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MODEL BASED DEFINITION – RECOMMENDATIONS FOR SUPPLY CHAIN INTEGRATION

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Model Based Definition – Recommendations for Supply Chain Integration

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GLOSSARY

Term	Definition
Classification codes	A numerical code assigned to product definition data that outlines what data are included within the drawing graphic sheet, data set, or both.
Data set	A collection of data files that discloses the physical or functional requirements of an item
Data set identifier	A unique combination of numeric, alpha, or special characters that identifies the data held within a metadata record
Datum	A reference point, straight line, or plane used to measure the dimensions of a target
Drawing Graphic Sheet	Geometric elements and annotations in 2D that defines an item and the data elements of a sheet
Model-only Method	Complete product definition is contained with a 3D CAD model
Model and Drawing Graphic Sheet Method	Complete product definition is contained within a 3D CAD model and drawing graphic sheet
Pragmatic Quality Level	Definitions of the quality dimensions used, description of known dimension interdependencies, definitions of the methods applied for collecting the data to be used for measuring the quality dimension, description of the metrics used to measure quality dimensions, definition of each metric, purpose of each metric, description of measurement presentation, results for each validated dimension.
Property value tuple	The tuple is the fundamental building block of electronically stored characteristic data. Document requires use of property-value tuples when exchanging master data messages containing characteristic data.
Theoretically Exact Dimensions	Numerical values that are used to describe the theoretically exact size, profile, orientations or location of a feature or datum target and is not affected by individual or general tolerance
Semantic Quality Level	Documented conceptual model that includes relationships between data, methods used to verify data according to the model, description of how criteria derived rules are realised as measurements, and definition of compliance measurement and description of what non-compliance means for each rule. It also defines how deviations are registered and presented.
Syntactic Quality Level	Syntactic rules will define how compliance is measured, describe issues arising for non-conformance to data rules, describe what qualifies/quantifies as non-compliance.

ABBREVIATIONS

Abbreviation	Definition
MBD	Model Based Definition
MBE	Model Based Engineering
ASME	American Society of Mechanical Engineers
ISO	International Organisation for Standardisation
BS	British Standards
MRP	Material Requirements Planning
PLM	Product Lifecyle Management
PDM	Product Data Management
PIM	Product Information Management
TDP	Technical Data Package
S&OP	Sales & Operations Planning
ERP	Enterprise Resource Planning
TED	Theoretically Exact Dimensions
PIN	Part or Identifying Number
CAGE	Commercial and Government Entity
GD&T	Geometric Dimensioning and Tolerancing
OEM	Original Equipment Manufacturer

EXECUTIVE SUMMARY

Model-Based Definition is a term that is gaining more recognition and use by manufacturers across various industries. MBD models are 3D CAD models that contain all the necessary information to produce a part, including information that would normally be found on a 2D drawing, and the model is ultimately the master file, or the “single source of truth”.

The increased use of CAD models as a manufacturing source led to the American Society of Mechanical Engineers (ASME) creating a standard to define and capture data difficult to outline on engineering drawings and ensure universal interpretation. The adoption of MBD has been slow in some industries due to a lack of understanding of the standards, availability of MBD ready software, lack of understanding of data sets and data management to ensure interoperability of systems and traceability of data. Additionally, difficulty in change of companies’ cultural environments also poses a hurdle towards adoption of MBD. In addition to defining what MBD is, and reviewing MBD and data standards, this report provides recommendations that will allow companies to adopt MBD practices and ensure interoperability of data across their supply chain. These standards further define the requirements of any data in any format.

By defining the data set, companies must develop a data management plan to establish minimum requirements for data quality. Minimal requirements for data handling and curation must also be defined in accordance with current MBD standards, and data should be maintained according to up-to-date data quality standards, even if they do not directly relate with core MBD implementation ideals. Effort should also be made in the direction of training and education less digitally literate suppliers to facilitate supply chain integration.

If companies can implement MBD practices, create a data management plan to handle the data created, and be transparent with their supply chain on the standards that they use, they will be in a better position to collaborate with suppliers and manage those data transactions and relationships.

1 INTRODUCTION

Model-Based Definition (MBD), also known as Digital Product Definition, is a strategy to move to 3D Computer Aided Design (CAD) models and away from 2D paper-based drawings. The 3D CAD model can contain all the information required to convey design and manufacturing information, that can be used to simulate processes [3]. To enable this process ASME Y14.41, Digital Product Definition Data Practices, was published to establish the requirements and reference documents that are applicable to the creation and revision of "digital product definition data" [1]. ASME Y14.41:2019 is the latest revision and BS ISO 16792 was first published as an adaptation of ASME Y14.41 with the current revision being BS ISO 16792:2021.

The standards focus on the data sets that are required to define the product definition. Therefore, it is important when adopting MBD practices that companies understand that they need a data management system. Within this report the applicable data standards will be reviewed, and recommendations will be made to enable companies to understand the role that data sets and data management takes when adopting MBD practices.

NOTE: All references to ASME Y14.41 and BS ISO 16792 shall be assumed to be the latest standards, 2019 and 2021 respectively, unless otherwise stated.

2 WHY MODEL BASED DEFINITION?

2.1 PURPOSE OF MBD

MBD is gaining interest and adoption in industry to enable the sharing of Product and Manufacturing Information (PMI) with other functional departments within the same company and their suppliers. The industries leading this adoption are the automotive and aerospace industries [4]. The main driver of MBD is to remove the need for 2D drawings and documentation and contain all the information required to design, manufacture, procure materials, quality check, etc. for the part in the 3D model. MBD can be used by engineers to lead product development activities such as sourcing, quality, inspection, the creation of technical publications and work instructions [4]. The aim is to have a "single-source of truth". A "single source of truth" ensures that everyone in an organisation bases decisions on the same data. In relation to MBD, this is in the form of the 3D model which is the one authority source that contains all 3D annotations with all data required to manufacture, inspect, and test the part and purchase parts or materials [13].

There are several advantages for a company to move to MBD:

- Reduction in time and interpretation - creating 2D drawings is time-consuming and open to interpretation, but with MBD models the dimensions and GD&T are already located within the model therefore reducing the need to add these to a drawing and save engineers time [4]

- Focused annotation – reduction in annotation that would normally be added to drawings, allows engineers to only add PMI to verify manufacturing conformance and add what is required for other functional departments to process their tasks [4]
- Fewer files to maintain – reduction of risk associated with the duplication of data, where it is transcribed or reinterpreted [6]
- Quicker response times – any changes are made to one file, and this would trigger notifications to all who can access it, so any changes are captured by all [5]
- Reduced risk – reduction in manually reproduced errors [5] and risk associated with the duplication of data, where it is transcribed or reinterpreted [6]
- Quality is improved – reproduction of data, misinterpretation etc. can introduce an opportunity for defects within the product or process, that can impact cost, time and money, and reputation or repeat orders if the defect has entered the supply chain [6]
- Reduction in costs – work and engineering changes are only done once, so time creating visuals for various disciplines within the company are reduced [6]

NIST (National Institute of Standards and Technology) conducted a study to test the digital thread, which is the flow of information about a product's performance and use from design to production, sale, use and disposal or recycling, in support of model-based manufacturing and inspection [12]. The report details a comparison that was used to test their hypothesis that "model-based processes outperform drawing-based processes". Some conclusions focused on the delivery time from a model-based supplier compared to that of a drawing-based supplier. Ultimately the model-based supplier could deliver parts within weeks, while the drawing-based supplier could take months. The drawing-based supplier must be able to read and interpret the drawing and determine the product definition from the drawing. They will go back and forth to the customer with questions which stops production while they wait for answers, leading to prolonged, unaccounted for lead times. This not only costs the supplier money due to possible penalties from the customer, but also all the costs associated with starting and stopping production and possibly affecting other products going through the company. Ultimately it could put strain on the customer/supplier relationship leading to a bad reputation and a loss of orders.

Despite the advantages, one of the reasons that companies have been slow to fully adopt MBD relates with the difficulty of integrating their established PMI systems. There are also high capital costs, interoperability, technological limitations, and companies' cultural change [7]. The following sections will look at these in more detail and discuss the resolutions to these that have been implemented in industry.

High capital costs can come in the form of changing existing systems e.g., CAD and business systems. Most companies will use some type of CAD software, however not all are MBD ready, so they need to be changed. Even if they are, upgrading the software might be required. Depending on the software and the number of licenses the company has, this can be costly. In addition to software costs there are training costs to ensure users can utilise the software to its fullest potential and create MBD models that contain all the PMI information required by other departments or suppliers further down the supply chain. There is also the issue of interoperability of the data within the files with other business systems. There are systems such as PLM and ERP that can use these files, however the company would need to make sure that the information that these systems require are correctly added to the MBD model. If a company does not have the correct software to create models with MBD and software that can read the data held within it, then that is a technological limitation. Furthermore, a company requires software applications that can read PMI. This software can include numerically controlled (NC) tool paths, tolerance stack-ups, coordinate measuring machines (CMM), and many more. Not only does this software require PMI but it also requires the engineer to know how to apply the PMI so that each software package can read it correctly [4].

Interoperability is another challenge that adopters of MBD face. Companies that regularly use CAD will be familiar with the challenges faced when sharing CAD files or being given CAD files of different formats. Most CAD software packages can save files in neutral formats to enable interoperability with other packages. However, converting files to neutral formats can mean information is lost in translation. For models to be MBD ready, they have an additional layer of annotation in terms of GD&T and PMI that requires translation which adds additional requirements to the accuracy of the translator. Furthermore, there are interoperability issues with different revisions of the same CAD software. Often files cannot be opened in different versions of the same software or – if they can – some information is lost. The STEP file format was created by the International Standardisation Organisation (ISO) to enable the sharing of CAD models between different CAD platforms to enable interoperability. STEP AP242 was created to amalgamate the requirements of STEP AP203 and STEP AP214, which were primarily used to introduce application protocol for managed model-based 3D engineering. Part of the guiding philosophies of STEP AP242 is to convey machine-readable PMI in such a way that manufacturing operations can program code automatically according to the 3D PMI [8].

A companies' culture encompasses the way they structure their day, how they address problems, how they work as a team, how they interact with clients and suppliers, just to name a few. The cultural change required when a company adopts MBD not only affects the engineers defining and designing the products, but it affects every person and department that has any interaction with that product. This change requires leadership and commitment from higher management within the company. Adopting MBD includes changes to procedures, processes, working practices, and organisational policies to fully embrace the advantages of using MBD. Leaders must recognise all the stakeholders and their requirements internally and externally. Furthermore, a company's leadership needs to recognise that they need supplier buy-in. Suppliers will need to access the MBD models and information, and the manufacturer can lead them through the process of adopting MBD and guide them [4].

2.2 REQUIEREMENTS OF MBD MODEL

What is included in a model depends on what is being manufactured and who will need the information it contains; MBD standards have defined a basic content for a model, see section 2.2.1. However, the standards do not define the amount of information required – that would be determined by the part itself and who needs to interact with it. The content includes annotations, attributes, the CAD design model which includes the model geometry, geometric elements, supplemental geometry, and supporting documentation. There will be a minimum amount of information that is required to make sure that the product can be manufactured [9]. It is important that all those who will interact with the model decide what information they will require from it. Figure 1 shows possible information that can be used to build a MBD model and what functions within the company may need access to that information. This figure is loosely based on the information contained within *Towards Identifying the Elements of a Minimum Information Model for use in a Model-Based Definition* from MSEC2017 [9].

One of the most important requirements of the data within the model is that it is interoperable. All systems that interact with the model must be able to read and extract the data required for their function. It should be determined if the model needs to be saved in a neutral format, what format that should be, how the data could change, and what checks are required to ensure that data is not lost.

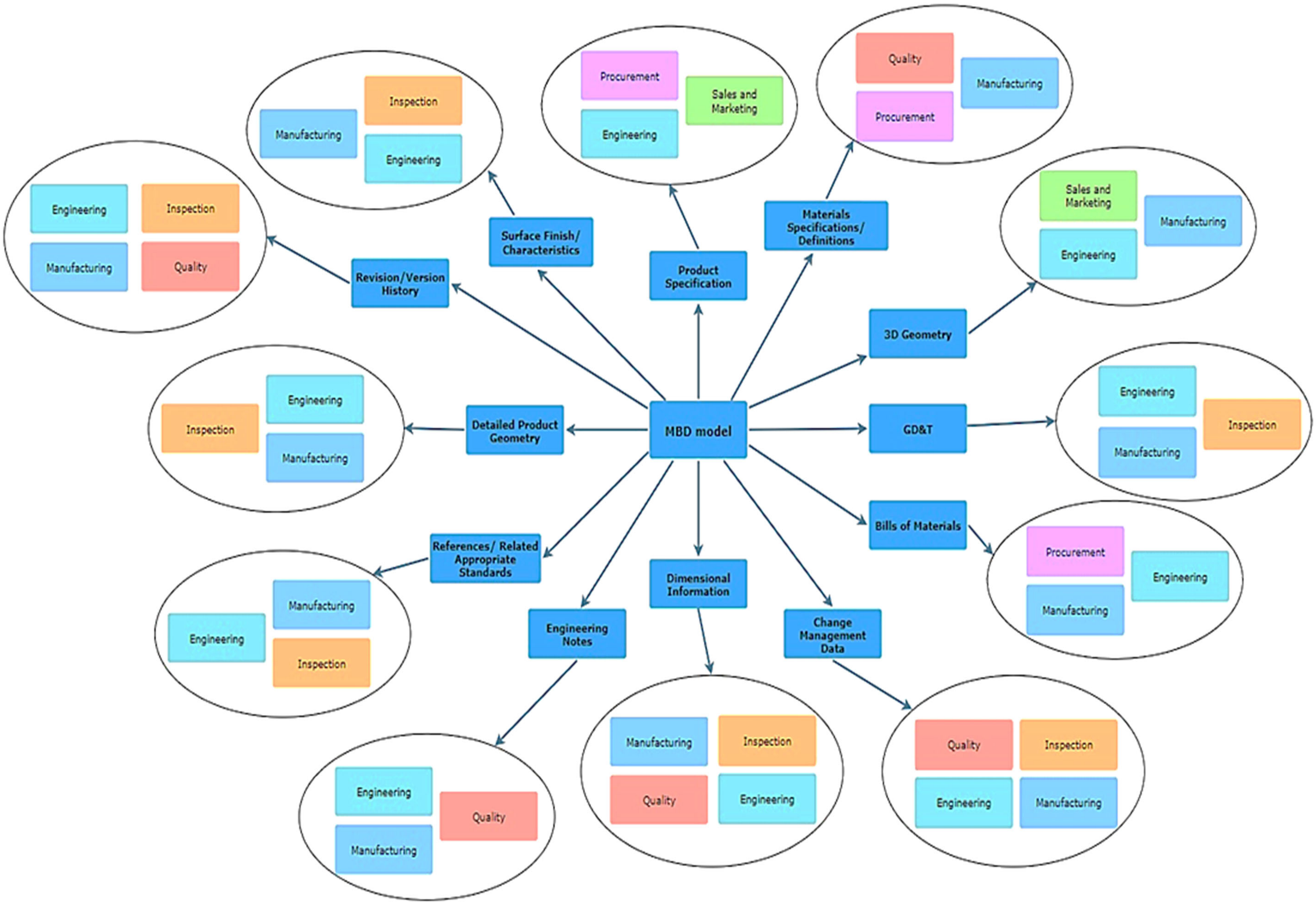

Figure 1 Possible information contained within MBD model

Model Requirements

ASME Y14.41 and BS ISO 16792 are currently the industry standards for preparing and revising digital product definition data where the data set created is based on a 3D CAD model. A design model is defined in the following way and state that the design condition shall be specified in a note or accompanying documents:

"Design models represent a product in ideal geometric form at a specified dimensional condition, for examples nominal, minimum, maximum, or mean." [2]

Both standards require the model scale to be 1:1 and the number of decimal places of the model shall be specified in the data set, the precision of which shall not exceed that of the model. ASME Y14.41 adds an additional clause specifying that the units shall be included within the data set, and these shall be Metric or U.S. Customary. ASME Y14.41 clause 6.1.2 specifies the following:

a) Design models not fully modelled shall be identified as such (e.g., partially modelled symmetrical part).
b) Features that are not fully modelled shall be identified as such (e.g., threaded holes that are only shown as holes).

In addition to the requirements above, BS ISO 16792 specifies an additional requirement for thin parts where the thickness is not modelled. The thickness is shown by an arrow representing the direction and a note added stating the thickness as per ISO-129-1. The standard then details additional clauses that ASME does not include. These are listed below [2]:

- *6.4 Assembly model completeness*
- *6.5 Part reference numbers*
- *6.6 Identification method – specifies use of visual representation in terms of colour, greyscale, mapping, hatching or transparency*
- *6.7 Installation model completeness – specifies requirements to show installation model completeness*

Clause 7 in both ASME Y14.41 and BS ISO 16792, details the "common requirements for the application, display management, and query of product definition data in models and drawing graphics sheets." Within "common requirements" both standards specify the requirement for "display management" but in addition to this, ASME Y14.41 adds requirements for hard copies and leader lines. Clause 7.2 and 7.3 in ASME Y14.41 and BS ISO 16792, respectively, detail general requirements for annotations that are to be applied to the design model. These general requirements focus on associativity. Associativity defines the following relationships between digital elements.

- attributes, to capture additional information "that is not shown using geometry or in the model annotation" and can be available on demand
- annotation planes
- leader lines

- direction-dependent tolerances (ASME Y14.41) or specifications (BS ISO 16792)
- indicating limited application of a tolerance (ASME Y14.41) or indicating of restricted area (BS ISO 16792)
- query types which define the types of queries for which the model shall contain the information needed

In addition to these requirements, both standards have figures relating to each to visually inform the reader what is to be included in the model. With regards to drawing requirements, both standards refer the reader to a clause within each standard and additionally other British or ASME standards that specifically outline these requirements.

INTERNATIONAL STANDARDS

2.2.1 MBD Standards

ASME Y14 standards were established to guide individuals/companies through the product development process. ASME Y14.41 Digital Product Definition Data Practices was created in response to companies utilising CAD models and generating data for industrial purposes. The first version of ASME Y14.41 was issued in 2003 with immediate adoption across industries including the US Department of Defence. BS ISO 16792 is based on ASME Y14.41 and has continued to be revised in line with the revisions of the ASME equivalent. Both standards therefore follow a similar format, cover the same topics and reference equivalent standards. ASME Y14.41 is more self-contained than BS ISO 16792 in terms of detailing the process or recommendations explicitly, in comparison to BS ISO where an existing standard covering that topic is referred to and its recommendations highlighted.

Both ASME Y14.41 and BS ISO 16792 follow a similar format in terms of the topic of each clause. The requirements for the data set identification system are set out in clause 4 as well as how the data management system shall be structured and controlled. Both standards define a data set as providing a complete product definition, in that it contains an annotated model and related documentation. There are general recommendations, related data, and data management. “Data set identifiers” are described under general requirements. They are a combination of numeric, alphabetic, or special characters that are used to create a unique ID to identify the dataset. BS ISO 16792 refers to classification codes that can be used to identify the content of the data sets in clause 4.1; ASME Y14.41 refers the reader to ASME Y14.100. Both standards use a similar figure to describe the content of a product definition data set, however ASME Y14.41 has visually added the requirement for a “Model (PIN)” and “Drawing Graphic Sheet”.

The product definition is a collection of files and data that defines the physical and functional requirements of a product [1] [2]. These definitions highlight the importance of the data sets and the data contained within them; therefore, creators and users of this data need to be aware of what data is required and its importance to ensure the product definition is not lost. BS ISO 16792 differs from ASME Y14.41 in that it firstly defines “fundamental requirements” that are common to annotated models and drawings, models only, and drawings only that are accompanied with 3D models [2]. These fundamental requirements include resolved dimensions, ability to query a model, annotation requirements and planes. Both standards then describe "General model requirements" including the following sub clauses [1]:

- Associativity - the established relationship between digital elements
- Coordinate systems - representation of cartesian coordinate system in a product definition data set
- Applications of supplemental geometry - geometric elements that are not intended to represent a portion of an item but are included in product definition data to communicate design requirements
- Part features not fully modelled - part features that are shown using partial geometry definition, annotations, attributes, or a combination, i.e. a simplified version
- Assembly model completeness - a model in which the product definition is an assembly of two or more items
- Installation model completeness – a model where the product is an installation that shows parts or assemblies and partial or complete representation of the installation site

The "General method requirements" are defined in clause 5.3 for BS ISO 16792 and clause 5.2 in ASME Y14.41. These clauses describe the methods used to capture the product definition when it is contained within a model only or a model and drawing only. When the model contains the complete product definition, that is called the "Model-only Method". The following items shall be contained or referenced within the data set when using this method:

- Notes
- Parts lists
- Marking requirements
- Dimensions and tolerances
- Data set title
- Data set number [2]
- Data set identifier [1]
- Approval indicators and approval date
- Contract number when required
- Originator's name and date

The difference between the two standards in this clause are that the legal owner for the data set should be specified [2] and the "Design activity identification" and the "CAGE Code" shall be contained within the data set [1]. The "CAGE Code" is a code used to identify a Commercial and Government Entity.

Most of the requirements for "complete product definitions" are identical for both standards when they are presented in a model and drawing graphic sheet. In both standards, the annotation displayed on the drawing must be able to be interpreted without the use of a query, but in BS ISO 16792, an additional clause is added which adds an additional restriction that "except for model value queries to extract TED values". Furthermore, the model and drawing should be connected in a way that clearly identifies their relationship.

ASME Y14.41 added the following requirements for the “model and drawing graphic sheet” method:

“(j) Dimensions, tolerances, datum specifications, and notes on drawing graphic sheets may be shown in true profile views and refer to visible outlines or appear in axonometric views.
(k) The use of color is acceptable on drawing graphic sheets prepared by digital data files.”

Management Data, as referred to in ASME Y14.41 clause 5.3 and BS ISO 16792 clause 5.4, should contain the following where applicable:

- Application data
- Approval
- Data set identification
- Design activity transfer
- Revision history for the data set
- Reference to BS ISO 16792 or ASME Y14.42
- CAD-maintained notation
- Design activity identification
- Duplicate original notation
- Part or identifying number
- Unit of measurement (if other than millimetres) [2]; Metric/US Customary Notation [1]
- Navigation data
- “a definition of the original data and the content of the full data set; this can be the use of classification codes according to Annex B, or any other unambiguous indication” [2]

The Management Data that shall be contained within the data set and on the model.

If management data will be added to the model, ASME Y14.41 requires that it be added as an annotation plane. BS ISO 16792 does not specify a requirement for where the management data shall be placed. It is therefore important to define what standard is being followed when adding management data to a model.

Clause 5.4 and 5.5 of ASME Y14.41 and BS ISO 16792 define the requirements for “Protection marking” or “Security marking”, respectively. Both standards state that marking shall be placed in the file or in referenced documents, the requirements are applicable to models, and marking shall be placed on an annotation plane that shall not rotate with the model. ASME Y14.41 details requirements for models containing classified information or intellectual property of a company and if models require any government notices etc.

Another difference between the standards is how they describe the requirements for views on models. BS ISO 16792 refers the reader to ISO 128-3 but describes exceptions or additions to views on models in section 5.6. These exceptions or additions are focused on saved views and sectional views. ASME Y14.41 simply refers the reader to ASME Y14.3 without exceptions to additions. ASME Y14.3 provides requirements for orthographic views on drawings including sectional, auxiliary and multi views.

Clause 9 in both standards outlines the requirements for the data set concerning model values, and resolved, basic, size and limit dimensions. Both state that "all model values and resolved dimensions shall be obtained from the model" and outline different methods for obtaining these values. Requirements for attaching and displaying basic dimensions as per ASME Y14.41, TEDs as per BS ISO 16792, and size dimensions, which shall always include a tolerance, are described. BS ISO 16792 adds a caution to this requirement, because in using the system of coded size tolerances as per ISO 286-1 conflict can arise between the nominal size value and the nominal CAD geometry. ASME Y14.41 states that "basic dimensions not displayed on a drawing graphic sheet shall be obtained by querying of the model"; this statement is not mirrored in BS ISO 16792. The requirements for drawing graphic sheets in both standards refer to their presentation in axonometric views only. Axonometric views are a type of orthographic projection technique where the part is orientated to show features such as length, height, and depth by showing 3 faces.

Datum Applications are defined in clause 10 and clause 11 in BS ISO 16792 and ASME Y14.41, respectively. Datums are a point of reference used to measure the dimensions of a target, and these points can be a plane, straight line, or a point. In addition to model requirements for datums, the standards detail requirements for displaying datums on drawing graphic sheets in axonometric views. With regards to the application of datums, the requirements that are applicable to models are described in terms of the following.

- relationship between the datum reference frames on the model and coordinate systems
- identification of datum features and where these are placed on the model
- how to query datums
- requirements for identification and attachment of datum targets
- requirements when two or more features are combined to establish a datum

Although the standards follow the same topics and structure each in a similar way, one of the main differences are the included appendices. ASME Y14.41 includes Appendix I for reference only as the included material is being moved to ASME Y14.3. The appendix discusses exceptions or additions for views in models including when orthographic views are to be used and the requirements for axonometric views, with accompanying figures. BS ISO 16792 includes the following appendices.

- Annex A – Former practices for information only. This annex describes drawing indications that were included in a previous edition and why they have been removed from the current standard.
- Annex B – Classification codes for drawings and data sets for information only. The classification codes define what data shall be included within the drawing, data set or both, and whether the model, drawing or both define the complete product definition.
- Annex C – examples for information only. Each example provided shows how specifications are attached to 3D models and examples of query and response behaviour.

In conclusion, both standards cover the same topics and contain the same clauses but as previously discussed there are several differences specifically regarding additional clauses and additional standards that are referenced within each. It is important to be transparent with regards to what standards are being followed to ensure conformity of products and interoperability with other companies.

Referenced standards within MBD standards

The MBD standards detailed above reference various existing standards on the following topics:

- Geometric, dimensioning and tolerancing (GD&T)
- Engineering drawing practices
- Technical product documentation
- Document management

Although the referenced standards cover the same topic areas, they are not replicas of each other. It is therefore important to state what standards body is being followed.

When referencing these standards, both ASME Y14.41 and BS ISO 16792 state that only the dated standard shall apply but when no date is indicated than the latest version shall apply. In some cases, when only a portion of the standard applies, this would be outlined within the standard. ASME Y14.41 states that if there is a conflict between the referenced standard and the text of Y14.41, then Y14.41 takes precedence.

Table 1 - Standards referenced within ASME Y14.41:2019

Standard	Description
ASME Y14.1 – 2012	Decimal Inch Drawing Sheet Size and Format
ASME Y14.1M – 2012	Metric Drawing Sheet Size and Format
ASME Y14.2 – 2014	Line Conventions and Lettering
ASME Y14.3 – 2012	Multiview and Sectional View Drawings
ASME Y14.5 – 2018	Dimensioning and Tolerancing
ASME Y14.24 – 2012	Types and Applications of Engineering Drawings
ASME Y14.34 – 2014	Associated Lists
ASME Y14.35 – 2014	Revision of Engineering Drawings and Associated Documents
ASME Y14.38 – 2007	Abbreviations and Acronyms for Use on Drawings and Related Documents
ASME Y14.100 – 2017	Engineering Drawing Practices
IEEE/ASME SI 10 - 2016	Standard for Use of the International System of Units (SI): The Modern Metric System

Table 2 - Standards referenced within BS ISO 16792:2021

Standard	Description
ISO 128-2	Technical product definition (TPD) – General principles of representation – Part 2: Basic conventions for lines
ISO 128-3:2020	Technical product definition (TPD) – General principles of representation – Part 3: Views, sections, and cuts
ISO 129-1	Technical product definition (TPD) – Presentation of dimensions and tolerances – Part 1: General principles
ISO 1101	Geometrical product specifications (GPS) – Geometrical tolerancing – Tolerances of form, orientation, location and run-out
ISO 2553	Welding and allied processes – Symbolic representation on drawings – Welded joints
ISO 3098-1	Technical product documentation – Lettering – Part 1: General requirements
ISO 3098-5	Technical product documentation – Lettering – Part 5: CAD lettering of the Latin alphabet, numerals, and marks
ISO 5457	Technical product documentation – Sizes and layout of drawing sheets
ISO 5459	Geometrical product specifications (GPS) – Geometrical tolerancing – Datums and datum systems
ISO 7200	Technical product documentation – Data fields in title blocks and document headers
ISO 8015	Geometrical product specifications (GPS) – Fundamentals – Concepts, principles, and rules
ISO 10209:2012	Technical product documentation – Vocabulary – Terms relating to technical drawings, product definition and related documentation
ISO 11442	Technical product documentation – Document management
ISO 21920-1	Geometrical product specifications (GPS) – Surface texture: Profile – Part 1: Indication of surface texture
ISO 25178-1	Geometrical product specifications (GPS) – Surface texture: Areal – Part 1: Indication of surface texture
ISO 80000-1	Quantities and units – Part1: General
IEC 82045-2 (BS EN 82045)	Document management – Part 2: Metadata elements and information reference model

INTERNATIONAL DATA STANDARDS

The ISO 8000 family of global standards details the requirements for the transfer of data between different partners. It does so by establishing the concept of master data, identified by means of an unambiguous identifier detailing the version and the syntax (i.e., file type) that the data conforms to. The required syntax to access master data should be available to every involved partner. On master data becoming public, requirements for accessing it should be made clear. Particularly, ISO 8000-8 specifies prerequisites for measuring information and data quality when executed within processes and systems for quality management. This process is done on three quality levels: syntactic, semantic, and pragmatic. Rules for each quality level must be established between all involved partners, through collaboration and discussions, to ensure compliance with ISO 8000.
ISO 8000-110 further provides details on the notion of master data and its requirements. It additionally specifies that master data should comply with requirements that make it capable of being checked algorithmically by computer software by all partners involved. Semantic encoding is specified as a means for such and stipulates that:

- For each data dictionary entry that contains a supporting definition for the property value tuple, the entry is downloadable from the Internet. The data dictionary shall be downloadable free of charge under the term of its license for level 2 compliance.
- The data dictionary supports an application programming interface (API), available over the Internet, for resolution of an entity reference to the data dictionary entry that contains the supporting definitions. The reference shall be in the form of an unambiguous identifier. The API shall be usable free of charge under the terms of its license.
- The data dictionary entry that defines the supporting term is contained in the same data set as the property value tuple.
- Each property value tuple must include an unambiguous identifier that refers to a data dictionary entry which specifies the applicable properties.

In addition to the ISO 8000, ISO 11442 also specifies requirements for good data management of technical documents. It defines the features, such as ownership, of technical documents from its moment of creation to release, review and archival. An original document is defined as a document without any intentionally identified source and that is stored in storage archives with controlled access. A signature document comprises a document carrying a signature. Document replicas can consist of:

- Clones, which are exact copies with no data loss.
- Equivalents, which have some data loss, but for specific purposes are identical to the original.
- Essentials, which hold all necessary information to capture the purpose of the original document but have significative data loss.

Original documents should be committed, in trusted formats, to an archive master for long-term storage. When stored, original documents can be retired for revision or archived when redundant. Not every user should have authorisation to access a technical document at every stage in its design. Different users have access to documents during distinct stages of design:

- Users within the creator team can access original documents while at the "In preparation," "In review" and "Approved" stages.
- Normal users can access the original document when in the "Released" stage.
- On request access can be granted for original documents that are in the "Replaced" and "Withdrawn" stages.

Adequate rules for document revision must be predetermined and agreed upon by all partners and the document life cycle should be consistent across all platforms. International data standards are only defined by ISO conventions and no direct similar ASME standards exists.

2.3 GAP ANALYSIS OF STANDARDS

MBD Standards Landscape

Figure 2 below illustrates the current ISO (orange) and ASME (green) standards applied to key topics within MBD. Whilst these can successfully instruct the user on most aspects within their respective topics, this investigation did identify areas where more information is required to best ensure the frictionless adoption of MBD. In most areas where more information is required, existing standards can be utilised to bridge such gaps. These suggested standards for implementation have been highlighted in light blue. As stated in the previous section, a general data standard, analogous to the ISO 8000 family, does not exist for ASME. This has been highlighted in yellow in Figure 2. Future work may consider interactions with ASME working groups to formulate a new ASME standard which mirrors that of the ISO 8000 family, such that a general data standard for data management practices can be followed by collaborating partners operating under different standards bodies.

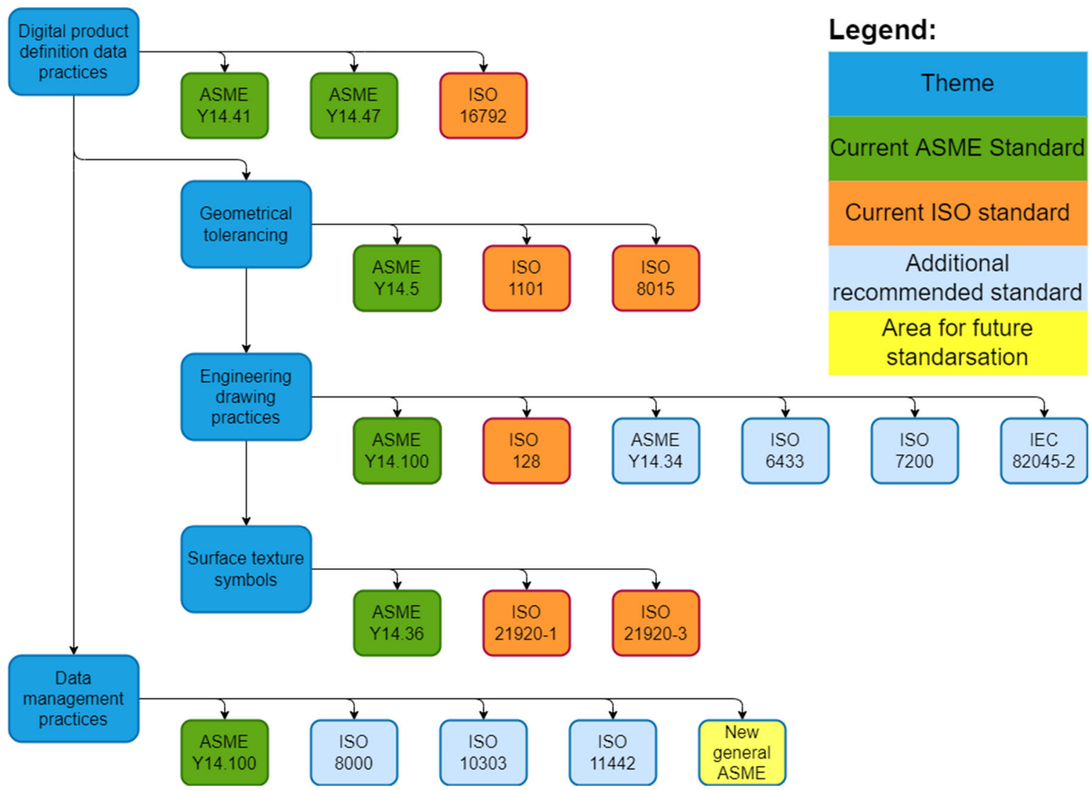

Figure 2 The standard landscape of an MBD system with recommendations and identified gaps

3 PRACTICAL RECOMMENDATIONS

3.1 MBD RECOMMENDATIONS

Section 2.2 highlights the importance of interoperability of data in that all systems that interact with a model must be able to read and extract the data required. The MBD model is defined as a “single source of truth” in that it contains all the information required to design, manufacture, and inspect the part. The data contained within the file is also required by the supply chain. The product definition created in systems such as PLM, PDM, or PIM, can be imported into Supply Chain Management software to feed information to sales & operations planning (S&OP) and materials requirements (MRP) software, and the manufacturing details contained within the file can feed production planning which details the manufacturing of the products in terms of the number and types of products, components, who will be the manufacturer, where will these be made, and what machinery is required [11]. The lack of effective interoperable data can affect the product quality, increase costs, and increase lead times if the data needs to be translated and verified by each system that requires it. When mapping out the adoption of MBD throughout a company, consideration must be given to the functions of the supply chain and what data they require to ensure lead times are met. Quotations for procurement can use the information contained within an MBD model or the data files associated with it. This information would typically be provided in a Technical Data Package (TDP) that would be given to potential suppliers for them to provide bids against [12]. The information from the TDP, contained within a MBD model, will not only inform the suppliers about the design and manufacture of the part but it will also inform them what machines, tooling, and raw materials are required and ultimately the cost of all these that will have to be included in their bid.

The benefits of using MBD are not only to the internal functions of a company to enable the production of a part, but also to its supply chain to ensure that procurement receive realistic quotations, lead times are reduced, materials requirements are accounted for in advance of production, and operations can be planned accordingly. If companies are adopting MBD, it is important for them to ensure their suppliers are using the same practices and/or the same software to ensure interoperability, and if they are not then this needs to be accounted for and possibly collaborating with them to ensure a seamless relationship.

3.2 DATA RECOMMENDATIONS

Due to the inexistence of an ASME data quality standard, it is recommended that entities that follow ASME sets of standards familiarise themselves with the existent ISO 8000 and ISO 11442 standards and utilise them to guide their data management and data quality practices. Doing so would increase the interoperability of work done in partnership with other entities which follow international data quality standards. In addition, it is proposed that the development and creation of an ASME standard, equivalent to the ISO 8000 series, be initiated.

Under the assumption that both leading industry partners will be utilising the same software package and transferring data files via a common application, that allows for internal document life-cycle management, no interoperability issues are expected to exist between the multiple internal departments of both leading partners if they both agree with the same definition for MBD and adhere to it.

The most vulnerable point where data loss is expected to occur is when external partners and/or suppliers require access to data present on the data exchange platform, which was provided by either of the leading partners. While data exchange platforms are designed to allow for suppliers to visualise and access data present in its system, even without direct access to proprietary software, the lack of such software may lead to suppliers needing to convert the original data files into formats they can work with.

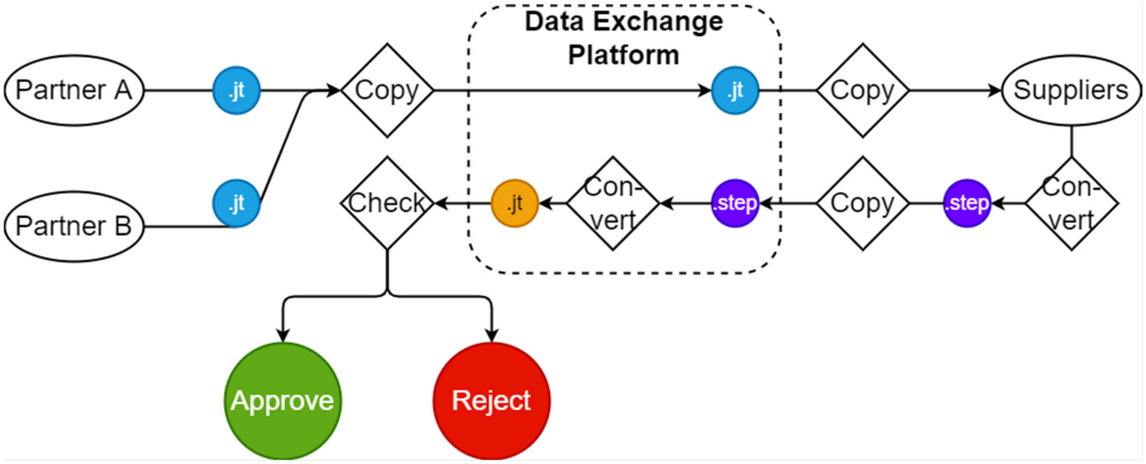

Figure 3 Proposed mechanism for data loss assessment of converted files retrieved by suppliers from the data exchange platform

It is our core recommendation that, to ensure accurate quantification of data loss, suppliers which have converted data files need to provide those files back into Teamcenter, so that they can be retrieved by the prime and verified, via software packages such as ITI CADIQ, to assess any data loss/degradation. The process, highlighted in Figure 2 for the conversion of an arbitrary JT file into a STEP file, is akin to a 2-factor authentication process: the converted file must be sent back to its origin and inspected for data loss, prior to it being utilised by the suppliers. The tolerances for data loss must be agreed in advance by both leading partners by establishing a set of minimum standards that all involved entities in the supply chain must adhere to. This allows for the classification of the converted file in accordance with ISO 11442 to determine its suitability to perform the required tasks. Depending on the requirements, data contained in the converted file can be deemed sufficient for the task to be performed without any constraints. In this case the process is approved. In the eventuality of the data contained in the converted file not being sufficient for the required task, the process is rejected. In the eventually of a file rejection, the supplier in question should be provided with training and tools required to adequately retrieve and handle data from its originating source. Should the supplier not comply with the minimum requirements established by leading partners, it will not be able to integrate with their supply chain.

4 CONCLUSION

To conclude, this report suggests that, for the proper implementation of MBD and to ensure adequate data flow in a common supply chain environment, the following measures should be taken:

- All leading industry partners must establish with each other what global standards, or parts of standards, they are following for their implementation of MBD practices. This process must be as transparent as possible to ensure conformity of products and interoperability with other companies. Additionally, benchmarking exercises aimed at identifying areas which areas require more investment from the partners to ensure a seamless supply chain integration can be undertaken.
- Minimal requirements for data handling and curation must also be agreed upon and established by the partners. This can be achieved by agreeing to utilise a common

data exchange platform, with an adequate data management plan in place. Said plan must be written and developed with input from all partners.

- Data quality and curation must be maintained in accordance with the developed data management plan, which establishes minimum requirements for data quality. These requirements should be in line with the ISO 8000 and ISO 11442 series of standards. An additional recommendation is that the development and creation of an equivalent ASME standard to the ISO 8000 and ISO 11442 series should be made to further facilitate the integration of companies following different Standards bodies.
- Third-party suppliers needing to be integrated into the supply chain must conform to the minimum set of requirements established by the leading partners. These requirements should comply with those followed by OEM's to ensure that they are aligned and understood, and where needed OEM-specific differences need to be adhered to by the suppliers. Data that has been retrieved and transformed by third party suppliers should be verified and any data loss or degradation quantified prior to any practical application. Third-party suppliers that fail to meet minimum requirements must update their internal structures to integrate with the supply chain, in a process that should be led by the leading partners.

Integration of multiple supply chains is not an easy task but is expected to be more easily achieved when leading partners establish and agree on a set of minimum standards before any practical action takes place. The proposed measures are aimed at facilitating that process to ensure an easier integration, and the inclusion of third-party suppliers.

5 REFERENCES

[1] "NSC MBE Maturity Index Issue A," Sandia National Laboratories, 5 April 2022. [Online]. Available: https://www.sandia.gov/mbit-mbe/2022/04/05/nsc-mbe-maturity-index-issue-a/. [Accessed 16 February 2023].

[2] S. Frechette, "Model Based Enterprise for Manufacturing," NIST.

[3] O. Wu, "A Solid 'STEP' Towards MBE:STEP 242," [Online]. Available: www.engineersrule.com/solid-step-towards-mbe-step-242.

[4] ASME, "Digital Product Definition Data Practices - Engineering Drawing and Related Documentation Practices," ASME, 2012.

[5] BS-ISO, "Technical product documentation — Digital product definition data practices," BS-ISO, 2021.

[6] iBASEt, Enabling the Digital Thread, iBASEt, 2019.

[7] Lifecycle insights, *Realising value from MBD initiatives.*

[8] C. Jackson, "How Procurement uses Model-Based Definition (MBD)," [Online]. Available: https://www.lifecycleinsights.com/tech-guide/procurement-uses-model-based-definition/. [Accessed 29 November 2022].

[9] GD&T Basics, "Basic Dimensions and How to Report," [Online]. Available: https://www.gdandtbasics.com/reporting-basic-dimensions/. [Accessed 29 November 2022].

[10] K. Z. N. H. T. H. J. A. B. F. S. Ruemier, “Promoting Model-Based Definition to Establish a complete Product Definition,” *Journal of Manufacturing Science and Engineering,* vol. 139, no. 5, 2016.

[11] N. H. T. H. A. B. F. J. A. Miller, “Towards identifying the elements of a minimum information model for use in a model-based definition,” in *International Manufacturing Science and Engineering Conference*, Los Angeles, 2017.

[12] C. Tagetik, “Supply Chain Planning Process Flow: The Importance of MPS, MRP, and DRP,” [Online]. Available: https://www.wolterskluwer.com/en/expert-insights/mps-mrp-drp-help-supply-chains. [Accessed 29 November 2022].

[13] E. S. A. A.-A. K. Goher, “Model-Based Definition and Enterprise: State-of-the-art and future trends,” *Institution of Mechanical Engineers,* vol. 235, no. Special Issue, pp. 2288-2299, 2020.

6 APPENDIX

6.1 MBD BENCHMARKING QUESTIONNAIRE

A questionnaire was created to understand how both partners are adopting MBD practices and how they capture and use data. The questionnaire uses questions from the NSE MBE Maturity Index [1], which was created to allow organisations to assess themselves as an MBE. The levels defined within the index are shown in Figure 4 NSE MBE Maturity Index. The questions focus on design activities, product data management, manufacturing activities, quality, and enterprise enabling. One reason for adopting and using MBD practices is that all data required to design, plan for manufacture, manufacture, inspect, certify, and ensure adherence to quality procedures, should be contained within the model and data set. Any changes should trigger a change or a notification on a file that data within it has changed to ensure traceability throughout the organisation.

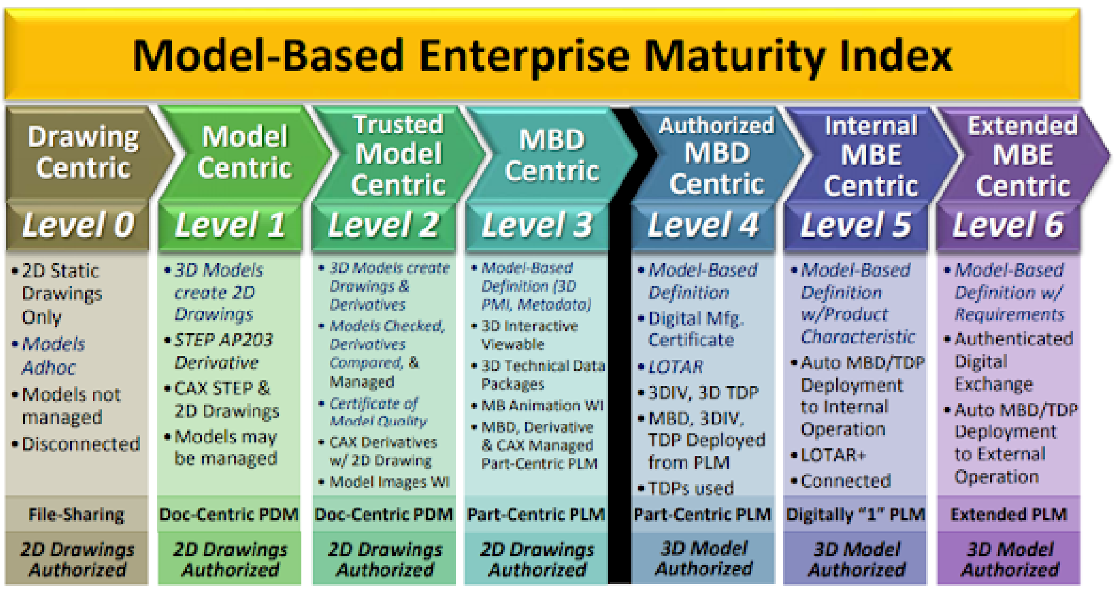

Figure 4 NSE MBE Maturity Index

6.2 DESIGN ACTIVITIES

The questions relating to design activities determine what activities are involved in designing a product and as an organisation's maturity in the MBE process grows, the product definition will become a trusted model-based definition dataset. Most answers provided for this section are of level 4. Level 4 is defined as being an "Authorised MBD Centric" with authorised 3D models and uses a Part Centric PLM.

Both partners have answered that the MBD model with supporting documents is defined as the product authority within the company. If the model is the product authority that should be the "single source of truth" for the part. If the model is the "single source of truth" it should contain all the information required to design, manufacture, procure materials/parts, inspect, ensure adherence to quality processes and procedures. However, based on the results of the other questions provided by both partners, it appears that even if the model contains all this information, it is not accessible or being used in its native format by other functions within the company. The areas where more attention is required are having the product requirements in digital form, having the product requirements connected to product definition and how non-shape PMI is made visible and available.

Both partners have stated that the product requirements of their parts are stored in electronic form. Information being in an electronic form does not necessarily mean digital. Digital with regards to MBD means that the product requirements are stored within the data set. Electronic could mean the information is contained in a file of various formats on a network so that it available to all. However, to be MBD ready, this information should be available in a data set that can be accessed and read by all who require it. With regards to non-shape PMI, it is important to ensure that the annotations and notes that are added are linked to a feature or geometry of the model and compliant with ISO 1101 and ASME Y14.5 standards. If annotations and notes are not linked then when that feature or geometry changes, they will not be updated, therefore human intervention is required to update these, negating the point of using MBD in first instance. This process will add time and cost to the project. Using only manual checks to verify the model quality and certification shows a disconnect between functions within the company. An MBD model enables the verification of the model quality and certification, therefore completing these tasks manually loses some of the traceability of the data and increases the times for these functions as someone must interrogate the model to determine the features that are required to be checked, then checking them, then reporting the findings.

6.3 PRODUCT DATA MANAGEMENT

The questions related to product data management focus on activities that interrelate product data. Overall, one of the partners is fairly MBD capable regarding product Data Management, however areas of improvement include linking the design authority as part of the metadata in their part centric PDM system. Lack of integration between different functions within the company and leads to a loss of traceable data. On the other hand, the remaining partner stated that they are linked by electronic textual references. This shows a lack of integration between different functions within the company and leads to a loss of traceable data.

If the MBD model is seen as the product authority, then it should be explicitly linked to all other authoritative sources related to that part. Existing CM systems should be linked to the PDM to ensure traceability of data. A change management system should be in place to capture changes to documents, processes, any information related to a part or process, if changes are being made to any data held within the PDM, then the change process needs to be linked to enable traceability.

6.4 MANUFACTURING ACTIVITIES

Activities involved in manufacturing a product are the focus of the questions in this section. Given the scoring of both partners on this section, a disconnect between engineering activities and manufacturing activities is unlikely but possible. As a rule of thumb for MBD-enabled enterprises, work instructions should be consumed by the manufacturing function of the company in the same format they were provided in (i.e. conversion of 3D models to 2D should be avoided). Both partners also stated that procurement data packages are managed and delivered both to internal or external functions via disconnected electronic file directories and email. The MBD standards, ASME Y14.41 and BS ISO 16792, provide recommendations for transferring and sending data sets while ensuring that traceability of associated metadata is not compromised.

Additionally, some of the questions where it has been asked how manufacturing instructions or codes are updated if there is a change in the process or product definition have highlighted that these are done via procedural notifications. This means that updates are not automatic but there will be a notification that a related document or data has been changed. A notification does not mean that a change will be made to the associated document or procedure if it is not an automated process. Therefore in the case of work instructions or manufacturing codes the part could be made incorrectly resulting in further delays and costs for rework or scraping the part.

6.5 QUALITY ACTIVITIES

The questions related to quality activities focused on manufacturing verification, testing, inspection, and product acceptance, and how the information contained within the 3D model and data set is used.

Answers provided by both partners indicate that they have formalised their model-based definition with semantic PMI included in their models, with respect to how quality procedures and instructions use this information it is very much disconnected from the processes. The documentation created for test, measurement, inspection, etc. use images of models but the documents are not linked to the product definition, therefore any changes within the product definition do not trigger an automatic change in the documentation, but only triggers a notification that a change has been made and then the update would have to be completed manually.

Many of the answers to the questions stated 2D or 3D drawings, textural references, photographs, documents when answering how quality process definitions, inspection plans, work instructions are generated. Again, this shows a disconnect between functions within the company. If using MBD across an organisation then all this information could be found within the 3D model and data set, therefore their creation would be simpler and quicker and any changes to the source data could automatically update the documents.

6.6 CONCLUSIONS

Although both partners use 3D models and electronic systems such as PDM, based on the levels within the questionnaire they have not fully adopted MBD practices in all areas. If the 3D model is the product authority, then it should contain all information required for all other departments to complete their tasks or processes. The important factor in adopting MBD is traceability. The 3D model and associated data set should be the “single source of truth” and the data used by other departments within the company should be traceable back to it. If the data is changed further down the chain, that change should be reflected in documents/files/data sets that use that information.

Generally speaking they both possess all the necessary tools and infrastructure to fully adopt MBD, with the main barrier to implementation being on the disconnect between different functions of their respective enterprises. Other results previously discussed show that are in the process of adopting MBE practices and technology. This is not a process that can be implemented across an organisation in a short time, and they have advised that with regards to MBD they are implementing it in areas within the company and developing the capability before it can be adopted across the organisation. Currently a lot of the software/systems used are not connected and there is still a lot of manual updates that are being done. In order to adopt MBD practices these systems need to be more interconnected and linked to be able to capture all of the data required for all the departments within the company and ensure traceability.