined and organized MBDs provide effective and efficient communication mechanisms to support distributed and cloud manufacturing. ASME Y14.47 provides guidance to the design and manufacturing community for developing and organizing MBDs to be used and consumed directly in various processes across the product lifecycle. Specific to manufacturing, activities, such as process planning, logistics and scheduling, and analyzing operations could be completed more accurately because MBDs can quickly communicate information and be integrated with heterogeneous information about the product without the need of data re-entry by a human [30]. This improves the quality of the manufacturing activities too.

Further, a fully defined MBD schema enables generating context-specific information models dynamically by automatically linking related nodes of different domain-specific information models [6]. Linking manufacturing data with data from other domains in the product lifecycle supports information discovery [12]. An MBE would realize significant value by ensuring linkages for the required amount of information manufacturing needs to complete its tasks – forming a digital thread between needed information. Manufacturing can not afford to produce new domain-specific models, but instead would leverage existing domain-specific models by linking them together to encapsulate the entire product-lifecycle information needs. The links between the domain-specific models enable viewpoint-specific information to flow between product lifecycle phases and roles by allowing access to various sets of independent information required by each phase and role. Successfully producing models that can link together and enable information flow throughout the product lifecycle would enable industry to realize the relevant portions of the $57.4 Billion annual opportunity in deploying novel smart-manufacturing technologies.

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