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Digital transformation through Model Based definition (MBD) –

An Industry product life cycle perspective

A thesis

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Industrial Asset management

By

Abdulkader Mohamed Jawahir

Abstract

Due to technological advancements, the human lifestyle is keep changing with respect to the consumption of modern equipment's and it is inevitable to catchup with the trends. For example, touch screen phones made a big game change in the consumption of mobile phones and its usage. Right after the invention of smart phones, the mobile phones are almost replacing many extra equipment's and gadgets and even computers right now. Similarly, engineering trend like virtual reality, model centric manufacturing, artificial intelligence ...etc are demanding the way of engineering design to move towards model centric MBD and make the model as a Master of truth.

Even though there are many initiatives towards model-centric engineering, many of the industries and their manufacturing are still using 2D drawings due to easy handling and traditional inspection and so on. But to achieve and ready for the industry vision of digital twins, digitalization and IoT, allocate 3D models as a single source of truth is an absolute necessary. This is a paradigm shift to many industries especially the OFE sectors as well.

The goal of this project was to demonstrate the possibility and steps to implement with MBD based 3D models from design phase, to various life cycle stage of the enterprise till the model-centric CAD-to-CAM and CAD-to-CMM data interoperability in the company by taking an example test part. Also, to create implementation steps to help making guideline document in future for the organization in addition with the MBD quality checklist creation.

It is understood that the industry is ready for the MBD implementation with few additional workflows, trainings, guideline document enforcements added with some extra investments. The thesis also lists the expected benefits, practical challenges, lessions learnt and future scope in the MBD and digitalization area. The study company is Baker Hughes a full stream oil field equipment company. Finally, as part of study, there are lessions learnt in the area of digitalization, MBD, organizational behaviours, leadership interpersonal skills and asset management topics.

Acknowledgment

This report is my almost final step towards completion of master's degree in Industrial Asset Management at University of Stavanger. I will need to take one last subject during Spring of 2020. I am very happy that I decided to start my master's program in 2017. The program has given me a broader perspective in many subjects which will be useful in my private and professional life.

I would like to thank Professor Jayantha. P. Liyanage from the University of Stavanger for his guidance and advises that helped me to structure my thoughts and deliver this thesis.

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I thank my manager David Artime Fernandez and department head Kamran David Fatehi for supporting my thesis work by being understanding and kind to me.

I am especially grateful for all the support that I got from my wife Mohamed Hafza. Her care and patience have been a true source of motivation. Thank you for taking care of our family while I was busy with this thesis.

At Last, I owe everything and dedicate this thesis to my parents at India, Jasima Begum and Mohamed Jawahir. They both held my hand during my first step as a kid and since then never left it. Thanks for making me what I am today.

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Abbreviations

2D	Two dimension
3D	Three dimension
BH	Baker Hughes
BSI	British Standards Institution
Company	OFE sector of Baker Hughes
CMM	Co-ordinate measuring machine
CAD	computer aided design
CAM	Computer Aided Manufacturing
DAM	Digital Asset Management
IAM	Institute of Asset Management
IP	Intellectual Property
ISO	International Organization for Standardization
ICT	Information and Communication Technology
MBD	Model Based Definition
MBE	Model based engineering
NIST	National Institute of Standards and Technology
OFE	Oil field Equipment
OEM	Own equipment manufacturer
PAS	Publicly Available Specification
PMI	Product Manufacturing Information
QC	Quality control
SA	Spatial Analyser
SME	Small and medium scale enterprises

1. Introduction

1.1. Background

In modernization era, due to the technological advancements, there is an absolute need for continuous upgradation in the modern equipment's and it is inevitable to catchup with the trends. The sole goal of developing and improving digital asset is to empower the competitive advantage. Constant aim for the competitive advantage in the world accelerated the development of ICT and led to a new trend called "digital transformation". Nowadays every single piece of information, including knowledge, competence and intellectual property, is being created in a digital format to make it direct consumption.

For example, touch based mobile phones made a huge change in the consumption of mobile phones and its usage. The mobile phones are initially replacing the old-fashioned telephones before the touch phone invention. Right after the touch phones, the mobile phones are almost replacing many extra equipment's and gadgets and even computers right now. Same issue will be applicable to engineering. Engineering trend like virtual reality, model centric manufacturing, artificial intelligence ...etc are demanding the way of engineering design to move towards model centric MBD instead of 2D drawing based manufacturing.

Keeping this in mind, we can understand the need to upgrade every industry moving towards digital twin and enable the organization to ready for the data analytical capability by data science and big data. With a supported hypothesis, I believe this thesis will motivate the Industries to move towards the vision of the digitalization through Model Based Enterprise.

The thesis topic is chosen in the engineering design field due to the potential digitalization possibilities with CAD/CAM interoperability and the booming MBD technology. Currently, Avionics and research Industries are started to adopt and however many large scale and medium scale industries are started to initiate this and even though they still using the conventional 2D based drawings as engineering delivery.

The traditional method of design for manufacturing is using 2D drawings on their engineering assets and printed for the consumption across various product life cycle stages of the industry from concept development until service stage of the product. Even through the 3D models are being designed, assembled and analysed, still the manufacturing information of those 3D models are attached with 2D drawings for the documentation and control. In every

mechanical design, typically, 3D models are created initially as part of concept development and assembled and virtual checked against various design intends. 2D drawings are developed from the 3D model to create manufacturing information and relevant annotations. This does not have a direct link except the driving dimensions. So, the information is not completely relied on 3D model, but it is also relied on the 2D drawings attached with that. So, this ends up with two sources of truth, one is 3D model and the second one is 2D drawing attached with this.

Companies use PLM programs to handle their engineering drawings and a use 3D modelling software for the design. The PLM program interface with design, visualization till the manufacturing. Industries need to get their asset digitally ready for the digitalization, they need the existing 2D based drawings to be replaced by 3D models with product manufacturing information (PMI). This can be achieved by model-based definition (MBD) of the 3D models. So, MBD is making the 3D model as single source of truth and making the model as "Master" instead of having both model and drawings for the consumption.

Part of thesis, an example industry is identified who use the design practice widely, learn from various processes, demonstrate the MBD implementation possibility. The expected advantages from this thesis report is,

- MBD overview and how this helps in automation in mechanical industries
- Demonstrate the MBD implementation possibility
- Set this report as a basis for developing the guidelines and design checklist
- Lessons learnt on the topic
- Explain the need of digitalization and catchup with trend
- Digital integration between life cycle of engineering till quality check
- Emphasis the need of less manual interruption for increase in quality
- Understand the literature related to digital assets and MBD

While organizations utilize the guidance and requirements of typical ISO and ASME standards for 2D drawings, the condition of their 3D model PMI practices is still on development. NIST is coming up "International standard of Standards Based Design to manufacturing & quality in supply chain" NIST.GCR.15-1009 (2016), this is used as a reference for the MBD implementation these days.

1.2. Aim of Thesis

To solve the two sources of truth 3D model and 2D drawings for manufacturing, MBD has been developed and gaining popular among various 3D programs as this reduce the two sources of truth into single source of truth. In this, 3D model becomes the "Master" of information which can be directly consumed in every product life cycle stage of the enterprise. The challenge here is to shift the paradigm from 2D drawing based manufacturing into 3D model based and to ensure the 3D model with MBD can be consumed throughout the product life cycle stages of the Industry and practical challenges to implement it in the industry steps from engineering design, virtual validation, data management, and data inter-operability between manufacturing (CAM) and measurement (CMM).

The aim of the study thesis is to check the possibilities of implementing MBD based 3D model by building a test model based on the MBD practices and do a pilot check on different life cycle stages from design phase, lifecycle management stage, visualization, validation and till the model-centric CAD-to-CAM and CAD-to-CMM data interoperability in an example Industry. Also, to list the implementation steps which can be referred during the future development of guidelines document in the industry in addition with an example MBD design checklist. Every possibility in each stage of the product life cycle and practical challenges, future scope towards the MBD based implementation due to the various reasons will be captured.

As a part of the thesis work, the subjects of MBD and digitalization practices to be explored by an extensive review of books, literatures, internet and meetings with various leaders, sub-suppliers and experts in the example industry. NIST (2016) standard can be used as a reference for the detail evaluation. An example Industry relevant to the MBD and design processes to be chosen. However, the outcome of the study to be as generic as possible to fit to other industries.

Finally, as this thesis is part of the learning program, the aim is to learn the asset management topics, digitization, Organizations and their practical aspects, research skills towards the implementations, understand the MBD and design practices and Interpersonal leadership skills.

1.3. Scope of Work

As the thesis is part of master's program the ultimate scope is to learn & study by doing practical aspects of the literatures we leant. The scope of work is listed below,

- To learn and understand the application of the literatures including various assets, Industrial asset management, digital asset management, digitalization practices, engineering assets including 2D and 3D models, Model Based definition techniques and product life cycle management. Also, to conduct a detailed study of various standards like NIST (2016) and review and extract the frameworks those can be used in the organization as a reference document

- Identify and choose an Industry with similar practices of the title to do a pilot application of the MBD implementation towards a practical assessment. Also, to understand the topic, learn the company, its overview of business, the need for improvements and the process steps to prepare the practical application. In detail, study the product life cycle stages and how this has been managed in the organization.

- Define the scope, prepare an implementation strategy, develop a concept and a plan by means of road map or process flow block diagrams for the successful implementation. By doing this to understand, how the MBD practices can help to operate the data from definition until model-based engineering MBE methodologies.

- The practical application of the study is to conduct MBD implementation possibilities across various product life cycle stages and create implementation steps to help making guideline document in future for the organization. Also create an example checklist.

- Evaluate the application measures, list the benefits and practical challenges to improve the existing process for the successful implementation. Also, list the scope for future study as a continuation of the thesis for improvements in the MBD implementation.

1.4. Thesis Structure

Thesis will be structured as below chapters,

1) Introduction to this thesis is provided in Abstract and Chapter 1 "Introduction". The goal of these sections is to provide broader understanding and background information of the problem that leads to the study and research.

2) Chapter 2 "Digital asset and MBD – Literature review" elaborates the related literatures of the assets in general, digital assets, 3D models, MBD and digital asset management techniques as these topics to be broadly understood before proceeding the study. A broader review of the academic and company-based materials, and internet sources is reflected in.

3) Chapters 4 "Status quo – OFE industries" identifies the example industry, the current engineering design and PLM processes to cover a broader understanding of how the complex engineering industries are operating and using the engineering assets like drawings and 3D models. Individual sections are assigned to elaborate the description of drawings, 3D models and PLM. Chapter 5, "Business drivers for MBD" has been added based on the request from Digital head helps to identify the drivers and reason of every industries to move towards the MBD implementation.

4) Chapter 6 "MBD Implementation strategy & approach" focuses the principle, technical aspects of MBD techniques and how to implement the PMI information in the 3D models. This section also included with MBD framework, developed a concept for implementation and road map for planning.

5) Chapters 7 covers "Demonstration of MBD Implementation – test part" To assess the MBD implementation in the example company, a test part is developed with MBD and trail run to be conducted across various product life cycle stages of the company. The steps explained in this section must be referenced for the organizations guideline document which has to be built later stage.

6) Chapters 7 "Industry Application and improvement" recommends the application measures to be carried out for the successful implementation with future study scope.

7) Chapters 8 "Discussion" and 9 "Conclusions" are the final chapter of this thesis. Discussion section contains an executive overview what was done with the implementation, lessions learnt, practical challenges during thesis and future work recommended. Chapter 8 "Conclusion section" provides final remarks and a short conclusion with regards to the content of this thesis.

1.5.Methodology:

To carry out this project, relevant information from different sources will be collected and analysed. The information's are majorly based on meeting from digitalization head, digital support team, Creo technical support team, CNC / CMM software team, attended Webinar session from MBD, International standard NIST, academic literatures from IAM subject from University of Stavanger, PTC webpage, Journals, presentations from Digitalization team, internet databases and also based on my experience in 15+ years in Creo based engineering design. Some information is also collected from company process documentations from Agility page and internal database documents. There are thorough discussions with my supervisor at the University of Stavanger. Refer also Appendix E

The data about MBD implementation from NIST standard has been plotted into process flow and the report is based on the process steps listed in there. Refer MBD implementation strategy section. Creo techniques with semantic references are implemented into the 3D models and tested for the appropriate results.

The results are quality checked against the CMM and CNC programs with the specific CMM team from UK and CNC GibbsCAM software team from various parts of the BH unit. Improvements and guidelines are listed in the MBD implementation steps section and expected benefits in terms of hours are estimated in the benefits section. Further queries and improvements are listed in the Appendix section.

1.6.Limitations:

The MBD topic is kind of a new and latest trend to many industries. Oil field equipment companies often using the sub-vendor organizations for most of their projects and often they use small quantities of the equipment to be installed in a particular oil field. Small vendors are not fully ready to cope up with the Oil and Gas companies with respect to their digital capability.

As the OFE equipment are designed for a long-time design and service life, there was enormous amount of legacy / old drawings those must be converted into MBD models which is a bit time consuming process and it involved cost and time. However, the new products can simply adopt to the MBD implementation.

Tools to be used for MBD implementation always comes with an interface software's which is not an easy fix solution and it involves cost and time.

As MBD is a new technique with less guideline documents and less experts around the corner, it is taking enormous time to gain enough knowledge during implementation.

Due to multi-national set up of the complex organizations, not every sub-section of the organization used the same software program and platform on their processes. For example, some unit in Brazil works with SAP as a PLM tool and some unit in India operates with Oracle as their PLM tool. This needs an interface software to have a leaner communication flow between various departments.

Finally, due to COVID / Corona Virus situation, many of our workshop are having limited physical access for the MBD study and implementation. Also, CMM machine shop is not operating full time, in house CNC machine shops are not allowed for external personal except the foreman, and our sub-vendors are fully busy with the regular projects on few machines due to shifts. Also due to the change in work timings, less availability and workforce issues the response time was predominantly slow which was affected the in-depth of check of MBD implementation possibilities in the PCDIM, CMM and CNC machines except the relying on the information from software's.

2. Digital Asset & MBD – Literature review

As the intended topic of the thesis is part of asset management subject, it is inevitable to understand briefly about the assets, its management and digitalization of those assets.

2.1. Asset Introduction

By reviewing the definition of asset in Oxford dictionary (OED, 2007) one can conclude that an asset is anything that has a value to a person and an organization throughout the life of this asset. The asset life extends from its starting or creation till the end of the life cycle of those assets. The value of an asset can be defined in monetary units, depending on the price that it can be sold for or by asset's ability to produce value to its owners.

ISO 55000 (2014) defines asset type to be grouping of assets with common characteristics that distinguish those assets as a group or class, and provides examples of assets such as information assets, intangible assets, critical assets, enabling assets, linear assets, information and communications technology assets, infrastructure assets, moveable assets.

- Assets can be tangible or intangible. Tangible assets are assets that have physical existence and can be seen and touched. Tangible assets are also called physical assets. Typical examples of tangible assets are infrastructures, machines, cash, office space, workshop etc. Intangible assets are assets that do not have physical existence and typical examples are digital assets, intellectual property, knowledge, data base of materials etc.

- Business operation decides the assets to be operating or non-operating assets. Assets that are used during daily operations and generate cash flow are called operating assets. Typical examples of operating assets are cash, building, machinery, equipment, etc. Non-Operating assets are assets that usually generate income but are not used daily. Examples of non-operating assets are vacant land, stored data, warehouse, spare parts etc.

2.1.1. Physical Assets

Physical assets are the assets that can be physically sensed like seen and touched. Amadi-Echendu (2010. p.348) describes the physical assets into four categories as below,

- Equipment and machinery
- Infrastructure and buildings
- Furniture and office spaces
- Information technology

Most organizations rely on their physical assets, where infrastructures and office space are needed to accommodate employees and equipment; machinery is needed to ensure delivery of the products and services.

Amadi-Echendu (2010, p. 348), highlights that the lifecycle of a physical asset goes through 4 phases from creation to utilization. Need for an asset initiates the creation phase. During creation phase the concept of the asset will be developed, feasibility will be confirmed, and engineering activities will be conducted. Establishment phase consists of procurement of the components, construction and commissioning of the assembly. During exploitation phase assets will be operating and will be maintained. The last phase of the asset lifecycle is the termination and disposal of the asset.

When BSI PASS 55 was developed, there was significant discussion about the interdependencies between not just different physical assets within operational systems but also between physical and other assets classes such as financial assets, human assets, information, intellectual property and reputation, refer Figure 2-1
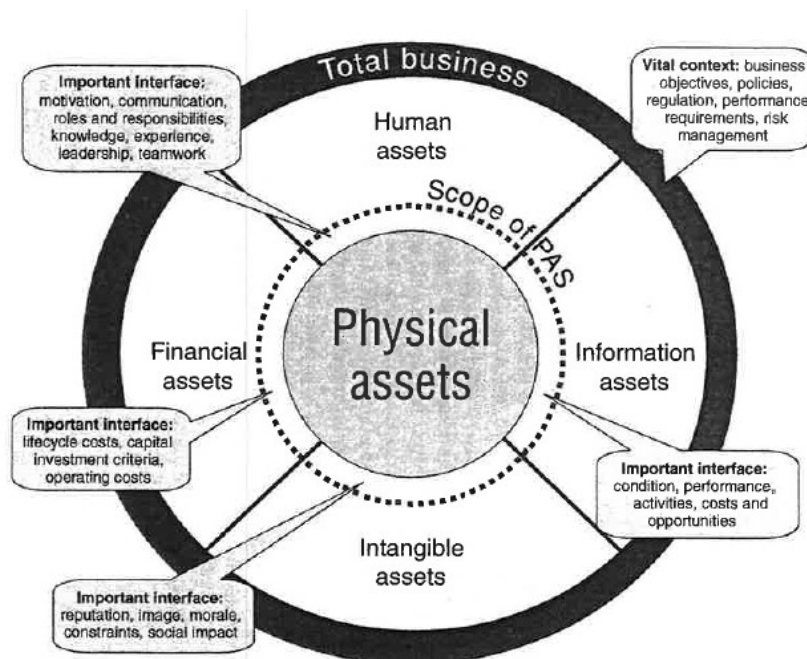
Figure 2-1 Asset types within organization (courtesy: Woodhouse, J., 2010, p215)

2.1.2. Digital Assets

A digital asset is a digital entity owned by an individual or company. Examples include digital photos, videos, and songs. These assets are not tangible, meaning they have no physical presence. Instead, they are files that reside on storage device, such as a local computer or a cloud-based storage network (Techterms.com, 2020)
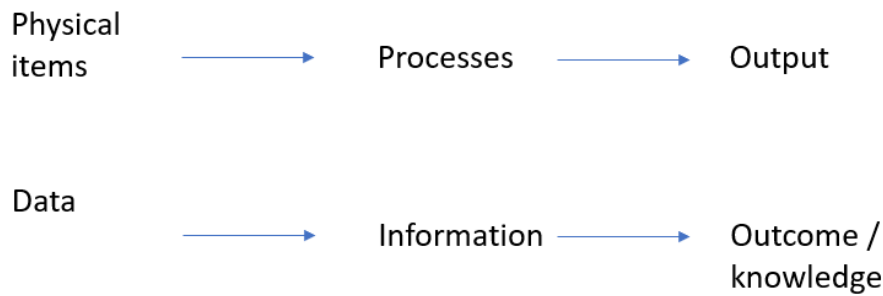
In accordance with Digitalassetmanagement.com (2015), lifecycle of a digital asset goes through 4 stages:

- Creation where organization defines need for assets, generates ideas, for example, about the content of the digital asset, plans timelines and develops assets. For example, when an organization develops new products or services, it needs to define what kind of digital assets, such as design drawings, 3D models and operational documents, will be produced; agree about content and the structure of the documents, layout of the drawings and 3D models; define timelines that are in accordance with project needs; and start producing assets.

- Management where the quality of the digital asset needs to be verified and asset released for use

- Distribution is when assets are finally uploaded to the tools and systems so the whole organization can be accessing the assets.

- Preservation when asset is being kept in the database for future use and revision.

It is important to highlight that, the relevancy of the lifecycle definition may be limited to media files such as photo and video files, 2D and 3D models, and documents.

In the thesis topic, the digital asset includes 2D drawings, drawing software licenses, STEP and 3D model files, digital approvals, other software include specification information's, material data and life cycle database and so on.

2.2.Engineering assets – Design perspective

Engineering assets are more than a physical thing. It is part of relationship between an object and an entity and a value is attached to the object by the entity. We consider these three aspects of an asset in turn (Amadi-Echendu, J., 2010, p8). Typical example for this is engineering drawings, specifications and 3D models...etc. Engineering specifications and geometrical information

containing dimensions and tolerances, geometrical tolerances, material specifications, NDT specifications, welding information ...etc are described in drawings for any specific part.

Engineering assets objects can therefore be likened to be base of a pyramid structure on which all other asset objects rest, as visualized in below figure. Above the base of the pyramid are various levels of financial asset objects that can in principle be created at will. Everything above the base of the pyramid is a financial asset objects and other are constructed in. Only the foundation of pyramid engineering asset is subject matter of the engineering asset here (Amadi-Echendu, J., 2010, p8).

The topic of the thesis involved the **engineering design items** including 3D models and 2D drawing and those are elaborated with suitable example in the below section.
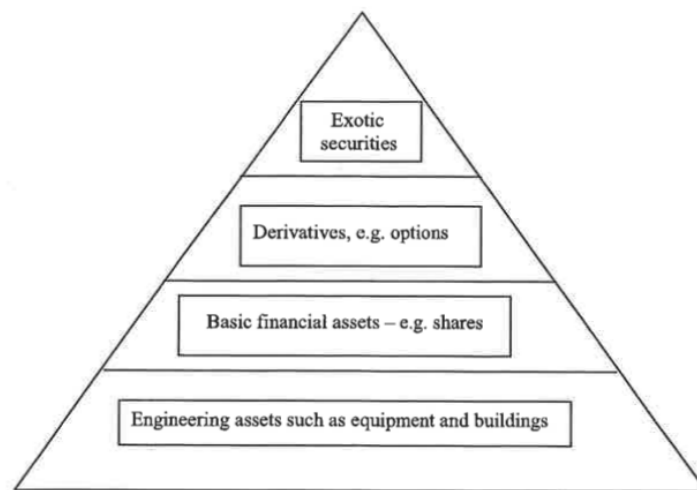
Figure 2-2 Engineering asset pyramid (courtesy: Amadi-Echendu, J., 2010, p9)

2.2.1. 2D Drawings

An engineering drawing is a technical drawing that is used to convey information about an object. A common use is to specify the geometry necessary for the construction of a component and is called a detail drawing. Usually, a number of drawings are necessary to completely specify even a simple component. The drawings are linked together by a master drawing or assembly drawing which gives the drawing numbers of the subsequent detailed components, quantities required, construction materials and possibly 3D images that can be used to locate individual items. Although mostly consisting of pictographic representations, abbreviations and symbols are used for brevity and additional textual explanations may also be provided to convey the necessary information (Basant Agrawal & C M Agrawal, 2013)
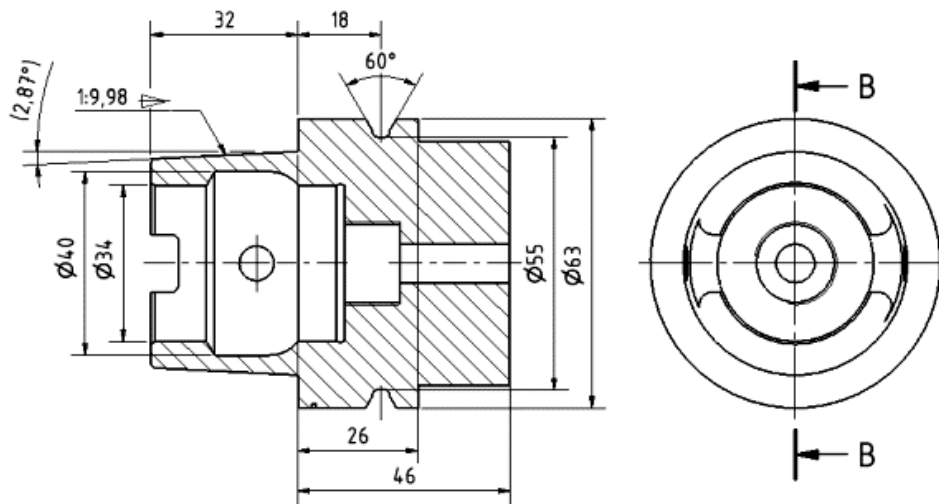
Figure 2-3 Engineering drawing (courtesy: Wikipedia)

2.2.2. 3D models

Three-dimensional (3D) models represent a physical body using a collection of points in 3D space, connected by various geometric entities such as triangles, lines, curved surfaces, etc. Being a collection of data (points and other information), 3D models can be created manually, algorithmically (procedural modelling), or by scanning. Their surfaces may be further defined with texture mapping.

3D models are widely used anywhere in 3D graphics and CAD. Their use predates the widespread use of 3D graphics on personal computers. Many computer games used pre-rendered images of 3D models as sprites before computers could render them in real-time. The designer can then see the model in various directions and views, this can help the designer see if the object is created as intended to compare with their original vision. Seeing the design this way can help the designer or company figure out changes or improvements needed to the product (Brighthub Engineering, 2020)

2.2.3. Product Manufacturing Information (PMI):

The geometrical information and shape of the component must contain the relevant information as listed below to assist the manufacturing to be able to manufacture and quality check. This data is called product manufacturing information (PMI) those are inbuilt in the 3D model itself. Those are,

❖ Dimensions
❖ Tolerances

❖ Annotations

❖ Datum planes

❖ Geometrical tolerances

❖ Material information

❖ Surface finish

❖ Welding symbols

❖ Marking data

❖ Coating information

❖ NDT

❖ Other manufacturing notes

2.3. MBD Software programs:

There are many commercial versions of 3D engineering modelling software's available in market. Examples such as Creo, Unigraphics, Inventor, CATIA, Solid works and MicroStation and so on. Any software can be chosen for the MBD implementation as long as the tool is embedded with this concept.

Creo:

Creo (previously Pro/Engineer) is already started implementing MDB framework in their commercial versions. PTC based Creo 4.0 software is enriched with MBD support functions. The important factor on the software is to facilitate the PMI understandable with the geometry so that the machine can understand. To enable this, Creo 4.0 has the recent "Semantic query" option which can be considered to check the PMI with machine reading capacity.

Teamcenter:

Siemens based Teamcenter program is widely used many companies for the product life cycle management. This program stores and consumes the 3D models and drawings directly in the PLM software and helps the organization to handle product and its part number. The created 3D models cannot be directly stored into Teamcenter as the Creo and Teamcenter don't have direct interacting facility. To enable this IPEM program helps and acts as an interface between these programs. IPEM is the interfacing program which helps to save the models and drawings to check-in into the PLM program. Teamcenter is more model friendly compared to other PLM software's.

2.4.Model Based definition - Introduction

MBD is a process by which designers embed all the necessary product manufacturing information directly in their 3D models, where everyone can access or consume the same data throughout the product life cycle (PTC corporation, 2020)

MBD is about making the 3D model as a "MASTER" with all the product manufacturing information embedded within the 3D model to make as a "single source of truth"
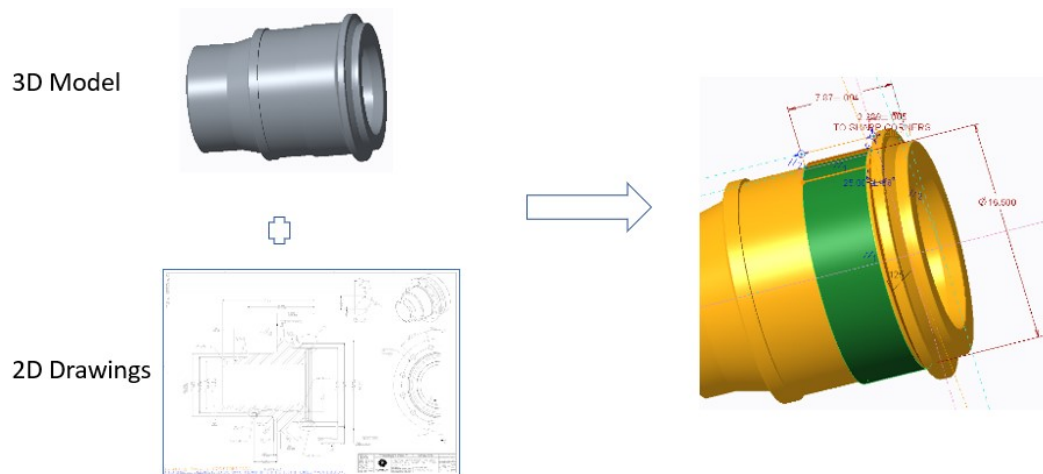
Figure 2-4 3D model with PMI

Based on NIST GCR 15-1009 (2016), Model-based exchange has primarily focused on CAD-to-CAD data interoperability and long-term data archival. Even with the drive for industry to become increasingly model-centric, there is still significant manual intervention when going from company to supplier with product design for manufacturing and quality inspection. In part, this is because the STEP model provides only shape geometry and does not contain the PMI necessary for CAM and CMM models and machine programs.

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

(3D)-shape-geometry model. This shape-geometry model is often provided in a standards-based format, STEP is most prevalent. In addition to shape-geometry, the CAM and CMM processes require product and manufacturing information (PMI) to fabricate and inspect the part. (NIST GCR 15-1009, 2016).

Engineering design organization is the owner the MBD and they key success factor of the MBD will be based on the accuracy of defining Semantic references so that the automated machines can understand and interpret.

2.5. Digital asset Management

2.5.1. Asset Management Fundamentals

There are several alternative definitions of asset management as per Liyanage (2012, p.15), Hastings (2014, p.4) and Too (2010, p.59) and it is understood that the definitions vary depends on the asset management organization it has been used. However, based on ISO, *Asset management is a coordinated activity of an organization to realize value from assets* (ISO 55000, 2014)

As per PAS 55 (2008), asset management is "Systematic & coordinated activities and practices through which an organization optimally manages its physical assets and their associated performance, risks and expenditures over their lifecycles for the purpose of achieving its organizational strategic plan*"*

Engineering asset management consequently demands an information system that captures data supporting decision making across the areas suggested by the requirements and implications. Ideally, the information system or the engineering asset need to provide seamless data interface between the physical, digital and financial systems and the changes between them of a set of assets to be also managed by the same system. The purpose for which the asset set is managed is defined by reference to the organization that controls the assets. It is evident however that in most organizations, the opinion of many engineers is that poor data quality is probably the most significant single factor impeding improvements in EAM (Amadi-Echendu, J., 2010)

2.5.2. Asset Management perspectives

Understanding them in various perspectives makes us to understand the asset management broader scale.

From global perspective, assets to be dealt in a global level. Due to the globalization, modern technological developments assets are getting complex as they are shared, interfaced and interact across regional boundaries. Modern asset management, after the rapid globalization, to be dealt in a global perspective due to regional restrictions, demographical reasons, commercial impacts, inter-mingling of various cultural aspects, educational differences, communication barriers and so on.

From the technical perspective, asset management is often viewed as a framework to facilitate more informed decision-making by combining engineering and business strategies and the compliance of them. Compliance these frameworks, regulations and standards will enable the resources, engineering infrastructure for the industry to adhere and run. Documentations and controllership of technical information are on-going process of asset management to do a real-time operation of technical systems. Failure to adhere the technical regulations will cause a major collapse in the assets, so it is essential to view the asset management in technical systems point of view.

As the engineering assets maintained by Oil and Gas industries are life cycle maintained, it is essential to understand the whole picture of the asset management in life cycle perspective. Haider, A (2007) invokes a lifecycle approach to the assets in his definition of Asset Management that, asset management entails preserving the value function of an asset during its lifecycle and maintaining it to as designed or near original condition through maintenance, upgrade, and renewal until sustainable retirement of the asset due to end of need or technology refresh.

By understanding the asset management in various perspectives gives a broader level understanding of the engineering design assets to be managed by considering the above perspectives. Product life-cycle management to have the above characteristics to be in built inherently. For detailed explanation of PLM, ref section 2.5.4

2.5.3. Digital Asset Management – OFE sector

Damglossary.org (2020) defines digital asset management as a collective term applied to the process of storing, cataloguing, searching and delivering computer files (or digital assets). Digital asset management systems, in accordance with damglossary.org (2020), centralize assets and establish a systematic approach to ingesting assets so they can be located more easily and used appropriately. (Damglossary.org, 2020)

In accordance with Diamond (2014, p.23), the primary components of digital asset management software are:

- Database

- Permission engine that determines who can connect to the system and what can do

- Metadata that are values generated by the operating system and include file creation and modification dates and information about the file format, size and location;

- Search Engine that allows searching for files in the DAM

- Processing Engine that allows processing and modification of the files in the system.

The digital asset management system will enable organizations to handle, manage and control their product-related documentation, drawings, 3D models and data at any moment. This system must back-up the digital assets, so the assets do not get lost or corrupt due to unforeseen issues and provide security from cyber-attacks and any other IT safety-relevant threads. To address the above factors, engineering organizations are typically using their product life cycle management programs to manage their digital assets like 3D models and 2D drawings.

2.5.4. Product life cycle management (PLM)

In industry, product lifecycle management (PLM) is the process of managing the entire lifecycle of a product from inception, through engineering design and manufacture, to service and disposal of manufactured products (Kurkin, Ondřej; Januška, Marlin, 2010)

There are several life-cycle models in industry to consider, but most are rather similar. What follows below is one possible life-cycle model; while it emphasizes hardware-oriented products, similar phases would describe any form of product or service, including non-technical or software-based products (Buy strategy, 2017).

Figure 2-5 Asset management – Subsea oil equipment life cycle

Above picture explains the asset management of subsea oil production equipment life cycle. Scope of asset management elaborates from the initial creation of subsea assets until the lifetime extension of the assets. After the initial investment and planning, asset management starts from inception, design, installation until retirement of the assets. The used equipment is getting refurbished to extend the design lifetime of the subsea oil production equipment to serve furthermore until the complete retirement age of the subsea equipment.

There are several software platforms available these days such as Teamcenter, ePIMS, SAP and combination of various software platforms. This platform stores, manages and acts as an interface between the 3D modelling design programs and shares / consumes across various organizational process steps. The PLM program serves throughout the life cycle of the product. For example, the subsea equipment to be managed at least 25 years of its initial life cycle and this needs a strong communicative and self-suggestive automated program which serves as a lifecycle management until the service and repair.

After creation of 3D models and drawings, those will be uploaded into PLM system to manage the 3D models throughout its life cycle stages. Refer Appendix C showing the landing page of Teamcenter as an example.

3. Status quo – OFE industry:

3.1. About the Company

The study conducted based on the broader perspective of various Oil field equipment manufacturing companies (OFE) those who involve engineering design and 3D modelling practices. Baker Hughes has been taken for example to understand the practical implementation practices however the concept and suggestions will be the same for many of the similar industries.
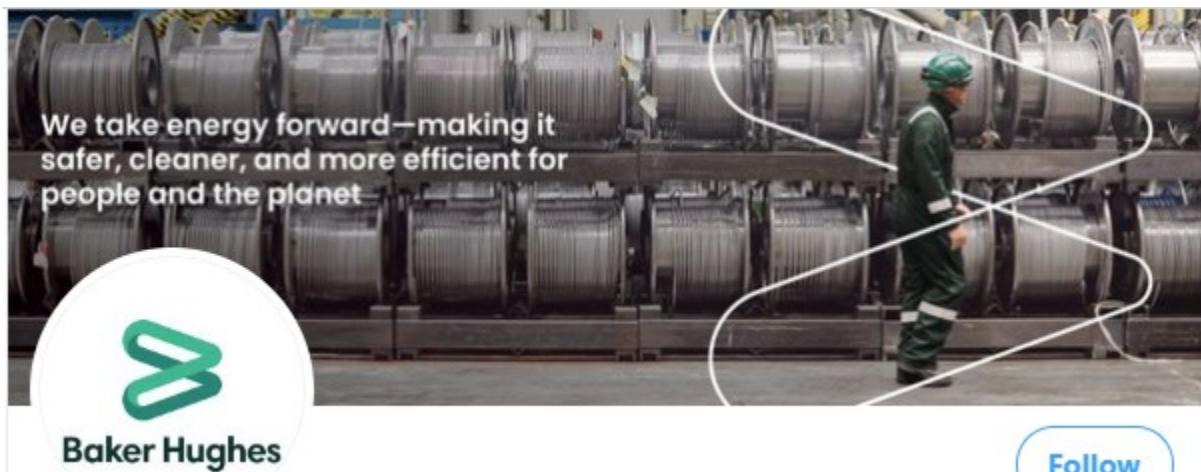
Figure 3-1 Bakerhughes – Full stream provider of integrated oilfield products, services and digital solutions (Bakerhughes.com)

Baker Hughes is the world's first and only full stream provider of integrated oilfield products, services and digital solutions (Bakerhughes.com). Company was created because of a division between GE Oil & Gas and Baker Hughes in 2018. Company consist of following product and service divisions:

- Oilfield Services that provide drilling, wireline and wellbore intervention services, and develop products corresponding to these services, etc.

- Turbomachinery & Process Solutions that develop and deliver turbomachinery and process equipment together, services, etc.

- Digital Solutions that develop and deliver sensors, measurement equipment, inspection technology and condition monitoring equipment, etc.

- Oilfield Equipment that deliver subsea productions systems, subsea services, subsea drilling systems, etc.

As the part of this thesis, it is Oilfield Equipment (OFE) division that has been evaluated for the digitalization practices. Engineering organization of the OFE creates, and is responsible for further maintenance of most of the digital specifications that predominantly consist of, but not limited to, trade secrets such as:

- Bill of materials and the list of all vendors that provide subcomponents;

- 3D models and assembly models

- STEP files for external share

- 2D Drawings, such as assembly, subassembly, detail weldment, detail machine, forging, hydraulic and electric schematics, layout, interface, etc.;

- Design verification packages, such as design criteria, guidelines and procedures, etc.;

- Field service manuals, such as disassemble/assemble manuals, offshore maintenance procedures, operating and service procedures, product design information, pre-operational check, etc.;

- Internal standards, such as design, material, coating, welding and non-destructive examination standards, fabrication operations, fabrication and test practices, and technical qualification procedures;

- PLM software

- Technical records, such as design and analysis reports, design datasheets and checklists, design processes, design specifications and requirements, risk analysis, etc.;

Engineering division of the organization creates the engineering assets and thus it has been considered for the study perspective.

3.2. Current steps of design consumption flow - Industry:

Below block diagram illustrates the current step of model and drawing consumption across various process flow steps of the Industry. The dotted line indicates the manual interruption during the communication between the steps.

The design items are 3D model and 2D drawings. Currently the design items are started with 3D models, but the detailing of the design items end up with 2D drawings. The 2D drawings are considered more authentic when it comes to the manufacturing information's. So, it is inevitable to unlink both model and drawings. Drawing is communicated across various process steps in the enterprise and that has many manual interruptions as described below.
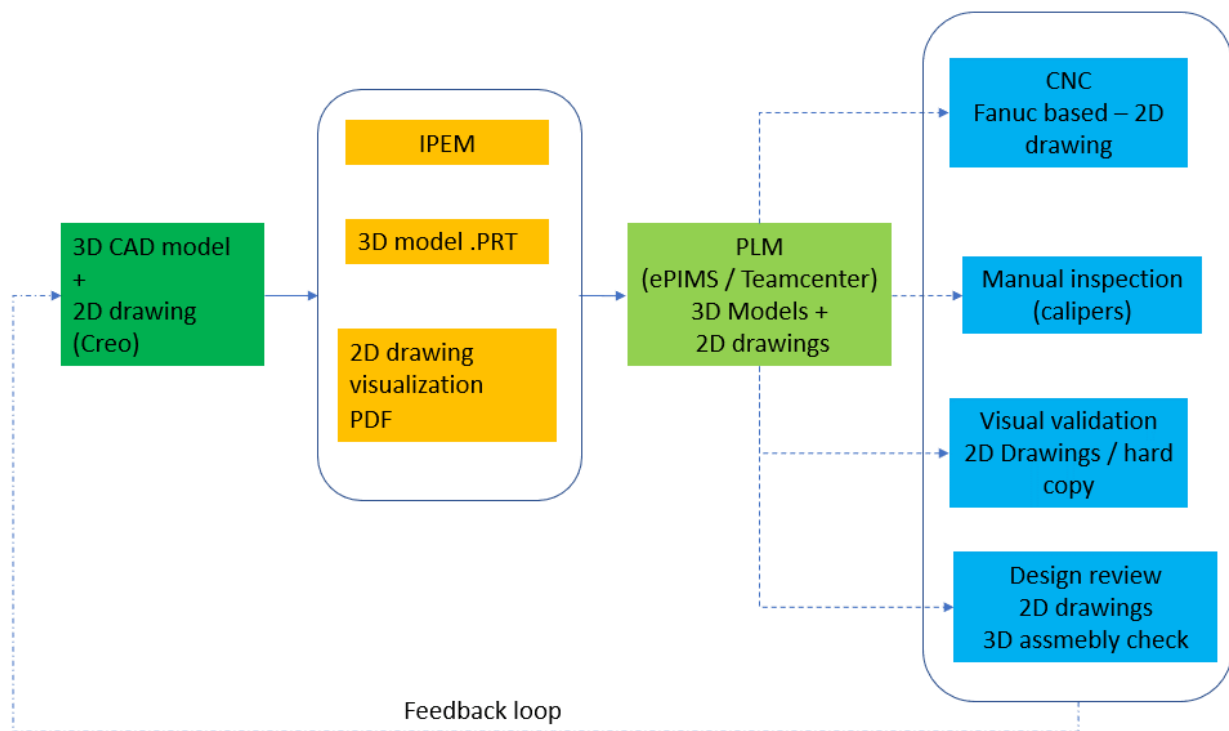
Figure 3-2 Current process – OFE Industries

3.3. Engineering design practices

Right after specification development, the concept starts with 3D models during engineering design. However, the models are designed and frozen, the manufacturing information's are plotted in the engineering drawings in 2D format. Since 2D drawings are considered more authentic when it comes to the manufacturing information's, all the dimensions and tolerances and PMI (refer section 2.2.3) are plotted in the drawing itself with number of sheets and undergo release process. This is the global practice in most of the industries.

Company is using Creo 3.0 program for 3D model creation and 2D drawing creation purposes. Creo has interfaced with PLM program using IPEM interfacing tool. This enables to download and upload into the PLM program.

3.4.PLM practices:

Refer section 2.5.4 for the literature understanding on PLM. All the engineering design items such as 2D drawings, 3D model files, technical design calculations, design reports, specifications, design review documents and various other procedures and manuals are stored, handled, revision controlled, managed using PLM programs. Currently the company is using Oracle based ePIMS and moving towards Siemens based Teamcenter. Teamcenter is more model friendly and highly recommended for life cycle management until service. Also, Teamcenter is upgraded these days which helps the modern techniques across various design initiatives. Creo can be used in-combination with IPEM, an extra interfacing program enable the files to be "saved-in" to Teamcenter.
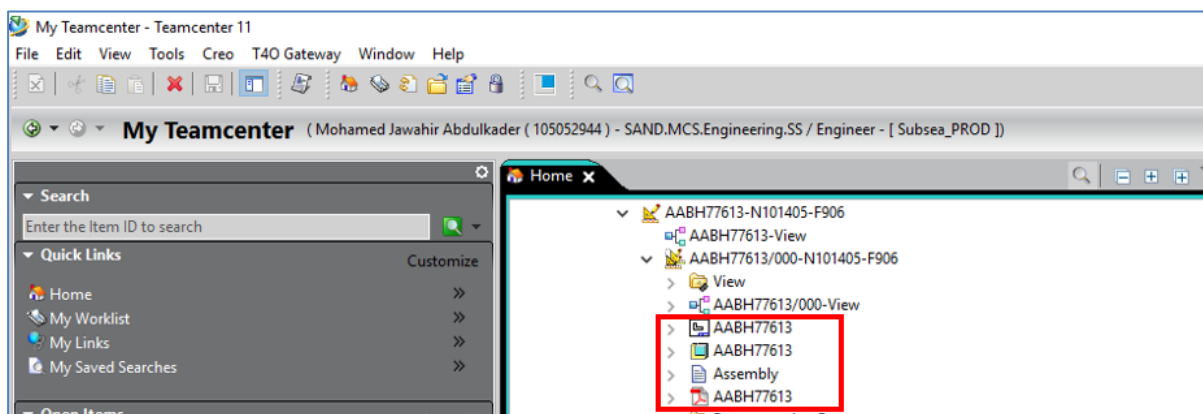
Figure 3-3 PLM practices - Teamcenter – 3D and 2D files
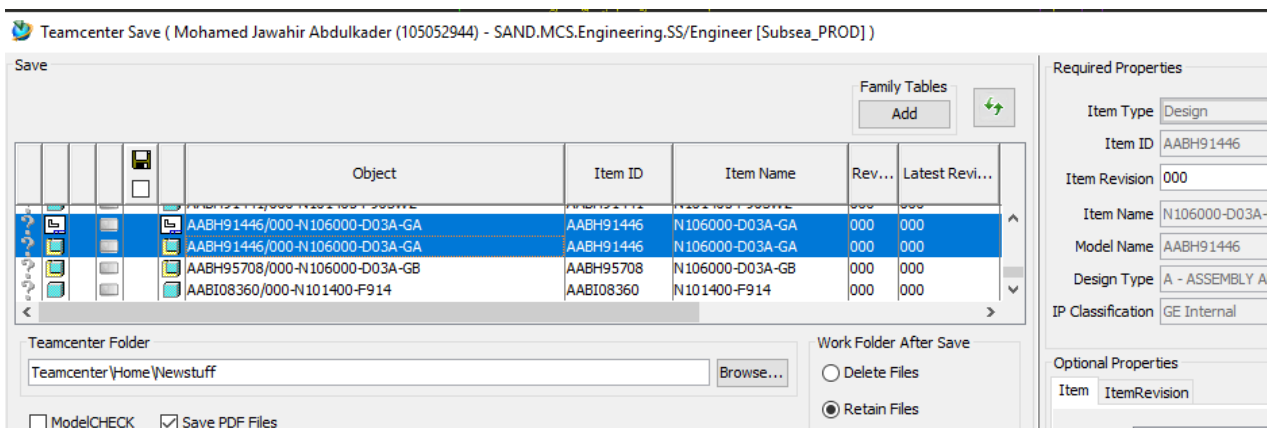
Figure 3-4 IPEM design files – 3D and 2D

3.5. Visualization & Validation process:

2D drawings are till now used in many industries as a controlled copy as a means of sharing the product manufacturing information, ref section 2.2.3. If printed as hardcopies, this will never be a controlled item. 3D models are predominantly used for creating concepts and to be able to present. This also makes the models to be interface checked against various other component models. 3D models are created to be able to make the drawings easily by plotting in the detailing section of the software.

3.6. Data privacy and IP:

Sharing across hardcopies is not recommended as the drawing is not controlled which is the major reason behind information theft, data privacy issues and IP related problems. 2D drawing files can be easily shared through mails and hardcopies.

3.7. CAM:

Local CNC machines are capable of FANUC program based which needs the manufacturing engineer or operator to re-program the FANUC code based on the released 2D drawings. Replica of the released 3D model to be created in STEP format for the CNC manufacturing purposes and this needs to be feed into the machine software. However, this does not enable the direct consumption of the 3D models and there is no integration between the models and drawings. Some vendors have high-tech manufacturing machines those demand a high-tech design items including model centric 3D models embedded with product manufacturing information's which can be readable by the machine's software.

3.8. CMM / Inspection:

Typically, across many Industries, still the Inspection and measurement control use 2D drawings to read the geometrical information against the manufactured parts for the quality control and make manual dimensional / quality check report. This is the same condition for the company and 2D drawings are published via PLM those will be accessed by Inspection control team. Also, measurements done using the conventional calliper based metrological equipment, calibrated for measuring the appropriate dimensions against the published drawing.

Some vendors have high-tech CMM/inspection machines those demand a high-tech design items including model centric 3D models embedded with product manufacturing information's which can be readable by the machine's software.

3.9. Analytical reflections:

The drawing creation is a critical and challengeable process even though this has been done many years. The 2D drawing has the comfortability making the engineers to "text-in" the specifications, tolerances and geometrical dimensions without retrofitting the actual specifications in the model. Specifications such as geometrical tolerances, surface finishes are simply stated as notes in the drawing which may not actually reflect the models due to the disconnection between the 3D models and 2D drawings. Also, each engineer has their own way of making the drawings with his own creativity. This varies between engineers even though they follow the drawing standards. There is always an alternate opinion about the drawing. So, creation and review and release take an additional time consumption and dealing with this cost extra for the manufacturing engineers before they feed-in to the machines

Stored 2D drawings in Teamcenter can communicate with other steps but not able to directly be consumed. Manual interruption required for consumption on other manufacturing steps. Also, the design item must be two files one is 3D model file and other one is 2D drawing file. Both model and drawing files are stored as two "separate" items. Find the Figure 3-4 indicating both the files. There is a risk of unlink and unsync data between both the files which may cause latest information in the drawing and not in the model. Also, it is risky of releasing only the drawing files and not 3D models which may cause outdated information or even deleted.

2D drawing are visualized only through the PLM software program and it needs access to the software, and everyone must have installed and using it across various enterprise units. Sharing across hardcopies is not recommended as the drawing is not controlled and the only alternate option is to share via PLM across the enterprise Ideally.

Model can be understood only based on the respective views and annotations placed by the designer in the drawing. If any error or unclear views placed, cannot be able to identify without help of re-design them or contacting the respective designer. This makes the 2D drawing more inefficient for the quality checking and visual validation.

3D models are not 100 % reflecting the drawings and not controlled. So, this needs additional review before converting it to STEP files. There is no process control of 3D models against the 2D drawings as those are not fully integrated. Also, the manufacturing information is "texted" in to the 2D drawings and not with 3D models. Due to this the CNC operator needs to do manual programming in the machine code based on the 2D drawing. Also, CNC operator or foreman has to approach engineering back and forth between drawings and models for manual extraction. This step slows the entire process and involves a lot of duplication of works and errors and consume extra engineering hours.

The dimensions and tolerances specified may not be clear enough to understood by the inspection team and this creates back and forth discussion between designer and QC which prone to error and waiting time. Also, measurements done using the conventional calliper to be calibrated and maintained in specific method to avoid error free measurement and this involved many manual process and time.

Due to the above reasons it would be beneficial to implement MBD and due its oneness of Master model which can be directly consumed.

4. Business drivers for MBD

4.1.Industry specific drivers

4.1.1. Paradigm shift from 2D based drawings to 3D PMI:

Engineering design sector is shifting from 2D drawings into 3D models based engineering for betterment of the design industry to enter into virtual reality, animation techniques, model centric manufacturing, artificial intelligence, digital twins, Interface and stackup check, ...etc and those are demanding the way of engineering design to move towards model centric MBD.

4.1.2. Step towards automation:

The high-tech manufacturing and inspection machines these days demand a high-tech design items including model centric 3D models embedded with product manufacturing information's which can be readable by the machine's software.

The current problem is the key specifications of the geometry such as tolerances and surface finish notes and other critical information are depicted as 2D drawings. So, the CMM

software has no clue over that information. So, the manufacturing foreman has to approach engineering back and forth between drawings and models for manual extraction. This step slows the entire process and involves a lot of duplication of works and errors.

So, to solve this problem, it is better to define the product manufacturing information (PMI) directly imposed into the models and avoid the 3D models. This way, the CMM and CAM software automatically read the PMI information and proceed upon the information without manual interpretation.

4.1.3. Digital twins:

Advancement in ICT and long-term commercial benefits of their successful usage contributed much to the ongoing change process. ICT industries play pivotal roles to establish the necessary reliable digital environment around offshore assets (During, Oakey 2002) & (Liyanage, J.P., Langeland, T., 2009).With millions of data which relates to these digital systems, it is extremely important to merge those assets with physical assets in a seamless manner. For this digital twin come into picture. Digital twins are one of the trendier digitalization initiatives among many Industries which is digital replica of a living or non-living physical entity (Saddik, A. El, April 2018).

Digital twins are the future of MBD. Below picture depicts the seamless interface of digital system with the physical marine vessels in Oil and Gas industry.
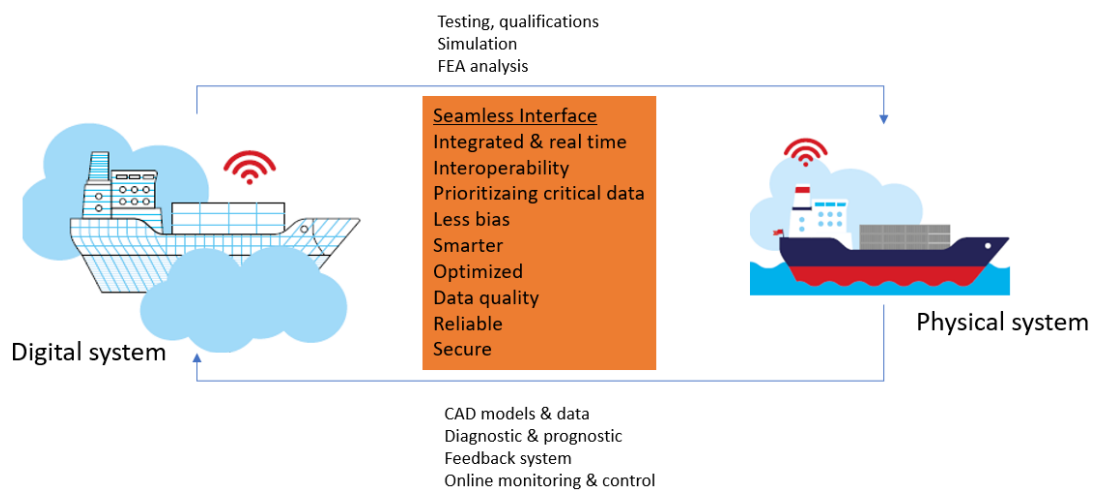

Figure 4-1 Realtime interoperability - Digital twins

Ideally the digital systems / twins communicate and collaborate with the physical system to benefit the performance of the asset by providing necessary alerts, automated self-rectification of the failures, diagnosis and prognosis, reduce judgemental bias, contextual proximity, closer

to the physical properties...etc. The digital system has been modelled by 3D CAD modelling software and analysed by the same to the closest proximity of the actual physical behaviour of the actual vessel. These models also used for simulation and analytical purposes. Among the millions of data, the digital system conceived, it is essential to get the "right real-time" data to the operator on a critical need.

For example, during an installation of offshore equipment, if any emergency occurs due to a leakage in one of the valves in vessel, the automated user interface system should diagnose the fault and provide appropriate information to proceed further. The digital twin system must be easy enough to pull the relevant data / manuals of the failing valve in a timely and efficient manner instead of lots of uncertain data which does not contribute to fix the problem.

Also, the factors like level of integration, achievable data quality, amount of necessary adjustments and appropriate data models are important on seamless integration of digital and physical systems.

4.2. OFE sector specific drivers

4.2.1. Competitive advantage:

Industries need to catch up with the trends and technology to gain the competitive advantage around the world. Oil and Gas equipment manufacturers are global operative and thus faces a highly competitive environments even though it need high capital investment. To gain the competitive advantage and business sustainability, industries are already automating their processes and digitize their data and knowledges. Engineering design also getting digitized a lot compared to 80's with the drawing board. Slowly phasing out of drawings and going towards 3D model-based PMI's until every consumption of these models.

Porter's five forces model:

Figure 4-2 - Porters Five Forces Model

This is evaluating the competitive situation in the market (Business plan, 2018). Below figure portraits Porters Five Forces Model illustrates the different market factors, where it is shown that current Oil field equipment (OFE) industry is affected by the existing competition, substitute products, new entrants of competitors, bargaining power of suppliers, and bargaining power of customers. (Porter ME, 1985) Porters Five Forces Model is used in Oil companies because of the wide understanding it gives when combined with a SWOT analysis.

SWOT analysis:

This comprehensive SWOT profile provides an in-depth strategic analysis of the company's businesses and operations. The profile will give as well a clear and an unbiased view of the Oil company's key strengths and weaknesses and the potential opportunities and threats (Business plan, 2018)

STRENGTH	WEAKNESS

❖ Diversified product and service portfolio	❖ Matrix organizations with a large number of approval levels
❖ Strong research and development department	❖ Legal Proceedings
❖ Originality of equipment provided	❖ A high amount of borrowed funds
❖ Experienced employees	❖ Dependence for raw materials supply
❖ High quality of business units	❖ Insufficiency of stocks
❖ Strong international reputation	❖ Organizational Bureaucracy
❖ High percentage of market share	❖ High competition on capturing market share
❖ Strong organizational structure and management teams.	
❖ Large employee base.	
❖ Large capital budget and high revenues and profit	
❖ Good alliances with strong and popular major businesses	
OPPORTUNITIES	**THREAT**
❖ Growing economy	❖ Government regulations
❖ Governmental support	❖ Intense competition
❖ Technology changes	❖ Exchange rate fluctuations
❖ Exploring new natural resources	❖ Fluctuations in the oil and gas prices
❖ Takeover and merger opportunities	❖ Increased IT security threats
❖ Research and development	

Table 4-1 SWOT analysis OFE companies

4.2.2. Language and symbolic representations:

OFE companies involved with various oil fields located across the geography and the subsea field typically located in the sea borders. For example, Nordic sea or Barents Sea located across the geographical locations and thus needs an international environment for various nationals to mingle around. 2D drawing created needs to be following international language requirements where few small-scale sub-vendors for design still using local language in the drawings. Also, the symbols to be adhered in a specific manner failing this may create issues while consuming the drawing on various locations. PMI embedded 3D geometry requires less "texts" and it is self-explanatory when it comes to understanding the design items.

4.1. Company specific drivers:

4.1.1. Enormous engineering hours on drawing:

The drawing creation is a critical and challengeable process even though this has been done many years. The 2D drawing has the comfortability making the engineers to "text-in" the specifications, tolerances and geometrical dimensions without retrofitting the actual specifications in the model. Specifications such as geometrical tolerances, surface finishes are simply stated as notes in the drawing which may not actually reflect the models due to the disconnection between the 3D models and 2D drawings. Also, each engineer has their own way of making the drawings with his own creativity. This varies between engineers even though they follow the drawing standards. There is always an alternate opinion about the drawing. So, creation and review and release take an additional time consumption and dealing with this cost extra for the manufacturing engineers before they feed-in to the machines. Find the below estimation for the drawing compared to 3D models.

Desc.	Model creation (hours)	2D drawing creation (hours)
Hub – for connection	15	20

The above table present only engineering drawing creation hours. Re-modelling right before manufacturing, back forth discussions over the specifications are extra. So, there is a huge potential scope in the cost saving if we eliminate the drawing creation and the hours associated it.

4.1.2. Poor quality drawings:

The 2D drawing has the comfortability manipulating write notes as dimensions, the specifications, tolerances and geometrical dimensions without retrofitting the actual specifications in the model. Specifications such as geometrical tolerances, surface finishes are simply stated as notes in the drawing which may not actually reflect the models due to the disconnection between the 3D models and 2D drawings. Also, the success of the drawing purely depends on the designers creativity and art in placing the views, adding relevant annotations in the relevant location...etc which cause poor quality if a less experienced designer created.

4.1.3. Benefits of model as "Master"

Below aspects are attracting and driving towards MBD / MBE approach in the company,

- Easy to demonstrate and develop the concepts
- Improved communication between the life cycle systems
- Seamless data transfer
- Readiness towards Virtual reality
- Improved organizational sustainability due to effective management of new 3D models and existing legacy design files
- improved efficiency and effectiveness due to continuously reviewing and improving processes workflow for the MBD

Figure 4-3 – Virtual reality design (courtesy: PTC corporation)

5. MBD Implementation strategy & approach

5.1. MBD Principles

MBD is about making the 3D model as a "MASTER" with all the product manufacturing information embedded within the 3D model to make as a "single source of truth" so that this will be consumed "directly" throughout product life cycle stages. Refer literature section 2.4 which describes in detail about the model-based definition and also refer Figure 2-4 for the PMI embedded 3D model for the model-based definition.
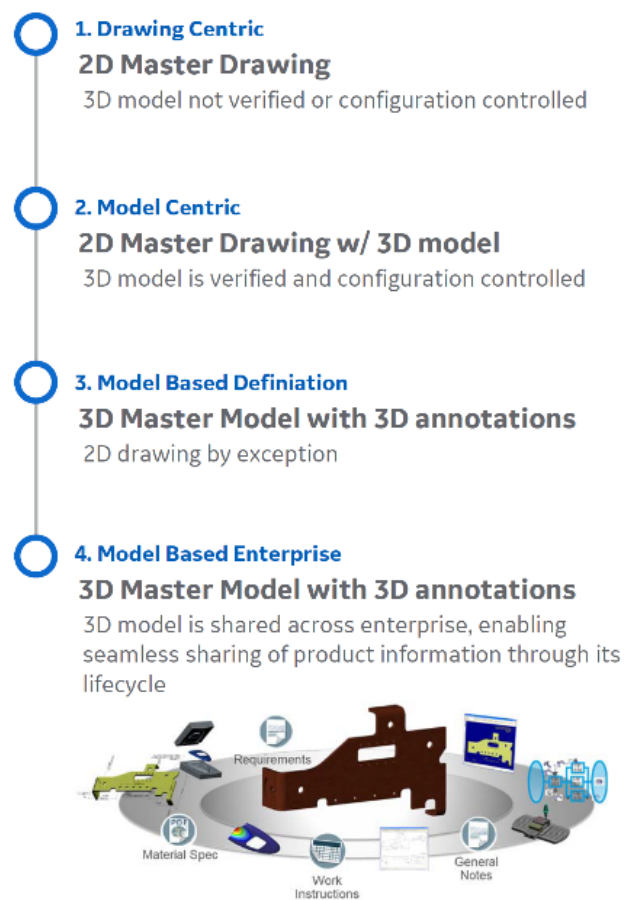
Figure 5-1 MBD to MBE principle (Courtesy: BH)

To achieve the industry vision of the model-based enterprise (MBE), the strategy must include model-centric data interoperability for design to manufacturing and quality in the supply chain. The maturity of MBE centric into various levels also depicted in the above picture. From level 1 the drawing centric, the MBD milestone move towards MBE extended which enables the model to be automatically drive the process. The model-based definition (MBD) is created by the engineering design team in the equipment manufacturing companies (OFE) using computer-aided-design (CAD) tools. The 3D models are predominantly used for

designing the equipment and those are typically detailed in the 2D drawings. Based on the MBD concept, the 3D model has been embedded with PMI and this will be managed in the product life cycle management system to control, store, maintain and consume the model data.

Model based engineering (MBE) is the next step of MBD in which 3D models are shared and consumed across the enterprise enabling seamless data sharing along the product life cycle. This enterprise includes Visualization, validation, CAM, CMM, inspections and service. The enterprise typically combined in the same OFE industry or fragmented with sub-suppliers, small and medium scale enterprise (SME) manufacturers.

Today, almost all manufacturing industry use computer-aided-manufacturing (CAM) and coordinate-measuring-machine (CMM) respectively for manufacturing. Traditionally, design data is provided by the design team of the OFE to either sub-vendor or within their manufacturing facility in the form of full-detail-2-dimensional (2D) drawings. More recently the data has also included a 3-dimensional (3D)-shape-geometry model. This shape-geometry model is often provided in a standards-based format, STEP AP203 is most prevalent. In addition to shape-geometry, the CAM and CMM processes require product and manufacturing information (PMI) to fabricate and inspect the part. Refer (NIST GCR 15-1009, 2016). Also refer the above Figure 5-1 describing the model consumption difference from MBD to MBE.

5.2. Approach - System engineering

Compared to ancient hierarchical based assets, the modern assets are increasingly becoming more complex, dynamic, interconnected and automated. Both the number and diversity of stakeholders have increased as global systems have become more prevalent. Also, it consists of multiple sub elements interact & interface together with complexity which deserves to be considered in a holistic perspective throughout its life cycle. So, it needs to be dealt in a systemic approach.

This approach is a framework that sees an organization in holistic perspective as a system composed of interdependent, interactive subsystems and connected to its respective environment, which is the surrounding elements in the systemic boundaries (Parnell, G.S., Driscoll, P.J., 2011).
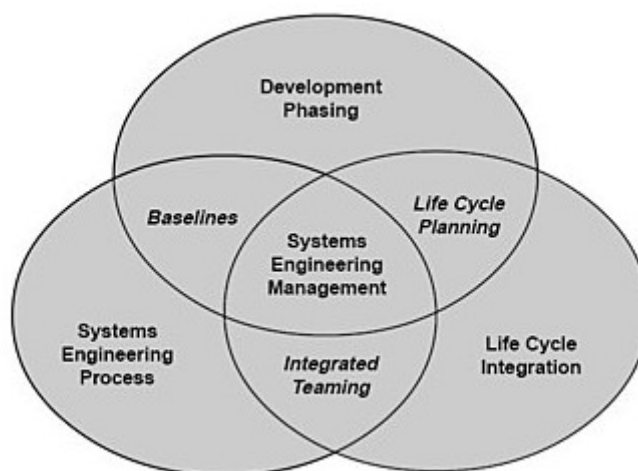
Figure 5-2 Systems engineering (courtesy: Systems Engineering Fundamentals)

Engineering design is part of the big system in the system engineering organization of Oil field equipment (OFE) system and it is quite appropriate to proceed with system approach to get the holistic view of engineering specifications.

Below factors to be considered during implementation of digital 3D assets,

❖ **Increased number and diversity of stakeholders:**
  3D models are used in various inter-department interfaces. This starts with engineering department and interfaces with manufacturing (CNC), Virtual validation, quality checking and service / maintenance departments. Understanding the needs and expectations of them and satisfying them is highly essential and entire sub-systems must focus towards their needs.

❖ **Inter-connectivity:**
  Change occurring in one system impacts immediately with those they are connected to (Parnell, G.S., Driscoll, P.J., 2011). A change in **specification** immediately reflects in the entire equipment made with the similar specification. These interconnectivity makes a complexity which to be dealt as one big system to track its outcome for better connectivity.

❖ **Increased inherent complexity:**
  Digital specification operates simultaneously with several sub-systems as depicted with few examples in the above picture. From the tender team until service this makes the entire sub-systems exhibit complex. An uncontrolled copy of the design specification is leaked, this creates a big damage to the organization. So, it is very

important to consider the digital assets in a systemic perspective to process inherent complexity.

❖ **System boundary and decision process:**

Defining the boundary of an organization is essential to have control over its performance and cost. Inter connecting multiple sub systems tend to act as a boundary less organization and systemic approach provides a clear boundary within which the system needs to be operated, performance measured and cost control (Parnell, G.S., Driscoll, P.J., 2011) System design process in each stage of the system ensures with a system toll gate which acts as a go no go gate.
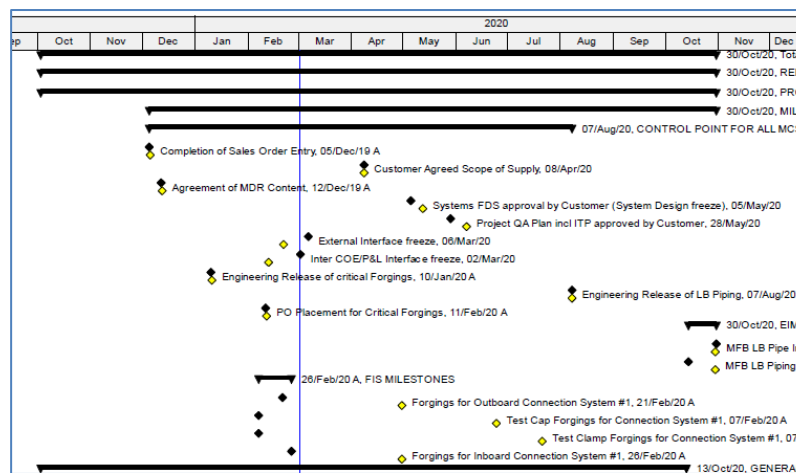
Figure 5-3 Toll gates (Courtesy: Plan from BH, 2020)

❖ **Life cycle:**

It is the conceptual modelling of the system or subsystem to calculate when it matures overtime. Due to the inter connectivity between sub-elements, the maturity of each sub-system makes imbalance within the entire organization. To treat this, the sub-systems has to be considered as one big system. In Engineering organization, design specifications like drawing or models are accounted on its life cycle from the design till obsolesce.

❖ **Performance level:**

Slow performance of PLM system makes impact in entire organization to fail. In system approach, this can be measured and monitored as one system.

❖ **Lifecycle cost:**

It is always better to handle the sub-organizations into one big organization to keep in control of the cost.

5.3.MBD Framework:

Refer NIST for the MBD implementation framework. This latest standard has recommendations and the framework on which the MBD establishment is described in detail which can be considered for the development of this thesis. Guideline document for MBD to be developed based on this as well.

Based on NIST GCR 15-1009 (2016), Model-based exchange has primarily focused on CAD-to-CAD data interoperability and long-term data archival. Even with the drive for industry to become increasingly model-centric, there is still significant manual intervention when going from OEM to supplier with product design for manufacturing and quality inspection. In part, this is due to the fact that the STEP model provides only shape geometry and does not contain the PMI necessary for CAM and CMM models and machine programs.

Figure 9 (page 14) of the NIST standard show the block diagram to demonstrate the data-exchange process from CAD-to-CAM and CAD-to-CMM, using commercially viable solutions.

NIST standard (NIST GCR 15-1009, 2016) also recommends performing an Iterative approach in the trial study and the issue resolution process,

☐ Perform data exchange for each process step

☐ Evaluate the output for the required model entities at each process step

☐ Identify errors encountered in the individual PMI elements

☐ Modify each sub-process algorithm to address the issue

☐ Re-evaluate the updated output until each sub-process converged to a viable end-to-end data exchange solution.

5.1.MBD implementation scope definition:

To test the MBD model across various departments in the company, the scope must be defined on all the stages. There are many unclear elements across various steps. Refer the below Figure 5-4 depicts the various uncertainties and the need to identify or define them as a part of scope.
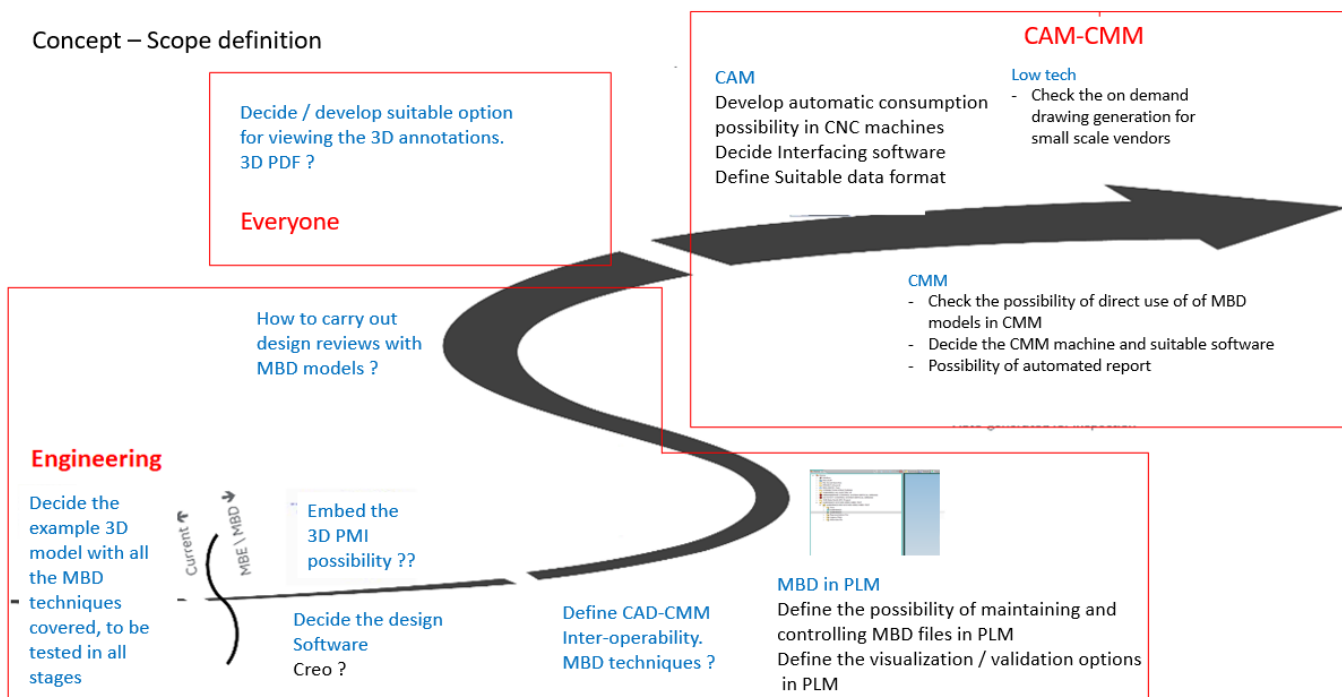
Concept – Scope definition

CAM-CMM

CAM
Develop automatic consumption possibility in CNC machines
Decide Interfacing software
Define Suitable data format

Low tech
- Check the on demand drawing generation for small scale vendors

Decide / develop suitable option for viewing the 3D annotations. 3D PDF ?

Everyone

CMM
- Check the possibility of direct use of of MBD models in CMM
- Decide the CMM machine and suitable software
- Possibility of automated report

How to carry out design reviews with MBD models ?

Engineering

Decide the example 3D model with all the MBD techniques covered, to be tested in all stages

Embed the 3D PMI possibility ??

Decide the design Software
Creo ?

Define CAD-CMM Inter-operability. MBD techniques ?

MBD in PLM
Define the possibility of maintaining and controlling MBD files in PLM
Define the visualization / validation options in PLM

Figure 5-4 MBD concept road map – scope definition

In engineering phase, from the Identification of relevant software, PMI implementation, combability with PLM and possibility of visualizing and validating in the PLM until direct consumption of MBD models in CAM and CMM machine software. The picture denotes all the scopes and however there must be more establishment during the execution phase.

5.1. MBD implementation for company - concept:

As the MBD is new to many industries when it comes to implementation, it is essential to portray a concept capturing all the process flow elements, sub-elements, file formats as this topic is majorly related to the 3D model software formats across various steps in the organization. Refer the Figure 5-4 for the implementation scope definition which triggers the need for a concept with process block diagram. Based on that idea, a simple block diagram concept developed as shown in the below Figure 5-5.

As the 3D model become a "Master" in the MBD technique, the process flow of the current step has to be re-designed to fit for MBD implemented models. Based on that a simple product example can be built and tested against various process steps of the enterprise. PLM is the centre of all the steps as this maintains and controls the model files from engineering design till CMM and CAM and also until the service. How, which method and what format the MBD models are shown. Governing document NIST is proposed to be followed and understood.
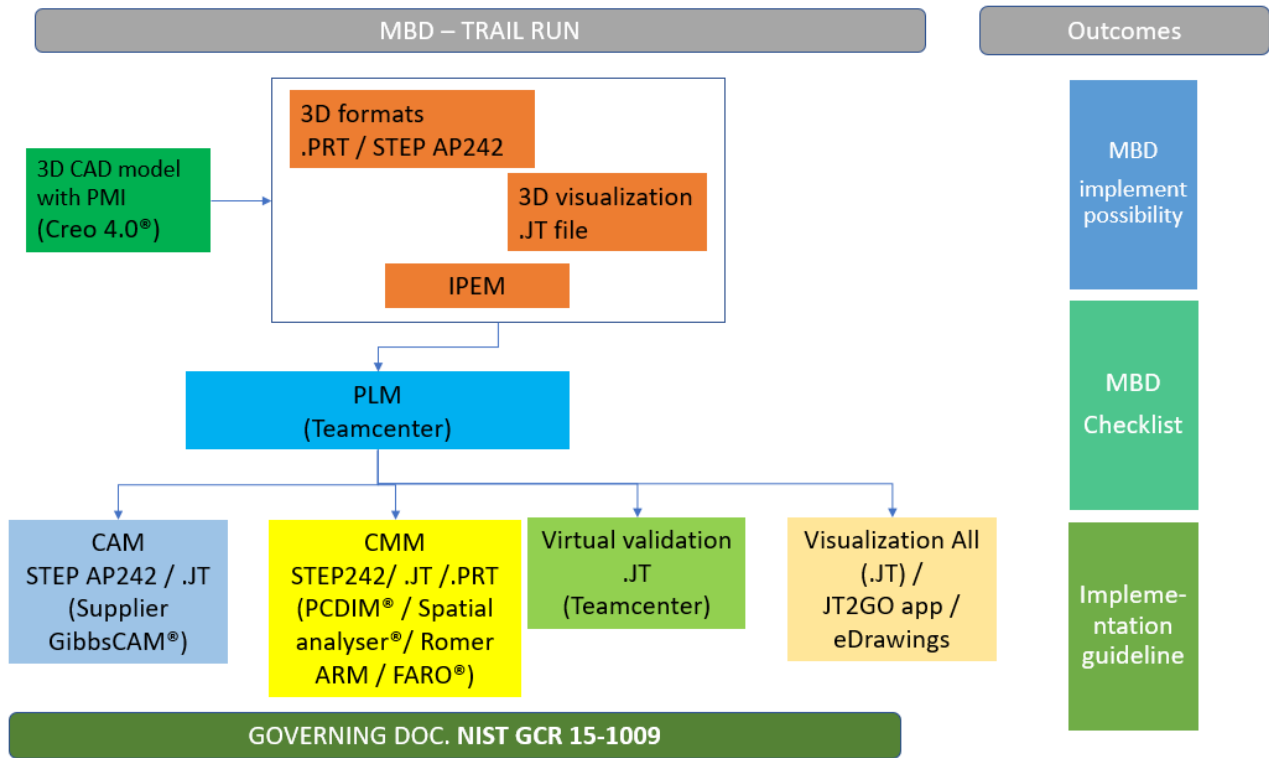
Figure 5-5 MBD implementation concept

Outcome of the MBD implementation trail run is listed and those are MBD implementation possibility, MBD check list and implementation guideline based on section 0.

For the company, it is proposed with appropriate software and platforms as those are more viable and easier to implement. The company already operating with the CAD modelling platform which is based on Creo 3.0 software. This needs to be updated with Creo 4.0 to have the MBD protocol enabled. In future, the internal guideline document can be developed based on the steps explained in detail and relevant workflow must be setup to enforce the MBD based lifestyle. Trainings to be assigned to successfully implement this process.

Various units of the company have already been started with CMM capability and the MBD to be tested as part of the study. CNC machines in the local site of the company does not equipped with the interfacing software for 3D models till now and initiation steps to be carried out. Local site is also considering the implementation of FARO arm or similar for the CMM purposes. The below criteria and steps are listed for the consideration of MBD implementation.

5.1.1. MBD implementation criteria to be considered:

No	Implementation Criteria and Steps
	Design Creation
1	Design software capability for MBD
2	3D models to have manufacturing information embedded "Semantic query" option to have fail-safe
3	PMI embed possibility for annotation, tolerances, GD&T and datums
4	STEP 242 creation compatibility
5	.JT file creation compatibility
6	Migration capability of existing legacy drawings
	PLM
1	Additional workflow for MBD review
2	Workflow for automatically creation .STEP file and JT file during check-in
3	Workflow for Semantic surface review
4	Manufacturing engineer (alternatively) position for additional review of MBD models
5	CMM machine reading compatibility against .JT / STEP files created with MBD
6	CAM software upgrade to consume MBD based STEP model
7	Semantic surface compatibility between various manufacturing processes
	Outcome Criteria
1	MBD to comply against governing document for the MBD process, NIST
2	Capture change in estimation to consider the MBR implementation hours
3	Make awareness in the organization on the MBD. Training / meeting
4	Workflow / Enforce all newly created 3D models to include PMI information

5.1.2. MBD implementation high and low tech:

Despite the industry MBE vision to become model-centric and the model-based hype from major CAD suppliers, there is still a reliance on 2D drawings. A survey of SME suppliers

shows that many of those surveyed still receive design data from their OEM customer in the form of full-detail-2D drawings.

Another large group receives a 3D-shape-geometry model combined with a 2D drawing containing the PMI. Only a small percentage of the SME manufacturers receive just a 3D model with embedded PMI. The design to manufacturing process is still very much drawing centric. The very few data exchanges that are model-centric with embedded PMI use proprietary, not standards-based models. To satisfy the small-scale industries on-demand drawing solution to be proposed. Refer the below picture of the proposed strategy.
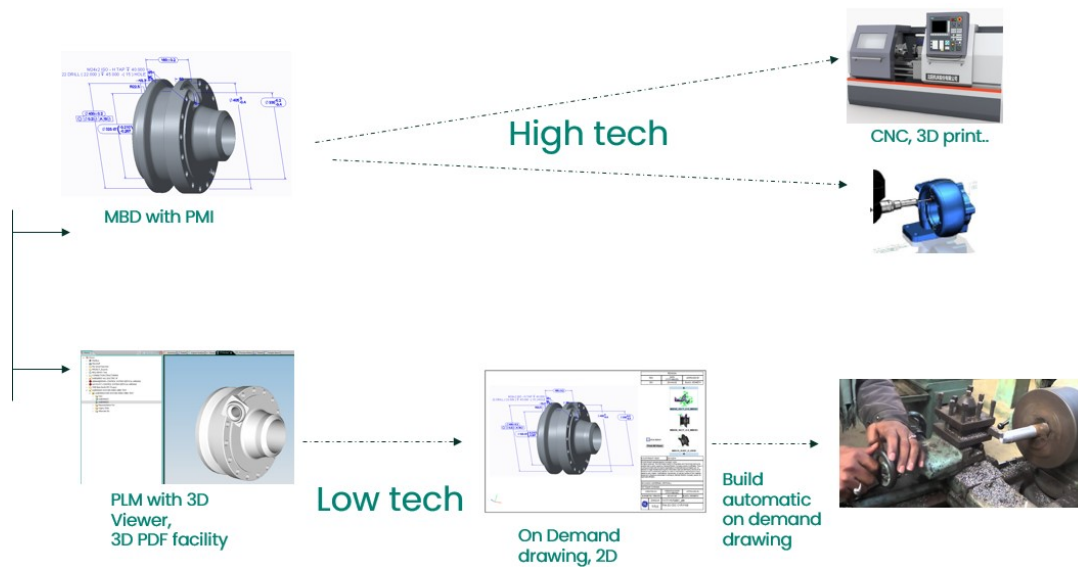

Figure 5-6MBD implementation strategy - low and high tech

5.1.3. MBD data collection strategy:

MBD related data can be collected on the below methods,

- Attend MBD webinar from CAPVIDIA
- NIST standard document, refer (NIST GCR 15-1009, 2016)
- Meetings with Digitalization team from OFE, BH
- Meeting with GE power digital team
- Knowledge sharing from BH Creo team
- MBD literatures and materials from internet
- MBD guidelines from PTC
- Guidance from UIS supervisor

Refer Appendix E for the pictures of the data collection methods.

5.1.4. MBD quality check strategy:

MBD model quality is planned to be checked during the test on various stages as indicated below,

- Design stage: Design review / additional manufacturing review
- PLM implementation stage: Check the MBD file uploaded or not and can be able to be visualized or not
- CMM: Inspect the MBD model and report if this works fine
- CAM: Feed and check with the CAM machine software about the consumption possibility. Also initiate and find the appropriate CAM software can be used for local CNC machines

NIST recommends below types of model quality issues (NIST GCR 15-1009, 2016)

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

5.1. Design software:

These days there are numerous software programs available for mechanical design after 2D drawings. As the company uses Creo as the modelling software across various units, it can be used, and it has the capability to design with MBD. Refer section 2.3 for more explanation and company uses Teamcenter for PLM which can be tested against the product life cycle of the model.

6. Demonstration of MBD implementation -Test part:

Below picture depicts the MBD implementation road map with various stages. Test part created and checked against each step and found the appropriate solution for the enterprise implementation.
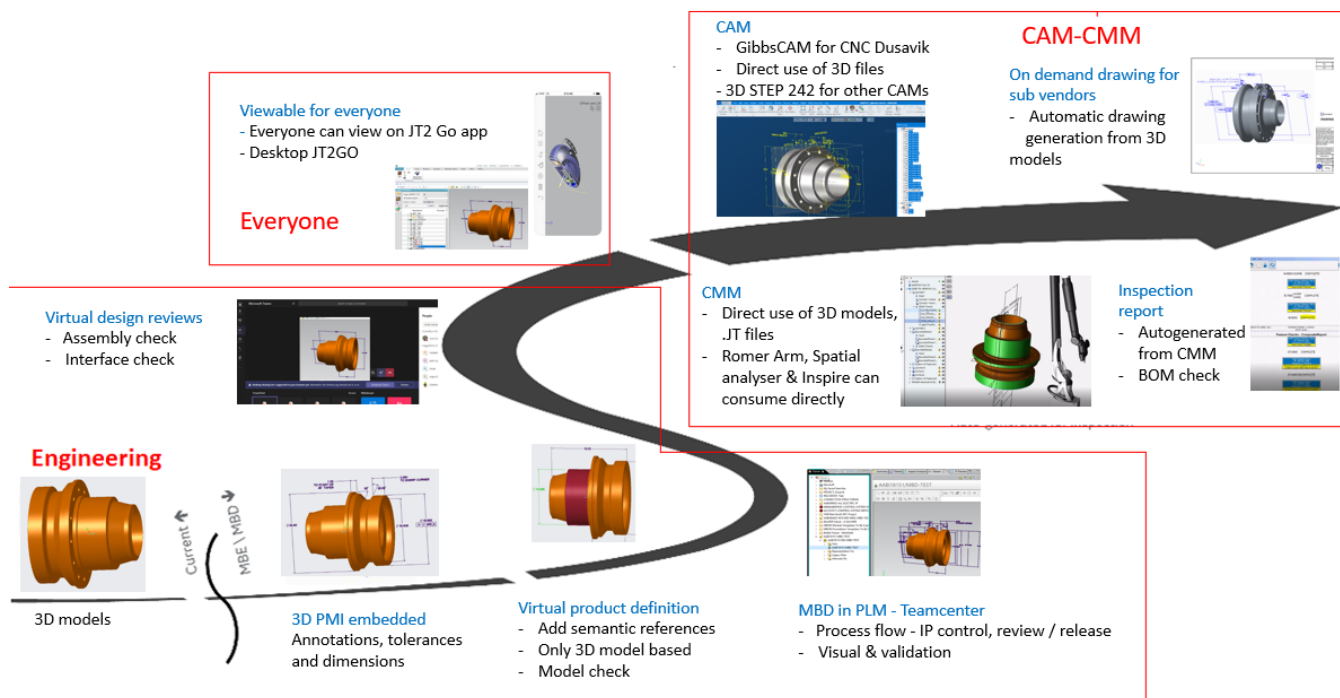

Figure 6-1 MBD implementation road map for hub

6.1. Test part – Hub:

Hub is the end part of pipeline in subsea environment and its 3D model has complex and precise detail dimensions and tolerances involved. Due to its complexity and inclusive of various annotations, this can be taken as an example for the study purposes.

6.2.3D model creation:

Refer section 2.3 for the introduction and details of the Creo 4.0 software, which has been taken as example for this case. The only difference between the regular 3D modelling is to create the model with respect to 3D annotations and 3D PMI. That means the drawing file .drw does not need to be created. It is essential to use the Creo 4.0 version which is highly updated and friendly to 3D PMI build-up. This means the driving dimensions to be set in a tidy-up manner by considering in mind that the same will be portrayed during the PMI visualization. Another important factor to be considered here is to setup the appropriate 3D

views, we call it as ISO views. For example, a hole to shown as separate view, it can be shown with zoomed out view on the hole itself. Find the typical 3D model of the hub which is taken an example for the case study in the below figure and show various views for the appropriate dimensions and annotations.
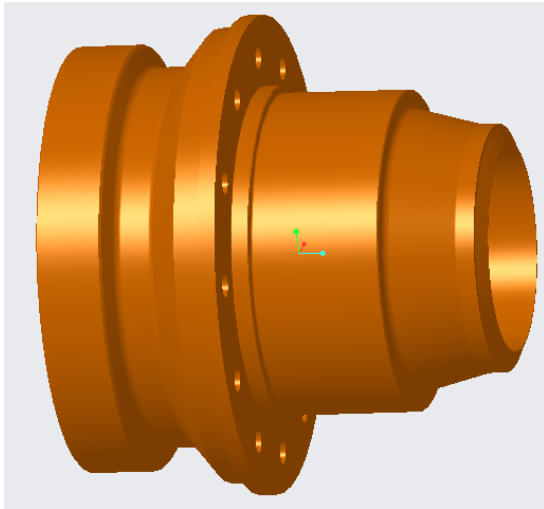

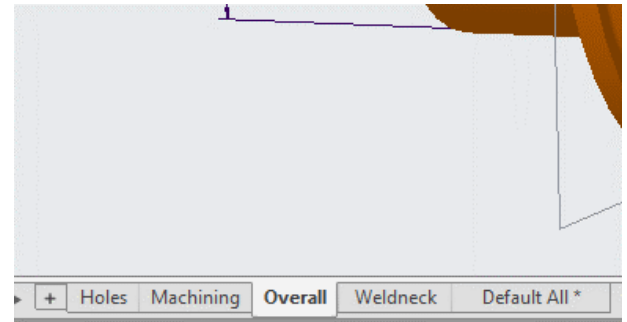*Figure 6-2 3D Model (Example, hub)*

Figure 6-3 MBD views

6.3. Embed 3D model with PMI:

Creo 4.0 version comes with improved facility to create and access the product manufacturing information (PMI). The annotate tab embedded with the Creo ribbon makes easy to work and navigate with PMI information. Upon creation of 3D models, various combination state to be assigned to make the PMI in the tidy-up manner and easy to visualize the various functions of the hub. The combination state in the view manager can help to sort this. To do this below steps to be followed (PTC.com, 2020),

1. Assign annotate tab
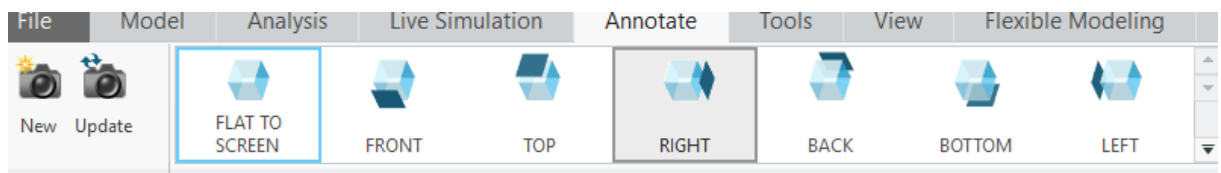
2. Select all in the view manager
3. Create a new combination state and name it as "machining" for example.
4. Orient the hub model accordingly to view all the PMI clearly

5.   Assign the orientation, cross sections, simplified representation, layer state and so on in the view manager tray

6.   Add relevant dimensions to be visualized as PMI. Both driven and driving dimensions can be added. Using the previous tool, annotate from model to fetch the driving dimensions those are set during the sketch.

7.   Select the appropriate surfaces to create the new driven dimensions. Add the surfaces under references to make it visible during the CMM inter-operable.

8.   Keep creating as much combination tab as possible to make it easy for clear dimensioning pattern

The below picture depicts the 3D model with PMI information as instructed above,
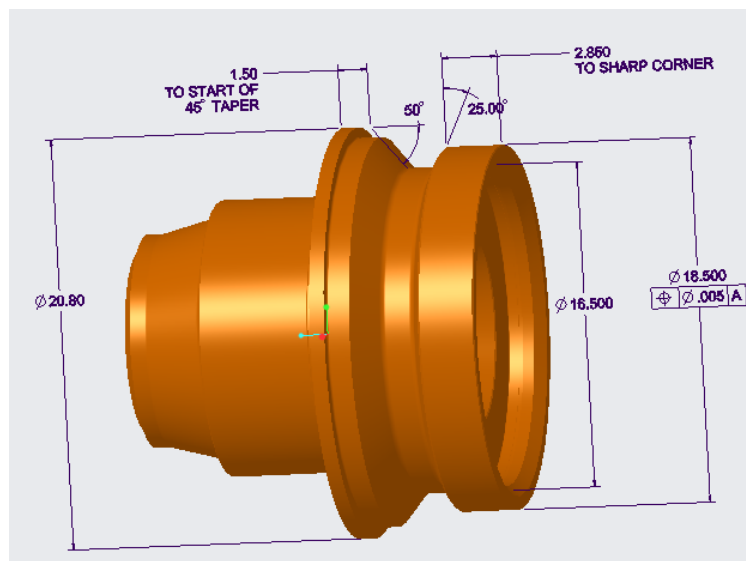
Figure 6-4 Hub 3D Model with PMI

6.4. Virtual product definition – Semantic references

This is the important aspect of the MBD which helps to move towards the MBE. The defined annotations and dimensions to be identified by the machine software. This option is introduced in the new software to enable this machine reading capability of 3D models embedded with MBD. The Creo 4.0 equipped with the additional feature of "semantic query" option which helps to identify the relevant surfaces of the defined dimensions. Upon creating the driving dimensions, the surfaces making the particular dimension has to be chosen and added with the dimension. To check this, we need to click the "sematic query" option and select the dimension which needs to be manufactured. Upon selection of dimension, it automatically highlights the appropriate surface. This confirms the right dimension and the

right surface to be machined during CMM or CNC manufacturing. However, Creo automatically takes the relevant references for As-driven dimensions. Refer the below picture indicating the selected surface.
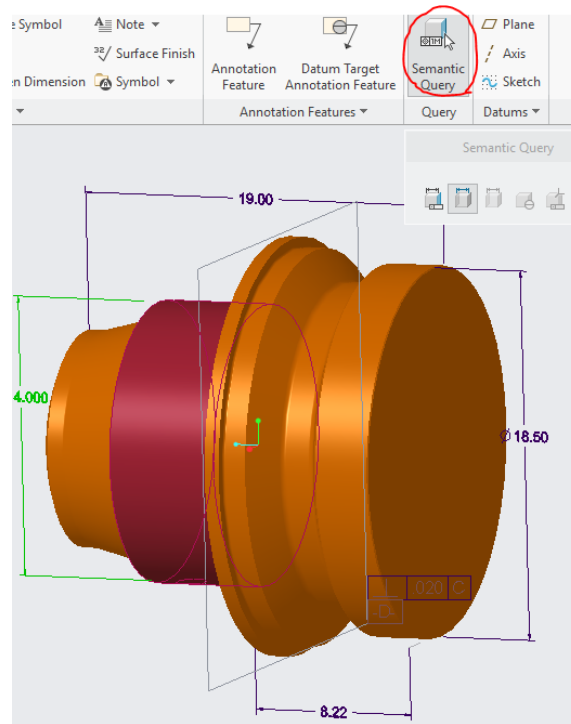

Figure 6-5 PMI embedded with "semantic" reference surfaces

6.5. MBD models in PLM - Teamcenter:

6.5.1. Process flow & Product life cycle:

The block diagram for the MBD process flow throughout the product life cycle stages are shown in the below picture. This indicates various 3D formats to be used for easy consumption between different life cycle stages.
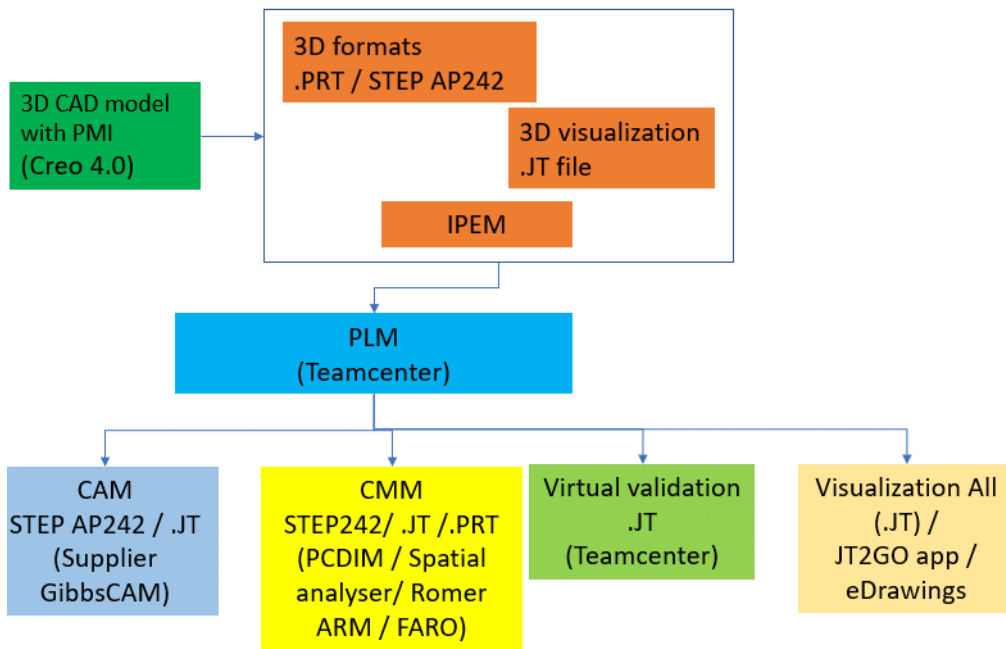
Figure 6-6 flow diagram – proposed MBD

There should be a link between the model creation and the model consumption. The first step to model consumption is enabled by product life cycle management system. In this case study, the company uses Teamcenter which was developed by Siemens corporation. This platform stores, manages and acts as an interface between the 3D modelling software's and the companies various design and manufacturing process. Creo based .prt 3D models are transferred using IPEM interfacing solution which simply check-in the models into the PLM platform. The checked-in models can be used and visualized as below picture. A separate workflow process to be created in Teamcenter to make the. JT files with the PMI information. The current platform does not have this automatic feature. However, this can be simply manual converted as stated below.
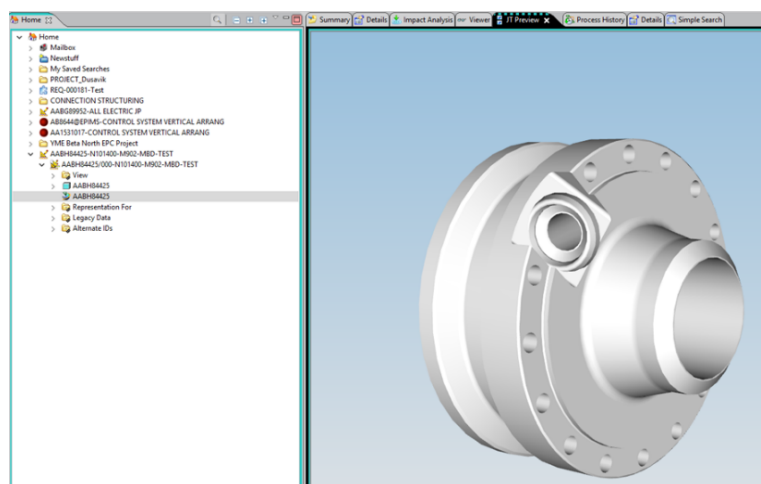

Figure 6-7 JT files for viewing

6.5.2. PLM - visual & validation (JT):

For manual JT file creation, Creo 4.0 software program to be installed and this is a new version in the market. Before creating .JT file, the 3D model to be created with appropriate PMI information to be arranged. Refer section 6.1. To create JT file, use the "save as" command in the Creo software and select .JT file. It is very important to select options in the wizard and select the "As is tessellated" option and also select "rich content" to export the PMI information's into the 3D model file. Refer the below picture,
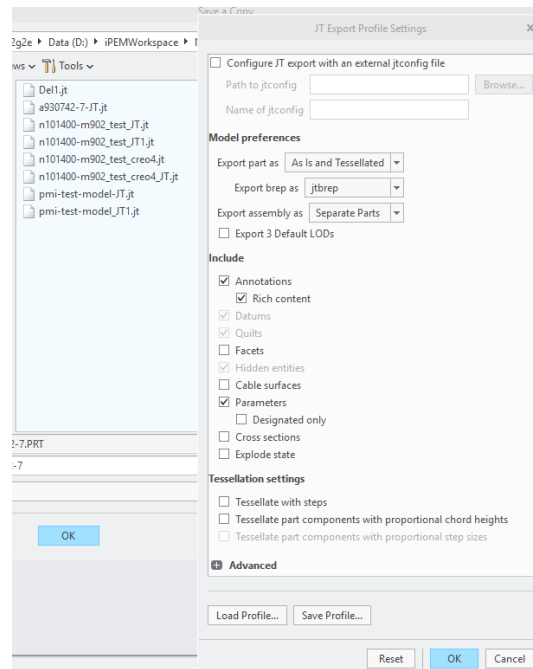
Manually created .JT file can be simply imported into Creo to perform a quick check of the PMI information and their appearances. The created .JT file can be manual uploaded into Teamcenter by using the below steps. Select the item ID and click new dataset. A wizard appears with the option of select the file type. Use the file type, direct model and a window appears to select the file from local drive. Upon selection of the created .JT file, press ok to upload into the Teamcenter. This file can be simply uploaded into Teamcenter PLM program which enables for easy consumption of the 3D model with PMI for manufacturing and inspection and throughout the whole process of the model based on MBD.
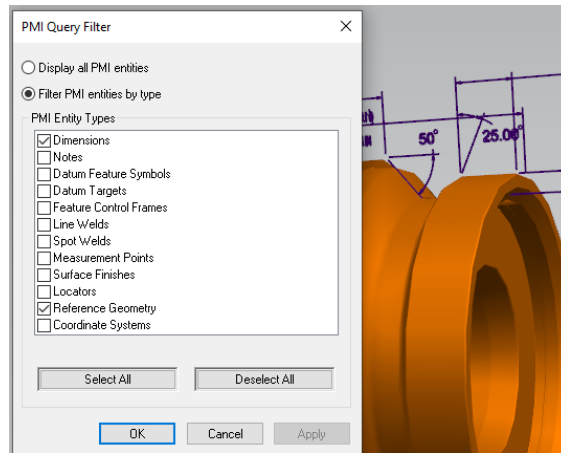
Figure 6-8 PMI filter selection in Teamcenter viewer

Models to be visualized through viewer tab in the Teamcenter user interface. Initially this does not show the PMI information in the 3D viewer window. To enable PMI information, the PMI button to be activated and select dimensions in the filter menu as indicated in the below picture.
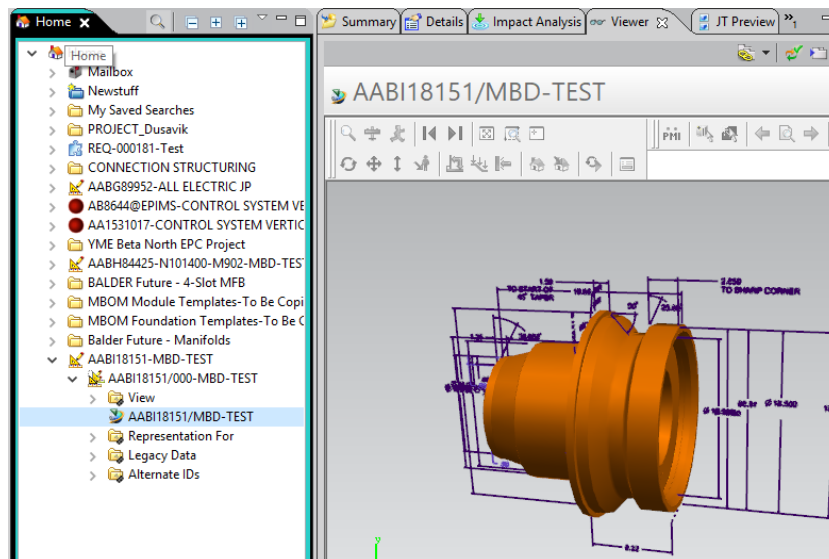
Figure 6-9 3D model with PMI in Teamcenter JT viewer

Default Creo program does not create the JT files with PMI enabled in regular commercial version. This needs a special configuration during the installation of the program and manually create the JT files with PMI information.

A separate workflow needed to have the JT viewer enabled in future so that every model created from Creo will be automatically JT viewed or can be 3D viewed in 3D PDF.

6.6. MBD validation everyone - JT2Go App:

For easy visualization, the known source as we aware is PDF formats. So, the models created can be simply used with the 3D PDF platform. This has the option of viewing the models in 3D and can be able to rotate, zoom and pan etc to make it easy for visualization. However, the siemens provide the JT2Go app or pc-based software free of cost, this can be easily availed and used for the visualization. To get this free software, visit official siemens webpage (JT2GO, 2020).

Upon installation of the JT2Go software, the MBD based .JT file can be simply imported or opened from JT2Go software. Again, this needs a configuration to connect Teamcenter and JT2Go to open from PLM. After opening the user interface looks like below picture,
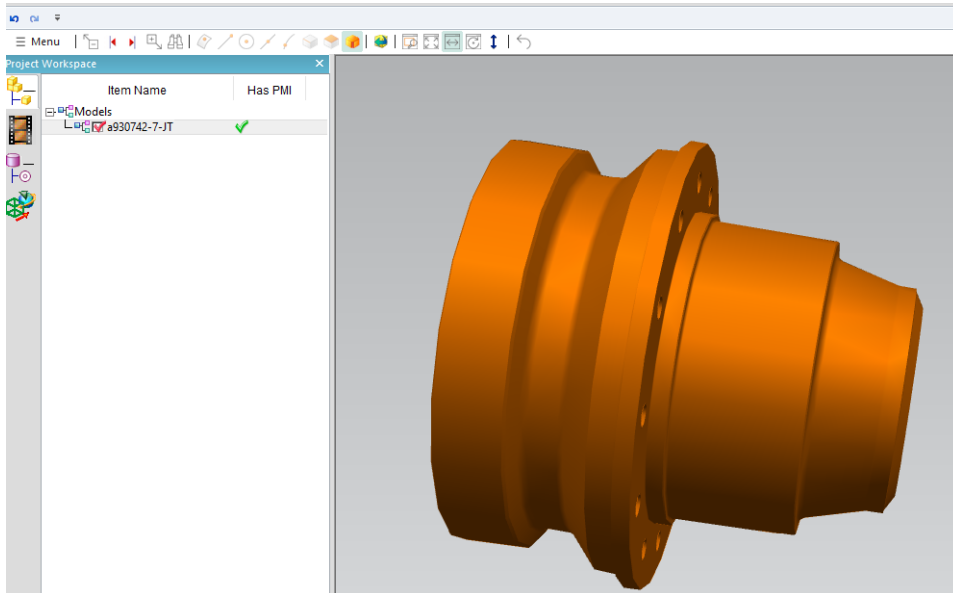
Figure 6-10 3D model with PMI in JT 2 Go viewer

Then select the model view option and toggle view as indicated below. This shows the various combination states with associated views listed as shown.

Upon selection of the suitable views, the 3D model with the PMI information is clearly visualized. Find the below picture showing the various combination states with the appropriate PMI data for visualization.

Figure 6-11 3D model with PMI in JT 2 Go viewer

App based JT2Go program can also be availed at App store or google play and can simply be used in any of the gadgets have these programs. However, this has the challenge of using the confidential documents shared among the personal equipment which can be controlled by using the confidentiality agreement or setting the .prt file with confidential status which can be only used in the company-based apps only.

Similarly, another commercial version of visualizing STEP file is eDrawings®. This is also freeware which can be downloaded and used for STEP file visualization as shown,

Figure 6-12 3D model with PMI in eDrawings

6.7.CAD to CAM:

Currently in many manufacturing companies and small-scale manufacturing vendors, 3D models are not 100 % reflecting the drawings and not controlled. So, it is not easy for the manufacturing to feed the models in the CNC machines. This needs additional review and modification on the 3D models. Also, typical CNC machines are FANUC program based and need a reprogram in the CNC machines before the machine can understand the 3D PMI.

To mitigate this, company initiated with an interfacing software to understand 3D model with PMI and can directly feed into CNC machine software. GibbsCAM® software interface program has been bought and installed in company-based CNC machines. GibbsCAM® software is tested in house with the developed MBD based 3D model for hub. The inbuilt PMI and semantic references in 3D model, can enable the CAM software to understand manufacturing information embedded. Refer section 6.4 for the detailed explanation of semantic reference selection. This confirms the right dimension and the right surface to be machined during CMM or CNC manufacturing.
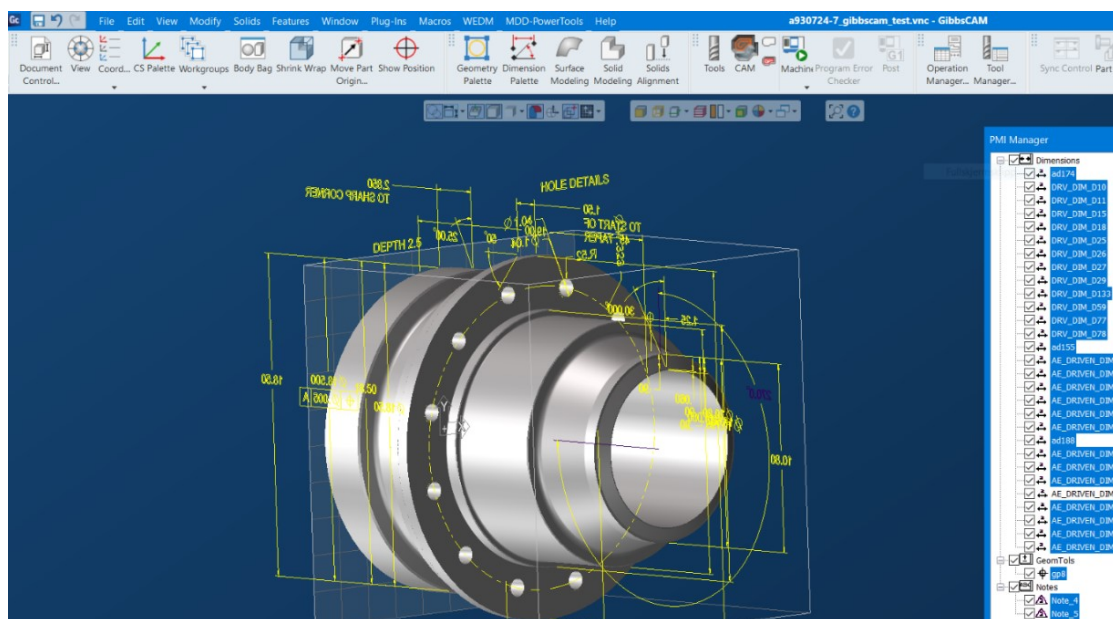

Figure 6-13 GibbsCAM – MBD model consumption

The goal is to consume the 3D models directly from Teamcenter which stored and handle the 3D models created with PMI. Workshop team with GibbsCAM® software have the access to Teamcenter. This need an interfacing script which can make the PLM and GibbsCAM® communicate to consume the 3D models directly. Part of study, the 3D models are manually sent to GibbsCAM® team which is consumed and tested in the CAM software. GibbsCAM®

program can consume STEP AP242 files and does not have the adoptability to consume .PRT and .JT files. Refer the above Figure 6-13 confirming the MBD consumption using GibbsCAM®. CAM program can understand the PMI information but needs many iterations to be make them understand the semantic references. However, NIST GCR 15-1009 (2016) recommend using ITIPDE library to convert STEP AP242 files into CAM understandable semantic surfaces. As per PTC corporation, they are already in the process of algorithm development in the upcoming Creo program provides the STEP files with semantic surfaces (Sematic references, ptc.com, 2020).

Instant quote:

There are numerous online based on demand quotation facility is available in the current market which is better with the MBD based model. For example, Xometry in an online based on demand manufacturing platform with a proprietary software platform to enable product designers and engineers to instantly access the capacity of a nationwide network of manufacturing facilities. This platform makes it possible for customers to receive instant pricing, expected lead times and manufacturability feedback. At the push of a button, the network can deliver high quality parts at consistently fast lead times while offering very low prices. Refer Xometry website (Online, 2019).

And in an industry the extra process of administration work across the manufacturing is also a matter and that is becoming more digital and agile each day, time is more valuable than ever. Instead of waiting for someone at each machine shop to sit down and spend several hours calculating how much material and labour goes into a project, instant quoting enlists Computational Geometry algorithms to calculate these variables in a matter of seconds.

So, it is essential to have the 3D model with the PMI information embedded on to it and a mere upload of this into the online portal of Xometry can simply create the quote and the lead time for manufacturing or 3D printing of the models. The process involves with upload 3D models, online proprietary platform analyses and provides quotation and lead time for the parts to be manufactured, order the part and shipment. This has been tested by uploading the MBD based models and got the quote right away.

6.8. CMM & inspection

CMM is the coordinate measuring machines those are sophisticated these days with software's combined with Robotic arms which can understand 3D models and makes the conventional Inspection and measurement process automated with less manual interruption. There are various commercial CMM software solutions available to interface the machine with models. This software can be feed with the MBD built 3D models which automatically identifies the PMI and the related semantic surfaces. This will be compared against the actual machined surfaces to inspect and create report for the deviations. Software's like Spatial analyser® enabled with Romer ARM, Inspire with Romer ARM and PCDIM® are equipped in the UK division of the company which has been tested against the MBD test model.

Spatial analyser® and Inspire® with Romer Arm:

Spatial analyser® and Inspire® software interfaces with portable measuring instrument Romer arm which is used to test the MBD model. SA allows various 3D model file types and the test formats created are. PRT, .STEP AP 242 and .JT. During the measurement check with .STEP format of MBD models using "feature check option", the software understand all the PMI data and captures few of the semantic surfaces information. STEP format to be enhanced for the full model consumption as is. As per PTC corporation, the upcoming Creo development version will be enhanced with algorithm to improve STEP files with semantic surfaces (Sematic references, ptc.com, 2020). After several iterations and update in the software, it is possible to make the model to be consumed. The same behaviour appeared with Inspire as well. Refer the below screenshots of both formats,
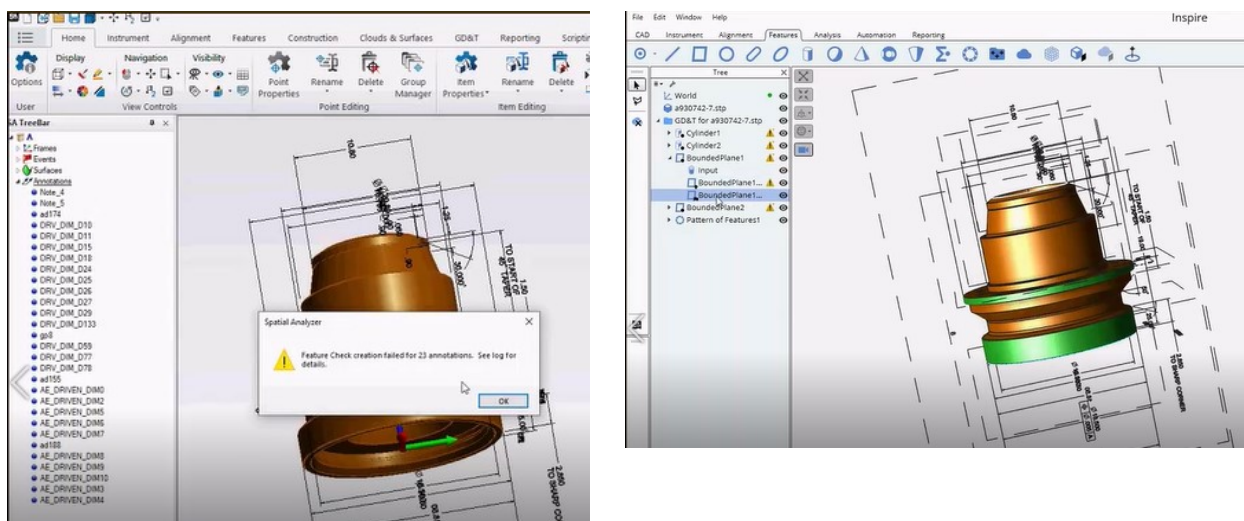

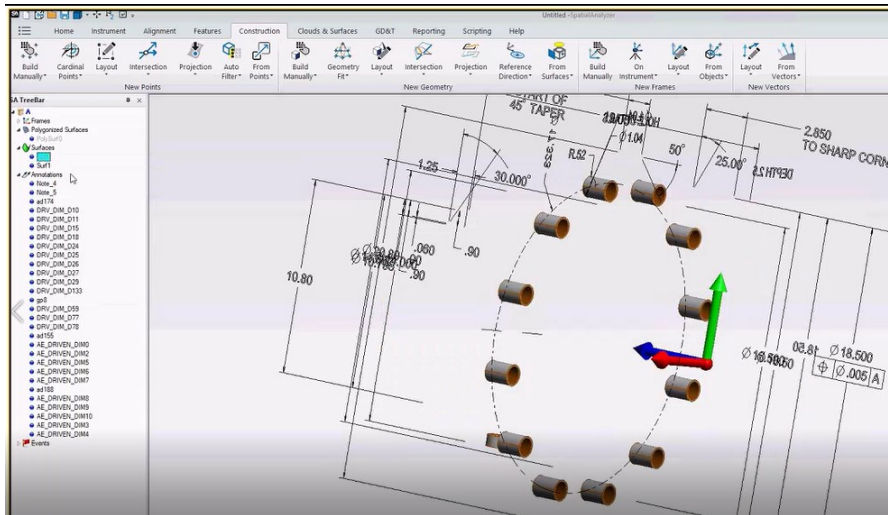*Figure 6-14 CMM testing – SA and Inspire (. STEP AP 242)*

Figure 6-15 SA understand hole features – STEP AP 242

While testing .JT format, it is clearly understood that this format does not help with consumption in CMM machines as this is majorly intended for visualization purposes. The software can understand the PMI and semantic references, but the graphical representation severely fails. Refer the below picture with the results in SA and Inspire programs,
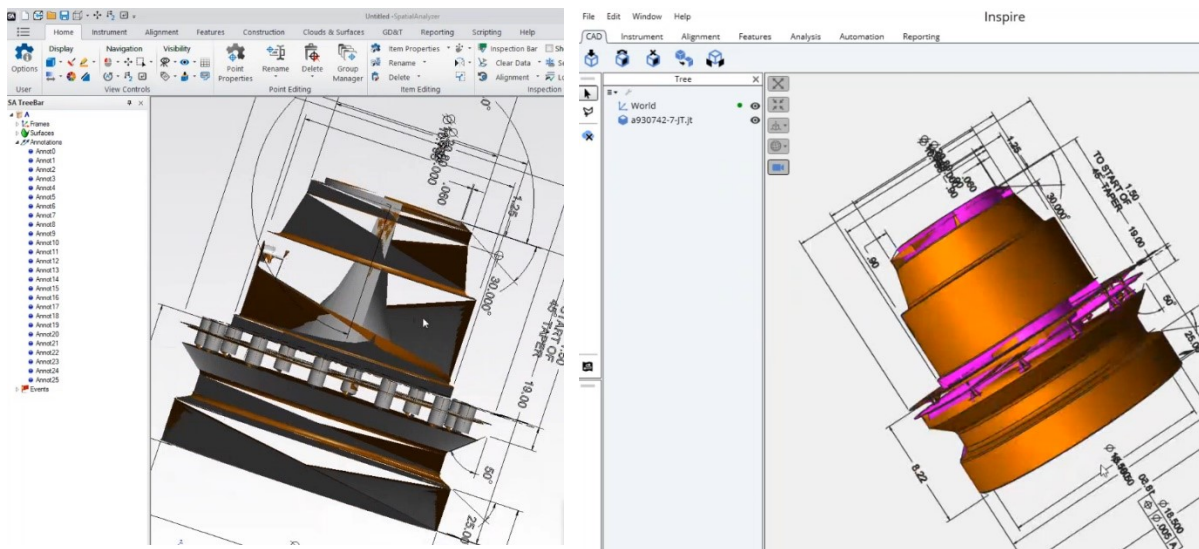

Figure 6-16 CMM testing – SA and Inspire (. JT format)

The best bet for Spatial analyser and Inspire programs for the model consumption is .PRT format which is Creo based. During the feature check of .JT file format, it is understood that surprisingly both can be able to consume most of the PMI features embedded in the MBD models and even understanding the semantic surfaces.

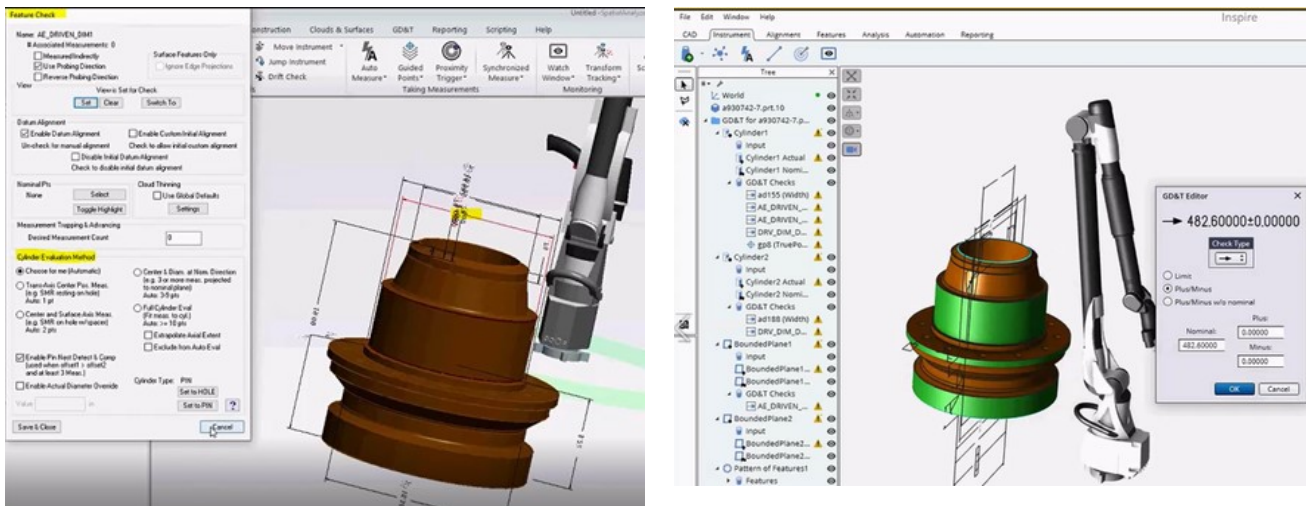Refer the below pictures as an evident of this,

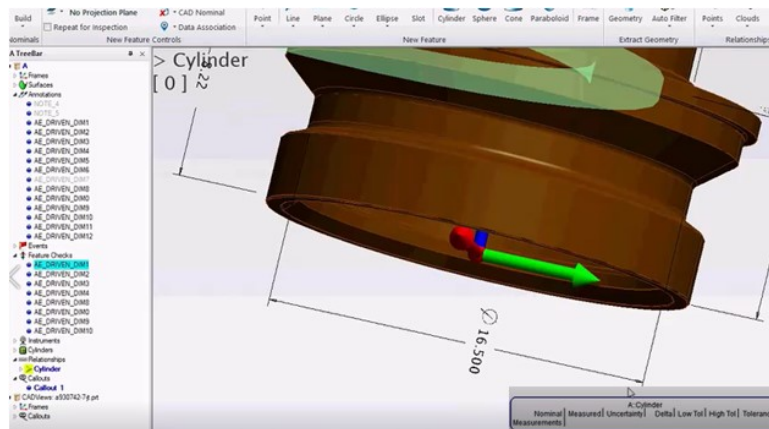*Figure 6-17 CMM testing – SA and Inspire understand MBD model (. PRT format)*

Figure 6-18 CMM testing – SA extract cylindrical surfaces (.PRT format)
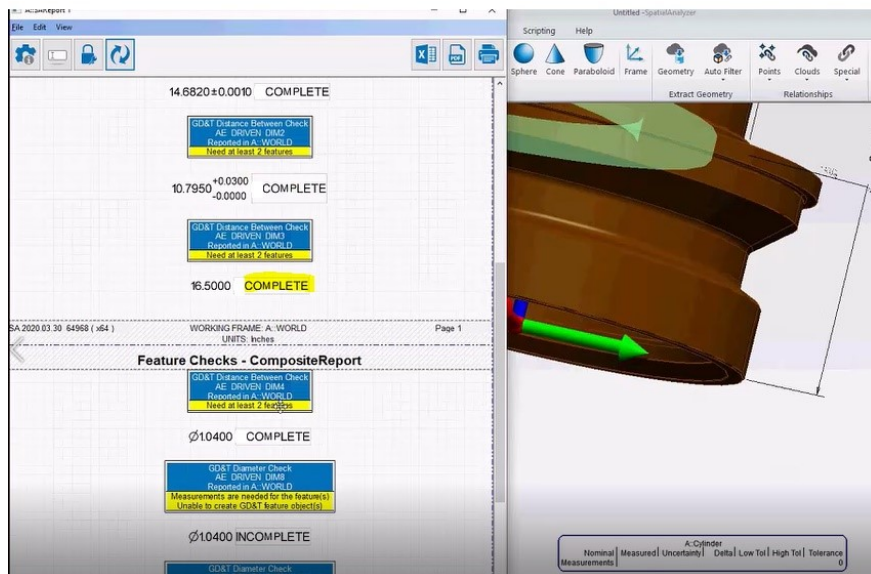

Figure 6-19 CMM – Inspection report – SA (. PRT format)

PCDIM®:

PCDIM® is the most commonly used CMM equipment with the specialised software which has been used these days in many organizations. The company has the CMM machine with PCDIM® software inbuilt to do the automated measurement. Three different format of 3D model with PMI have been tested those are .JT, .PRT and .STP AP242. Several iterations are performed to fix the small dimensional collisions and jump up of the notes. The STEP AP242 file is working perfectly fine with the machine. The PMI annotations in the 3D model is fixed multiple times so that PCDIM® software can understand and consume without any error. Refer section 6.4 for assigning semantic references. Find the below picture of the PCDIM machine which has been tested with STEP AP242 format and it can be able to understand the PMI information. However, this does not understand all the semantic surfaces due to the lack of semantic reference understanding by STEP AP242 formats. As per PTC corporation, they are already in the process of algorithm development in the upcoming Creo program provides the STEP files with semantic surfaces (Sematic references, ptc.com, 2020). Also, it is highly essential to have closer communication between the CMM software team and follow the guideline of them to make the successful creation of model with semantic referenced PMI.
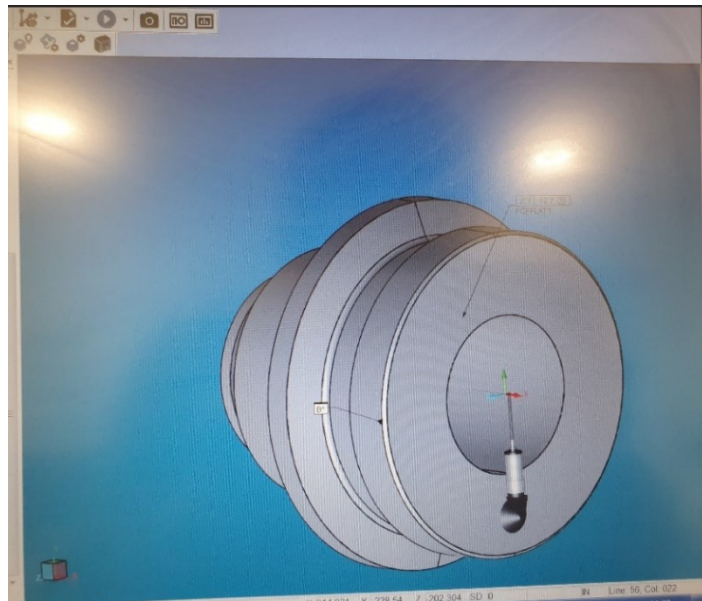
Figure 6-20 PCDIM machine – STEP AP 242 format

PCDIM® does not understand the .PRT and .JT formats and it throw error. Find the below picture depicting the error message from PCDIM machine. However, to mitigate this issue, the spatial analyser or Inspire to be combined with the CMM machine to get better results for the MBD based models.
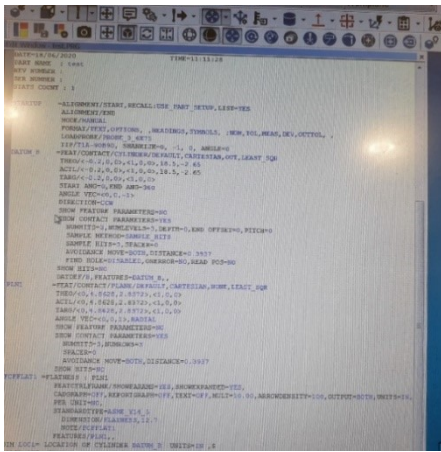
Figure 6-21 PCDIM machine – .PRT file   *Figure 6-22 PCDIM machine – .JT file*
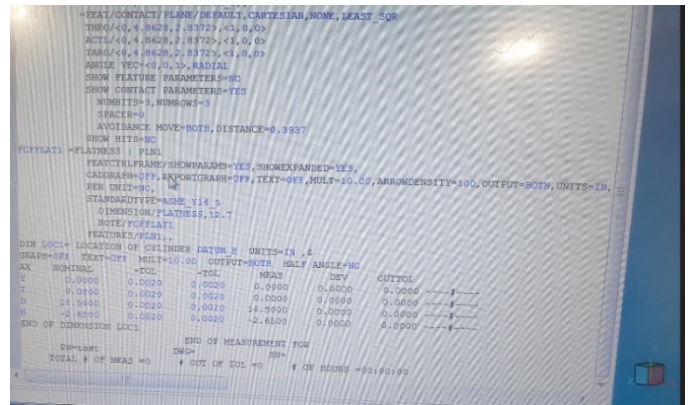
PCDIM® with Inspire or spatial analyser program combination helps to understand. PRT and .STEP file with PMI and semantic references. Refer the below picture,
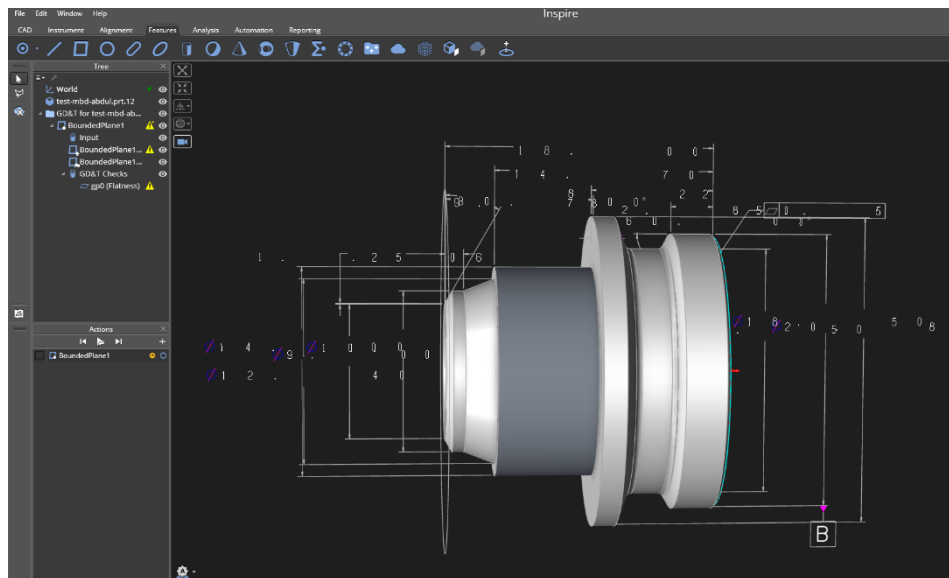
Figure 6-23 PCDIM machine with Inspire - .PRT format
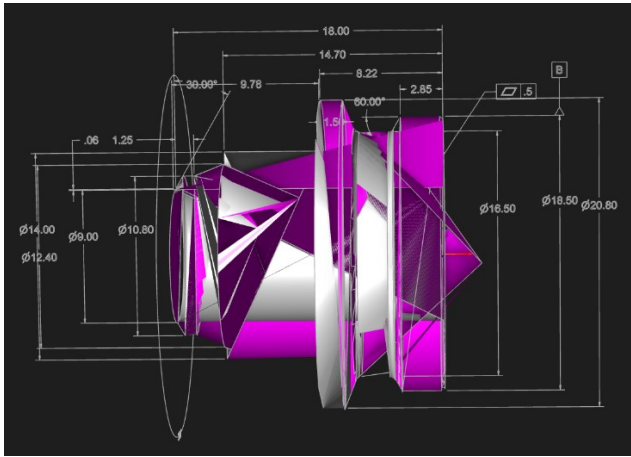
Figure 6-24 PCDIM with Inspire - .JT format   *Figure 6-25 PCDIM w/Inspire - .STEP AP242*
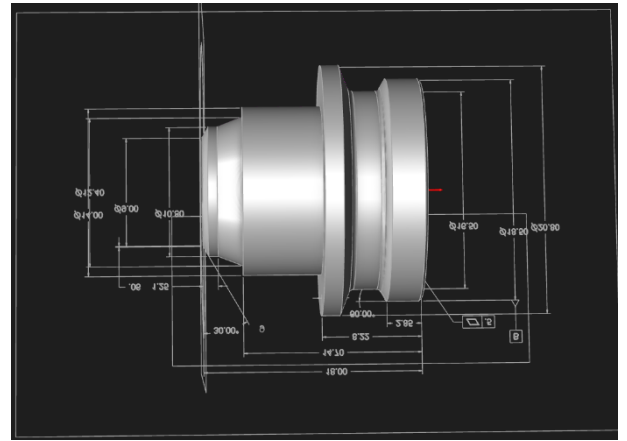
For the queries related to the semantic references and the way to fix them before consuming into the CMM, refer Appendix A – Semantic FAQs:

FARO® Arm:

FARO® Arm is similar to spatial analyser and Romer arm as described above and this is most popular CMM robot as of now among the manufacturing industries. The example model (.STEP) has been sent and tested with the FARO® Arm and it can be able to successfully understand the PMI information's.

Figure 6-26 Quality checking (Ferro Arm)

6.9.3D PDF / On demand drawing

The software has the capability to automatically build the views in 2D drawing from the MBD views. Views can be arranged later if any improvements needed. Below picture is only an example showing the view of the hub for presentation purposes.
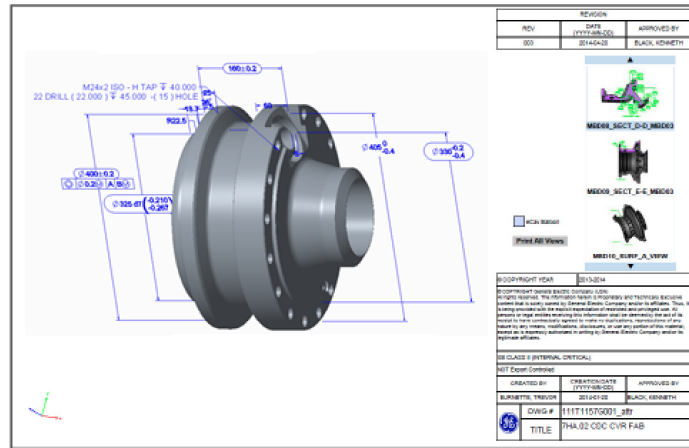
Figure 6-27 3D PDF / On demand drawing

7. Industry application and expected benefits

This section briefly recommends the steps to be implemented in the organization to get them ready for the MBD situation and further successful implementation. An assessment has been performed on various product life cycle steps to help understand the easiness of the implementation. Also, expected benefits of MBD is described in detail level of the organization with a list of future scope steps.

7.1. MBD application assessment:

The application assessment form depicted below, and the values are achieved based on the interview / discussion from the management and various inter-departmental teams. Refer the below table,

SI. No	Criteria – Life cycle	Easiness (1-Easy, 2-Medium 3- Hard)	Remarks
1	Implement Creo 4.0	1	Creo 4.0 version can be rolled out in future due to upgrade from PTC
2	Creating guideline document for MBD	1	Assign a resource for this. This document can be referred. Need a costing budget.
3	Workflow / Enforce all newly created 3D models to include PMI information	2	Convince the global team, local team and create a new QMS documentation to enforce this. This document can be based on guideline document.
4	3D models to have semantic surface references for inter-operability and consumption with CNC / CMM	2	Upgrade to Creo 4.0 can simply resolve this issue. However, this has some limitations that needs to be identified and communicated to PTC for future updates
5	Tender phase - CTR to include MBD estimate	1	CTR template to be updated with this

6	Training on the MBD and model creation with PMI	2	Training budget to be approved
7	Migration of existing legacy drawings	3	Conversion of legacy drawings (millions of old drawings). A huge cost involved. However, this can be started with new projects
8	PLM with MBD based workflow	2	PLM software team to be communicated and budget to be planned for this new workflow.
10	Interface software to automatically create .STEP file and JT file during check-in operation. Alternatively create a Teamcenter workflow.	3	Teamcenter administrator to assign this task. Budget to be planned for this.
9	All 3D models to be review / released	1	Need closer review and enforce the newly created models
10	Manufacturing engineer position for additional review of models on Manufacturability	2	Management to come-up with this budget. Alternatively design engineering to do additional review on this
11	CMM – PCDIM, SA and Inspire with Romer ARM, Faro ARM to be implemented the STEP file with PMI consumption	2	PCDIM, Spatial analyser and Inspire can consume the .STEP and .PRT files. However, the improvements on STEP AP 242 to be enhanced for semantic references.
12	CAM software upgrade to consume MBD based models	2	GibbsCAM has been initiated for the MBD model consumption to CNC machines. However, this software can consume only STEP files. Need upgradation in STEP with semantic references.

Table 7-1 MBD application assessment

7.2. Application and organization measures

To successfully apply MBD practices within the industry, below actions needs to be taken care of,

7.2.1. Engineering design:

The central critical element of the MBD implementation is the engineering design team and 3D modelling software. Here, the 3D modelling software Creo has been studied and the existing version of 3.0 to be upgraded to version 4.0 which is highly supportive of MBD practices and for semantic surfaces. As a pilot application, Creo 4.0 has been locally installed based on the appropriate license from PTC. Also, Creo 4.0 implementation process is initiated throughout the organization. Refer the below picture.
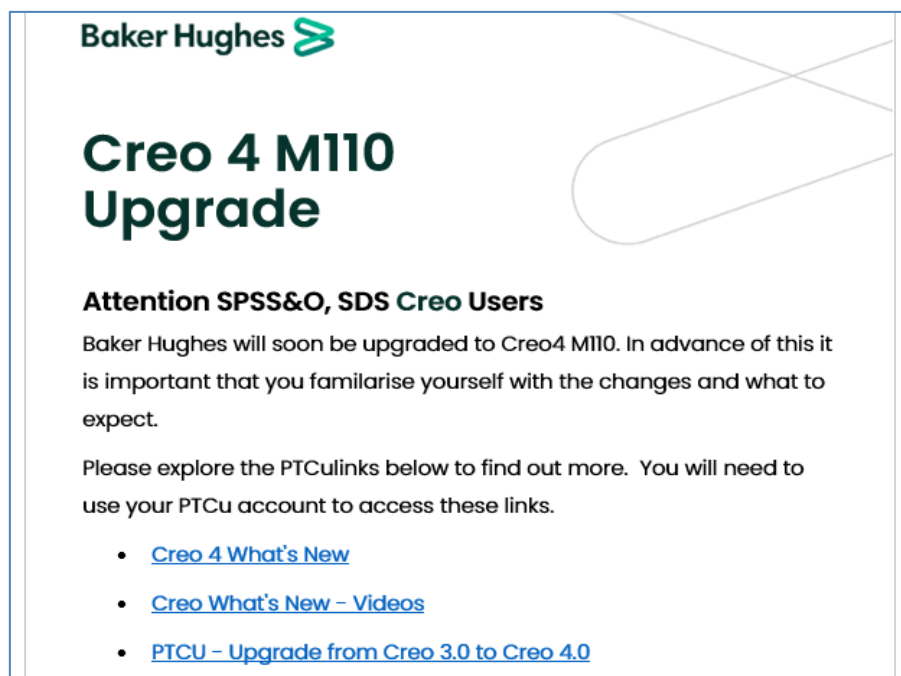
Table 7-2 Creo 4.0 implementation

7.2.2. MBD model review and validation:

The 3D models with PMI information has to be technical reviewed by reviewer and approver of the organization. As the 3D model is becoming a Master, it has to be completely checked against the right dimensions and property values on which the model has been built on. Also, this model is aimed to be consumed throughout the product life cycle process and manufacturing processes, the semantic references to be cross verified against those annotations. As the Creo has manual selection of semantic references, it is highly inevitable to

double check those references. For this either an additional manufacturing engineer or CMM expert need to involve in the technical review on the initial phase of the MBD application.

In alternate, an additional manufacturing engineering review position can be opened, and the person can be held completely responsible for this review. This assures the 3D model is made with error free and can be directly consumed to the CNC machines or CMM machines.

7.2.3. Checklist for MBD validation:

The model checking process can be established based on the checklist captured with all the relevant checks against the MBD based 3D model. Refer 0 for the example checklist developed for this purpose

7.2.4. Guideline document for MBD process:

To enforce and execute the MBD implementation throughout the organization, it is important to create a guideline document and released in the global database for the entire organization. In the company, Agility database is used as a quality management system to establish and govern the various engineering processes. Section 0 has enough information and acts as a base for creating this guideline document for the MBD implementation. This document to be formally reviewed and uploaded into the Agility database for implementation.

7.2.5. Visualization of 3D models for everyone:

As described in the section 6.5.2, the 3D model and annotations can be visualized in the JT2Go app, eDrawings desktop-based program which is freely acquired online. Any of the similar 3D visualization program can be used for this purpose, for example ANARK or 3D PDF. This does not need any extra investment for the organization.

7.2.6. Manage MBD files in PLM:

PLM program of Teamcenter can be simply upgraded with additional script to automatic creation of .JT files during upload from Creo 4.0. Also, an additional check point to be added in the workflow to review the models with MBD perspective and the checklist can be provided as a link for the check point. This workflow saves a lot of time on repeated reviews during the CMM / CAM consumption process.

PLM also needs configuration with JT2GO program to directly open from Teamcenter.

7.2.7. Direct consumption in CAM /CMM:

As company already initiated the GibbsCAM program for CAM, direct consumption of STEP file is possible. However, the semantic surfaces further researched for the STEP file format for the direct consumption. Either improve the possibility of identifying semantic surfaces or make the GibbsCAM to consume the .PRT format. The semantic enhancement is ongoing by ptc corporation (Sematic references, ptc.com, 2020). For CMM, both .PRT and STEP AP242 are currently supported in Spatial analyser, Inspire with Romer Arm. STEP AP242 format can be consumed by PCDIM machine. So, implementing the CMM machines in each unit and make a separate workflow for the MBD implementation and create inspection reports can be started right away for the similar hubs.

For CMM/CAM cases, the key is to build the model with proper semantic references in each and every annotation. Currently it works fine with .PRT with careful implementation of semantic references for driving dimensions and all the annotations and it needs the design expert to review and approve before releasing the model for consumption. For the STEP AP242, Algorithm development is ongoing for the semantic surface consumption and with this it is easier to consume (Sematic references, ptc.com, 2020). However, learning and understanding the criticality is the key and specialised training with guideline document establishment in addition with closer communication between the CMM software team will make the MBD implementation successful.

7.2.8. Future study and query fixes:

Technical queries related to semantic references are listed in the Appendix A and couple of queries and issues such as angular dimensional semantic references need to be fixed on the way forward.

7.3. Expected benefits

- Reduction in cycle time for drawing creation

Each new 3D model and drawings consume the approximate engineering hours as below for the example case. Detailing / drawing creation involves below activities which causes enormous engineering hours those can be saved,

- Creation and selection of appropriate template

- Maintenance of templates
- tidy-up of various views and annotations
- Placement of views and art of placing the views and annotations in a way that the drawing looks clean and neat
- Maintenance of model and drawing files
- naming both of them, parameter assignment and control of placement of other symbols
- various drawing annotations
- View position for understanding and change of position based on difference in opinions

Desc.	Model creation (hours)	2D drawing creation (hours)	MBD based model centric files
Hub – for connections	15	20	25

MBD eliminates these extra efforts and saves the hours used on those. There is always an alternate opinion about the drawing. Find the above table for approximate estimation comparison between conventional 3D + 2D combination and MBD based files.

- Eliminating the need of re-creating models for CAM/CMM

The existing situation comes with two different files of 3D and 2D which lacks 100% one to one information. This takes an additional time for reconfirming right before the manufacturing consumption of 3D models in CAM. But making 3D model as "Master" based on MBD, the time required to re-establish the perfect 3D model for manufacturing and back - forth discussions are eliminated. So, approximate engineering hours of each model of approximate <u>15 hours</u> is eliminated. This is only for one model and there are hundred are of them are executed in every week. Importing the model with embedded PMI required just 2 hours for CMM process preparation, set-up, programming, verification and inspection. When using the full-dimension-2D drawing the same activity required 10 hours. In all, exchanging a 3Dmodel with embedded PMI demonstrates more than <u>5-times</u> improvement in cycle-time over drawing-based or shape-geometry model- based practices.

- Reduction of cycle time due to automated CMM and inspection

As MBD based models can be consumed directly into CMM software for the inspection machines, the time required to do physical measurement and reporting process are saved. However, this depends on the accuracy of the MBD during MBD definition

- Digital readiness towards digital twins

More than time saving benefits, the important benefit of making the 3D models as "Master" makes the industry to get ready for the digital twins. Digital twins make the seamless communication between physical complex engineering equipment's with the virtual 3D models of them. Getting every industry towards digital twin is the way forward in future and there will be enormous benefits by the successful implementation of this.

- Trendy and the way to go

As the Industry 4.0, IoT and digital twins are becoming more and more trendy between industries, implementing MBD would be a trendy the industry and can able to lead the market with the catching up of trends and technologies.

- Demonstrate social responsibility and environment friendly solution

2D drawings cause printing of hard copy drawings for every process stage and thousands of prints are taken every day. Successful MBD implementation will eliminate the print outs and thus eliminates a lot of hardcopy print outs and that contributes the environment

- Digital integration between life cycle of engineering till quality check

- Significant increase in quality due to less manual interruption

- Improved efficiency and effectiveness

Due to review and quality control of one "Master" model instead of model + drawings, makes the design process more effective and efficient.

- Improved communication between the life cycle systems

Due to the "master" model and standard file types (.PRT, .JT and .STEP) maintained in PLM system, this can be simply used in other life cycle system until service.

- Improved financial performance due to reduced cycle time and respective cost

- Improved organizational sustainability

Due to effective product life cycle management of 3D models and making them digitally ready for further developments, the organizational sustainability and performance gets increased.

- Enhanced reputation

Through improved customer satisfaction, digital leadership, stakeholder awareness and confidence make the organization to gain the reputation

7.4. Scope for future improvements

○ Semantic references in Creo needs upgrade on the angular dimensions referenced from edges to make it clearer. This needs to be communicated to PTC for the further upgrade.

○ Semantic references as per Creo 4.0 for the driving dimensions to be assigned manually by the designer during PMI creation. Creo can accept any similar references for a particular dimension. This makes additional quality check on each individual surface with semantic references. This needs to be rectified by Creo new version and to be communicated on this. However, Creo automatically takes the relevant references for As-driven dimensions.

○ Checking Process Software – Design checklist to be improved with all the aspects of the MBD check and JT2Go software can be used for checking. However, this must be tested with huge assembly models.

○ Understanding and setting up the correct model in the first time with the appropriate semantic references are the key to the success of this process. Any initial engineering error leads to a major loss due to the cost of quality and re-work. Errors related to this needs to be identified and addressed. Ref the Appendix A FAQ section for future queries.

○ Some CAM software can consume only STEP files and CMM software are more comfortable with .PRT and .STEP file formats. Need upgrade on the semantic references work with STEP 242 file format. However, PTC is already working on this and this must be easy once they come forward (Sematic references, ptc.com, 2020).

○ Library Components process/direction (IFX tools works well, should be our future direction; requires purchase and can integrate current library into standard library.

○ Integrated Stack-up Application (1D in place but not used; need in-depth training and validation of application. Possibly need to address 3D stack-ups)

○ Spatial analyser / Inspire Software availability to all for the CMM consumption check or the CMM engineer availability in the initial phase of the project execution to be agreed

○ Legacy conversion of drawings. Company have many 2D drawings and 3D models without MBD's. Those has to be converted before they used on the MBD aspects. Need an automated process to proceed this.

8. Discussion

Overview

This section described the executive overview of the work conducted on the thesis, the learnings, practical challenges faces and future scope on the continuation of the thesis.

The overview briefly describes the work scope and tasks executed. Scope is to develop and check the implementation possibility of MBD based 3D models across various product life cycle stage of the enterprise. Make implementation steps as a reference document for global guideline document for BH. Develop checklist for MBD design.

Part of execution, an example test part is identified which is the hub of the subsea pipeline connection part. MBD 3D model for test part is developed by installing upgraded software as the existing software does not support MBD in the company. PMI and semantic surfaces are embedded. Road map and concept developed for implementation across enterprise. PLM has been tested with MBD models and possible with few additional workflows and scripts in the PLM software. Visual tools have been identified and proposed to the company for the easy accessibility of models to everyone. JT2GO has been tested with test part (.JT format) and found acceptable for semantic surfaces and consumption.

Part of MBE, CMM and CNC machine consumption has been checked. New software interface GibbsCAM has been identified and company is working with the integration of software integration in local unit. GibbsCAM has been checked and found ok for the MBD with PMI consumption and found it can work only with STEP 242 format. Worked with CMM team in UK and tested the MBD models with SA / Inspire and found ok for .PRT and .STEP formats. PCDIM team is found ok for .STEP format. However, STEP improvement on semantic references are already part of development from commercial versions of 3D modelling software.

It is highly possible to implement. Guideline steps are implemented in the thesis section 6 as a part steppingstone for the company document. Checklist is also developed.

Learnings:

Few points are captured as the learning steps during the execution of the thesis study even though there was more experience gained during the learning,

- Current trends in the digital industry and catchup

- End to end PLM solution across Industry and its practical implementation issues

- Digital twins, digitalization and automation in the subsea industry and its practical aspects the manufacturing set up, CAM / CMM.

- MBD and its design in-depth knowledge implementation across various industries. Studied with GE Power, Teams from various geographical locations for BH.

- Management skills, communication and Interpersonal skills - Get in touch with higher management in company especially Digital heads, NPI management team and Local site executive etc

- Confident to challenge the existing process in the Industry and negotiation skills to convince the teams with adopting new solutions

- Logistics and supply chain interactions during CAM implementation and understood the process

- CMM / CAM latest techniques

- International & Internal standards and their application on the design process

Practical challenges:

o Limited literature and references on MBD as it is a new technique

o Spent a lot of time on trial and error approach as the experts are limited globally. For ex. Semantic reference techniques for STEP 242 is not fully ready with the commercial versions and need to try various methods. Expensive webinars.

o Software available in the Industry is not updated with the MBD latest techniques and got special permission for study. Of course, this was time consuming

o Being a MNC industry, various sites have different goals and local unit has a tight cost target which makes the organization to not easily focus on changes.

o Also, various units have their own tools, software and implementing one process across the organization is too expensive and time consuming.

o Due to large scale MNC organization running the thesis is very time consuming. Each step needs a proper process, workflow to be followed, a lot of waiting time, delayed answers due to delivery priorities... etc are experienced

o Due to the Corona virus, pandemic situation, all the practical aspects of the implementation became a challenge and limited interaction with workshop. Planned to travel UK for the CMM techniques purpose and got cancelled

Future work:

Below aspects can be considered for the future as an extension of the thesis to make the MBD implementation improved across Industry,

- Improve semantic reference surfaces for easy consumption with fixing the bugs in the current technique and inform the software developing organization to make automatic cross identification of individual surfaces for driving dimensions. Also, few angular dimensions are not able to refer and need improvements or solutions
- Organizational guideline document based on thesis report section 6 to be developed and approved for enforcement in the company
- STEP 242 with improved semantic capability. Check with PTC for their latest revision to implement this issue
- Mentor the company for MBD implementation steps and drive changes to the organization by working with digital lead.
- Also refer section 7.4 for scope of further improvements

9. Conclusion

Study has been conducted for the MBD possibilities using a simple product example 3D model and assessed across various organizational process steps as indicated in the road map. The thesis study clearly identifies the MBD implementation is a highly possible in the company and similar industry with few additional processes steps, trainings, upgrade of design software, investments on the interfacing softwares and establishing guideline documents.

For engineering design, the PMI implementation is a highly possible with various design capable software programs. Though company using the Creo3.0 version, further update in the software program automatically triggers the MBD friendly Creo 4.0 which support the semantic references for the MBE friendly purposes. Same applicable to companies using NX, Solidworks and various other 3D programs with their latest versions. Making a guideline document on the technical details of annotation, dimensioning, GD&T techniques help the design team to follow the process easily.

On PLM, Teamcenter strongly supports the MBD based .JT files which can simply checked in into the item ID. However, this needs an additional upgrade or script in the software to

automatically create the .JT files during check-in operation. Also, the PLM need to automatically transfer various views created during the PMI creation. A separate workflow to be created and established for the process adherence on MBD implementation. An interfacing option to be built to open the JT2Go directly from PLM.

In the CMM, during the test with Spatial analyser and Inspire based Romer ARM, it has been understood that the software can easily consume .PRT and .STEP files. However, properly defined semantic reference is a key to the successful consumption of 3D models. Defining all the relevant surfaces makes an error free consumption by the CMM tools and this lies with the designer. However, few improvements to be studied in future on the angular, edge-based dimensions as the CMM tool can able to consume only the surfaces and calculates the edges from those surfaces. Also waiting for the updated STEP format for better semantic surfaces.

Based on the study proposal, GibbsCAM software team is working with Dusavik CNC machines for the implementation of automated 3D consumption process. Also, study has been conducted with GibbsCAM software interfaced for CNC machines which can consume the 3D PMI information from the MBD models build for testing. However, once again defining all the relevant surfaces makes an error free consumption by the CNC machine and this lies with the designer. However, few improvements to be further studies in future on the angular and edge-based dimensions for the 100% error free consumption. At the moment this can possibly consume only with STEP files and part of improvement scope in future is to integrate .PRT files as the CMM can easily consume with less error.

Even though the high-tech automation is the future for the industry, there are sub-vendors and small-scale industries are still using the conventional drawing-based manufacturing methods. To mitigate this gap, the on-demand drawings can be created from Creo 4.0 version which is kind of an automatic process which can bridge the gap between high tech and low-tech industrial process steps. There is also a room for further improvements during the successful implementation with additional adjustments in the process.

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# 11. Appendix

Appendix A – Semantic FAQs:

Few questions related to semantic surface definition are listed here.

1. How to select semantic surface reference for dimensions from interfacing surfaces? For example, which surfaces to be selected for 1.25 mm dimension. How does the CMM software understand?
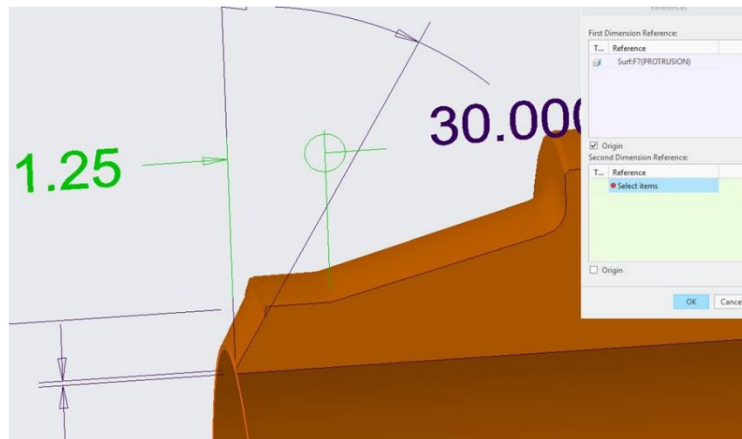

   Choose the flat surface plane which is forming the 1.25-dimension start point as a first reference surface. For the second reference surface, choose the cylindrical surface and angular surface interfacing both and forming the second end of 1.25 dimension. The CAM/CMM software makes as a separate feature and reads the dimension from that.

2. How to select the right surface for 0.06mm dimension as shown below as semantic references?
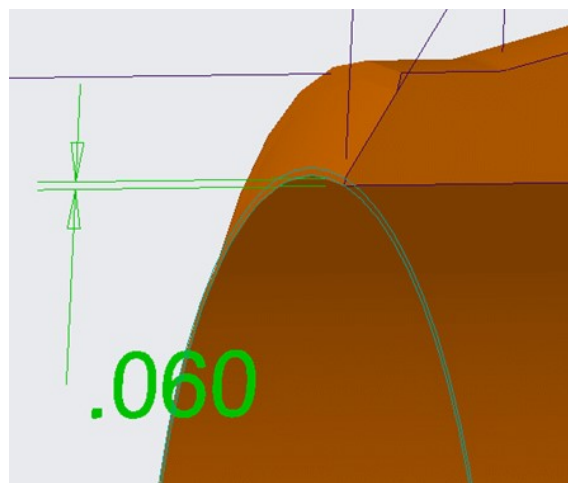

   For first reference, choose the inner cylinder diameter and for the second reference, choose the flat face and angular surface forming the second edge of 0.06 mm dimension. Software cannot be able to read by only the single surface formed from face.

3. Does the CMM software understand the edges directly and the annotation created from the edges?
   CMM software cannot understand the edge instead it understands the surfaces those who interfere and form the edges.
4. How to assign semantic references on the cross-sectional view? For example, the below dimensions formed shown. Can the edges be selected as references?
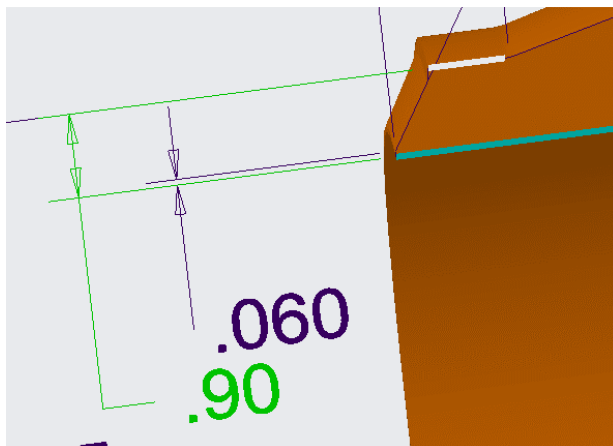
Selection of edges to the cross-sectional view does not help with semantic references as the dimensions are formed from edges instead of geometrical surfaces. The concept of semantic references are formed based on geometrical surfaces. For the above case, the dimension 0.06 to be formed from inner diameter surfaces and interfacing surfaces between face and angular surfaces.

5. What is the difference between Driving and As-driven dimension during semantic reference assignment?
   For Driving dimensions, semantic references to be manually assigned whereas As-driven dimensions automatically use the reference surface during the dimension creation itself.

6. How to assign semantic references for angular dimensions?
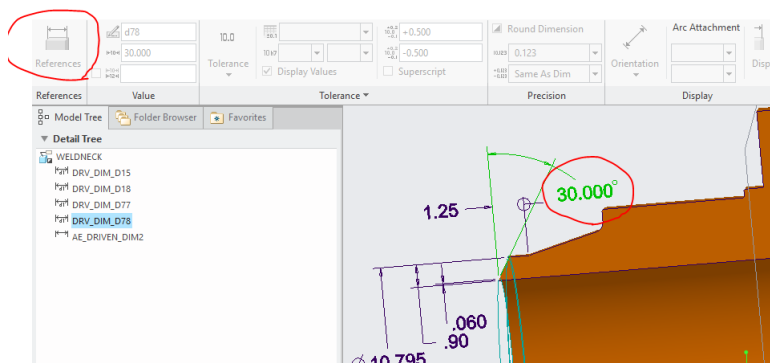
It is possible to assign semantic references for angular driving dimensions and the driven dimensions automatically use the references during creation. However some angular dimensions doesnot allow this which may be a bug during creation and it is necessary to carefully assign during creation.

For other queries, refer the relevant user guide / help page of the appropriate modelling software.
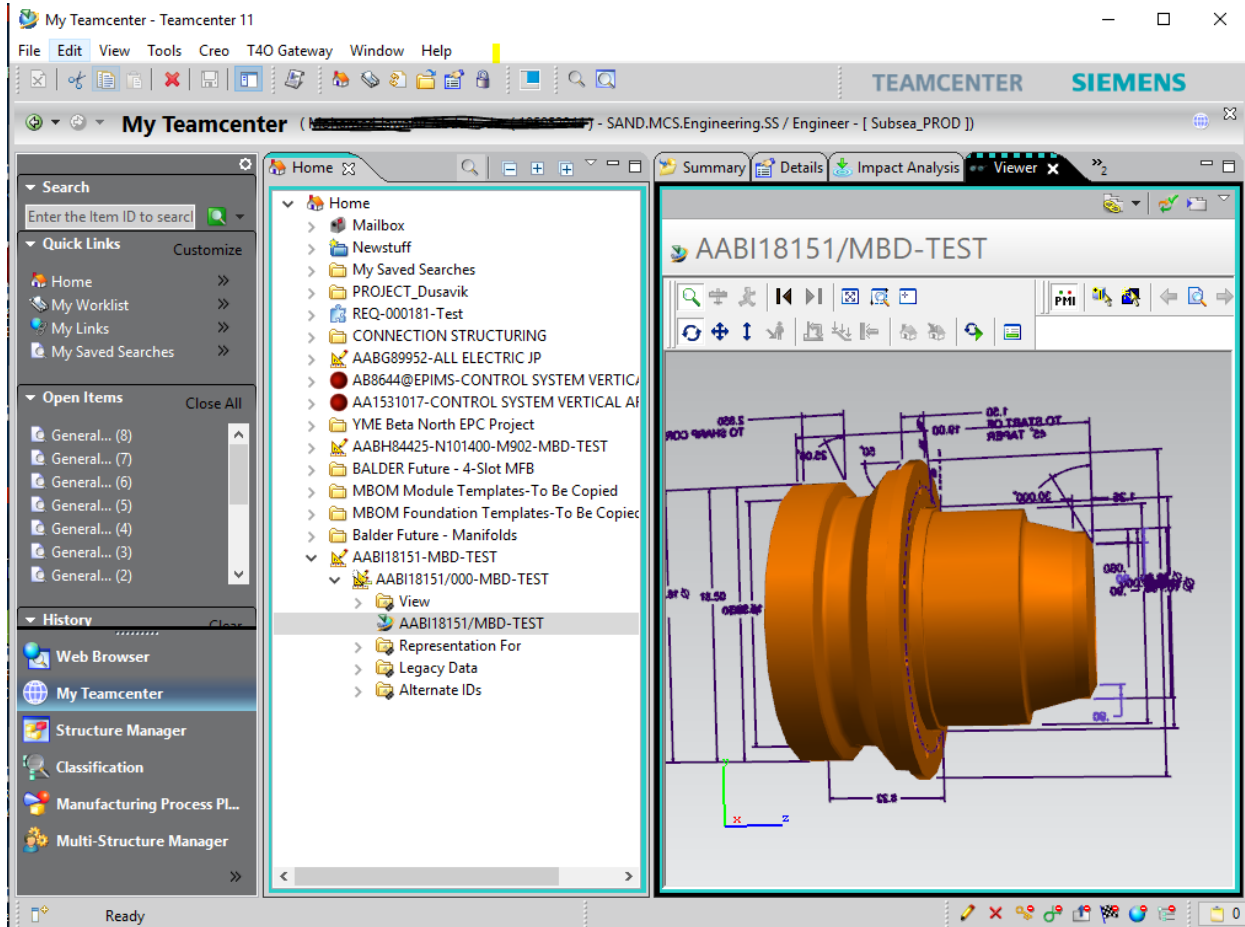
Appendix B – MBD 3D model

Due to the confidentiality of the hub model and drawing, the model is not attached instead a picture of the model is depicted below as it is only a test case.
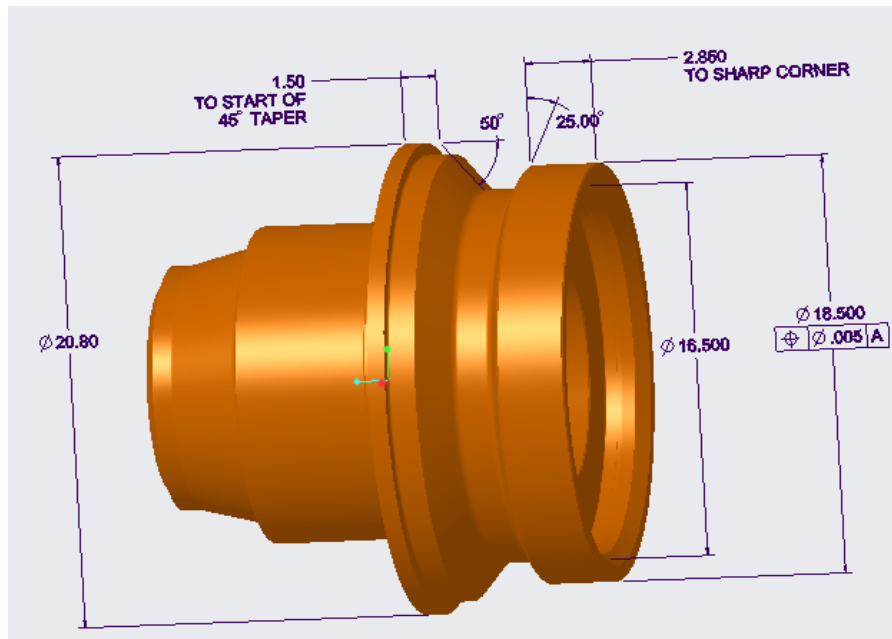
Appendix C – PLM

PLM landing page with MBD test part is shown for the illustration purposes,

Appendix D – MBD model quality checklist

MBD model quality checklist for the design review is created and attached below as a part of thesis report. For confidentiality reasons from Industry, only MBD related points are captured and shown below,

BH Quality Management System
Engineering
Creo model quality checklist for all products

This checklist is supplemental to:		●	Absolute Requirement
GL-ENG-060 Detail design checklist for all products		O	Conditional requirement
		X	Not Required

CONDITIONAL REQUIREMENTS:
Duplication of Ref Model (W/O NC program)
Modification of these features will result in a robust model, but has an impact on time and cost, hence these items are to be discussed with the engineer on case to case basis, if agreed only then are the features to be modified.
Duplication of Ref Model (With NC program)
Modification of these features will affect the duplication of the available NC program, besides impact on time and cost, hence these items are to be discussed with Manufacturing on case to case basis, if agreed only then are the features to be modified.

#	Check Point	Verified	New Model	Duplication of Ref Model without an NC program	Duplication of Ref Model, with an NC program
MBD specific					
37	Adhere as per O&G guideline document, OCG-ENG-0116.2 (TBC, based on section 6 of study report)		●	●	●
38	Implement PMI with appropriate annotations. All dimensions are shown not created		●	●	●
39	Views properly named		●	●	●
40	View position assigned appropriately as per the view and PMI for clarity				
41	Respects GL-ENG-024 thru GL-ENG-028		●	●	●
42	Semantic references for driving dimensions to be assigned and checked against annotations		●	●	●
43	Semantic references for as-driven dimensions to be checked against annotations		●	●	●
44	Misc. models not used were removed from association		●	●	●
45	Model dimension in Notes are parametric not a text.		●	●	●
46	Views are large and legible		●	●	●
47	Assign view name in flat to screen		●	●	●
48	GD&T datums to be added in semantic references		●	●	●
49	Model annotations are arranged and moved to the respective views to get tidy-up.		●	●	●
50	Features of Inheritance model not used as references for geometrical dimensions		●	●	●
51	PTC Modified parameter to be set to NO to ensure drawing and model are synchronized		●	●	●
52	Model to be in released state before publishing.		●	●	●
52	All driving and driven dimensions, GD&T and relavent annotations are assigned with semantic references appropriately. Refer Appendix A for the FAQ		●	●	●
52	Check and review all the assigned PMI and the semantic references to ensure they are directly consumed into CAM/CMM		●	●	●

#	Check Point	Verified	New Model	Duplication of Ref Model without an NC program	Duplication of Ref Model, with an NC program
Storage					
53	Checked into Teamcenter database. Follow the guideline instructions during save, OCG-ENG-0116.2 (TBC, based on section 6 of study report) with PMI rich content		●	●	●

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Creo model quality checklist for all products

#	Check Point	Verified	New Model	Duplication of Ref Model without an NC program	Duplication of Ref Model, with an NC program
54	Save as .JT file and start the workflow in Teamcenter to automatically inbuilt the MBD based .JT files. Follow the guideline instructions, OCG-ENG-0116.2 (TBC, based on section 6 of study report)		●	●	●
55	Save as STEP 242 file and start the workflow in Teamcenter to automatically inbuilt the MBD based .STEP 242. Follow the guideline instructions, OCG-ENG-0116.2 (TBC, based on section 6 of study report)		●	●	●
56	Release Level set appropriately		●	●	●
57	All status signals and locks are removed after modification		●	●	●

Appendix E – MBD data collection

Below pictures show the method of data collection for the MBD implementation. Attended special webinars from MBD experts, attended meetings with various teams in company such as digitalization head, engineering head, quality team head, CMM expert team, CAM external company experts, design engineering organization manager, Creo superusers and so on.
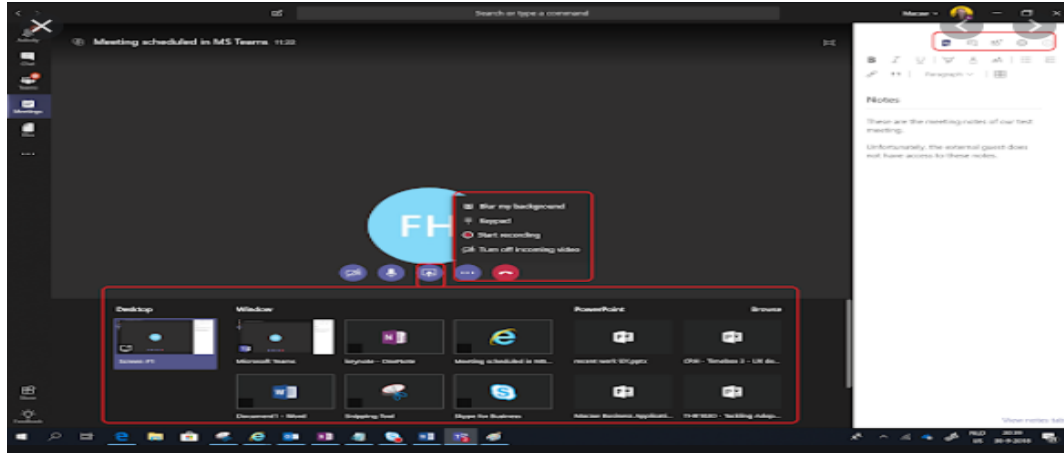
RE: Semantic query - clarification

Thomas, Nick
To Abdulkader, Abdul

↩ Reply   ↩ Reply All   → Forward   ⋯

ons. 06.05.2020 11.16

ⓘ You replied to this message on 27.05.2020 09.11.

Hi Abdul,

Your questions are all quite complicated..... My responses below for your review.

1. So the 1.25 dimension from an inspection standpoint is the distance between a. The plane (top face) and b. the centre of the circle formed by the intersection of a cone and a cylinder.
   The inspection here would be to measure the plane, measure the conical feature, measure the cylindrical feature, construct a circle from the intersection of the cone and cylinder, then check the distance from the circle to the plane. This needs maybe 3 or 4 different reference surfaces/features. These are the kind of features we need to have discussions with the inspection software companies to see what they are capable of doing

2. Also a very difficult dimension. We cannot use just the surface as probing will only collect a few points of the plane to define it and not 100% of the surface. This feature is really the difference in diameter of two circles constructed from intersection a. Intersection between top face and internal cylinder and b. intersection between the top face and conical surface. In this instance the inspector or CMM would inspect the top face, ID cylinder and external cone. Then circles would need to be constructed from the features and finally a mathematical operation to calculate the difference between the diameters. There are 3 reference surfaces and 2 additional constructed circles. Another one for us to clarify with the inspection software companies

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ⓘ Attendee responses: 4 accepted, 1 tentatively accepted, 1 declined.
You've received new time proposals for this meeting. Click Scheduling Assistant to view all proposals.

Send Update	Title	3D model with MBD - throughout the PLM
	Required	Fatehi, Kamran David; Artime Fernandez, David; Torkelsen, Stig Andre; Ogreid, Frank Ogreid; Bo, Ellen; Waage, Audun; Castello Branco, Joao Furtado; Rasaiya, Madhivannan
	Optional	Ather, Daniel
	Start time	ons. 22.04.2020 10.30 ☐ All day ☐ ⊕ Time zones
	End time	ons. 22.04.2020 11.00 ⟳ Make Recurring
	Location	Skype Meeting

Agenda:
3D model with MBD implementation initiatives across PLM / CAM / CMM

....

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