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Analyzing the opinion of industry professionals on model-based definition datasets to determine the most efficient method

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ANALYZING THE OPINION OF INDUSTRY PROFESSIONALS ON

MODEL-BASED DEFINITION DATASETS TO DETERMINE THE MOST EFFICIENT METHOD

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ABSTRACT

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Model-based definition (MBD) has the engineering and manufacturing industries moving towards a model-based enterprise (MBE) where traditional two-dimensional (2D) drawings may one day no longer be needed. With MBD, the product data will be contained in the three-dimensional (3D) computer aided design (CAD) model itself. MBD provides a wealth of benefits to users, including reduced time-to-market, product quality, and task efficiency. Even with all the benefits of MBD, there is still no best practice when it comes to implementing MBD. Different strategies of MBD datasets exist, however none have been compared to see which method is more efficient. This project will investigate different MBD datasets and survey industry professionals to get their opinions on the subject.

CHAPTER 1. INTRODUCTION

Model-based definition (MBD) is a strategy involving the move from two-dimensional (2D) traditional drawings to three-dimensional (3D) computer-aided design (CAD) models, with the 3D CAD model acting as the central knowledge artifact. MBD will be focused on the 3D CAD model providing all the information the 2D drawing would so that one day drawings may no longer be needed in an engineering and manufacturing environment (Quintana, Rivest, Pellerin, Venne, & Kheddouci, 2010). MBD has a wealth of benefits (Adamski, 2010; Briggs, Brown, Siebenaler, Faora, & Rowe, 2010), including task efficiency (Camba & Contero, 2015). This project will explore creation strategies of MBD datasets to find the more efficient method based on the opinion of industry professionals.

This chapter of the project will introduce the research and the purpose of the research in regards to MBD. It will introduce the research question and give scope and significance for the research on MBD. This chapter will also give the limitations, delimitations, and assumptions made in the research. A list of definitions of important words and abbreviations will also be given at the end of this chapter.

1.1 Statement of Purpose

The most efficient MBD dataset is currently unknown. The term efficiency in regards to this research refers to less time on task and less rework of a process (Cross & Lynch, 1988). An MBD dataset contains "the exact solid, its associated 3D geometry, the 3D annotations of the product's dimensions and tolerances, and the dataset management information" (Quintana, Rivest, Pellerin, & Kheddouci, 2012b, p. 82). MBD is growing in popularity within engineering and manufacturing companies to help improve efficiency of engineering and manufacturing tasks. However, there is a incomplete amount of information in academic literature and in industry as to specifics of the best MBD creation and usage strategy, especially when it comes to efficiency. There is no unique approach of MBD implemented in industry (Alemanni, Destefanis, & Vezzetti, 2011). It is known that implementing MBD processes can help improve a company's efficiency (Quintana, Rivest, & Pellerin, 2012a); however, there is little research comparing the efficiency of the MBD datasets.

Industry standards exist, including ASME Y14.41 (2003) and ISO 16792 (2006), which help provide how to establish the data within your model. These standards also help to understand and interpret the data presented (Camba & Contero, 2015). While these standards provide a foundation for how to set up the model, there are no standards to help implement the best method of MBD. No other standards have been established due to the fact current MBD is heavily software driven and extremely customized (Alemanni et al., 2011; Huang, Zhang, Bai, & Xu, 2013).

Different strategies of MBD datasets exist, including the concept of the master model dataset. The master model is the idea that one model is the central artifact that contains the entire product definition (Adamski, 2010; Camba & Contero, 2015; Hoffman & Joan-Arinyo, 1998; Qunitana et al., 2010). While other strategies of product definition have been discussed, such as multiple views (Bouikni, Rivest, & Desrochers, 2008; Bronsvoort & Noort, 2004), there is little research and literature on comparing different methods of MBD datasets.

1.2 Research Question

The research question being investigated in this project is as follows: "is the master model MBD dataset more efficient than an alternative method of using multiple models?"

The master model is being used as the main MBD dataset because it is the most popular strategy based on research (Quintana et al., 2010). The term "multiple models" for this research refers to "several models for one object, where their grouping constitutes the product models for one object. The disciplines that participate in the evolution of the product definition have the possibility to extract information from those models to achieve their functionality" (Bouikni et al., 2008, p. 63)

1.3 Scope

This project will explore MBD, its relevance, and the benefits it carries as a way to try to find the most efficient MBD process for usage. This project's goal is to analyze two concepts of MBD datasets and compare them in different categories including usage to try to analyze efficiency in an engineering environment based on the opinion of industry professionals. The master model concept is the main MBD dataset, and this method will be analyzed and compared against an alternative method. The alternative method that will be used in this research will be a series of models that contain the exact same relevant information as the master model, but spread out amongst multiple models or other non-3D CAD files. To investigate this research, a survey mechanism will be administered and feedback from industry professionals from various sectors will be analyzed. After the survey has been conducted, certain respondents will be asked to be interviewed to gain further insight and gather more information.

1.4 Significance

The concept of MBD has been around for some time. In fact, Newell and Evans (1976) and Semenkov (1976) showed interest in a unique product model nearly three decades ago (Hoffman & Joan-Arinyo, 1998). MBD has not been widely utilized in the past (Adamski, 2010; Briggs et al., 2010), but now its popularity has grown substantially in engineering and manufacturing industries (Huang et al., 2013; Quintana et al., 2010).

MBD’s popularity is due to the many benefits it provides. These benefits include reduction in manually reproduced data, reduced errors in design, better communication, quicker response times, fewer files to maintain, and reductions in cost (Adamski, 2010; Briggs et al., 2010). Other benefits include a reduction in time-to-market and an improvement of product quality. Reducing the need to create 2D drawings can help reduce development costs and delays, which improves and accelerates the delivery cycle (Quintana et al., 2012a). Examples of this can be found in Price (1998) and Quintana et al. (2012a). In 1998, Boeing worked on a redesign of the T-45 horizontal stabilizer using a virtual product development approach where all manufacturing processes were completed virtually. This eliminated the need to generate 2D drawings. Using the virtual product development approach, Boeing achieved a 62% reduction in time and a 42% reduction in cost (Price, 1998). While Boeing's case is rather singular and many other companies would not be able to report the same findings, it does give some perspective on the production attained from using strictly models without the accompanying drawings. In another example, Quintana et al. (2012a) helped quantify the benefits and efficiency of MBD with a case study in an aerospace company. A reduction of 11% was achieved in the average processing time and cost when administering an ECO utilizing MBD.

With more companies and organizations moving towards a model-based enterprise, it is apparent MBD must be utilized to the full potential. According to Alemanni et al. (2011), "companies need a common methodology to structure data in reusable, unified forms inside of 3D models" (p. 13). Since improving the efficiency of tasks is one of the largest benefits to using MBD, it is important to find the most efficient MBD dataset. With a lack of academic research on the most efficient MBD dataset, a survey will be conducted to compare two concepts of MBD datasets with a goal of establishing an understanding of which concept is more efficient.

1.5 Assumptions

The following are assumptions that will be made with this research. These assumptions are beyond control but may impact the study:

- There is a need to determine which method of MBD datasets is more efficient based on less time and less rework of a process.
- The respondents will have enough experience and expertise on the subject to provide beneficial information towards the project.
- The assortment of respondents from various industry sectors will provide beneficial information towards the project.
- The respondents will be able to read and understand directions provided.
- The respondents will cooperate and provide concise, definitive, and honest answers to the best of their abilities.
- Respondents will be able to complete the survey and interview in their entirety.
- At the conclusion of the project, it will be clear which MBD dataset is more efficient.

1.6 Limitations

The following will be limitations with this research:

- This study is limited by the respondents' cooperation and willingness to complete the survey thoroughly, honestly, and to the best of their ability.

- This study is limited to the number of responses of respondents, as respondents will be specifically targeted through e-mail and Internet sites with the survey being completely optional.
- Qualtrics Survey Software will be the only tool used to create the survey mechanism.
- This survey will be limited to the 2016 Summer semester, from the months of June to July due to time constraints.

1.7 Delimitations

The following will be delimitations for this research.

- This research will not create a new standard for MBD.
- This research will not create a new method for implementing MBD.
- This research will not provide a best method for implementing MBD.

1.8 Definitions

The following are definitions of key terms used in this project.

ECO: Engineering change order – "changes to parts, drawings, or software that have already been released" (Terwiesch & Loch, 1999, p. 160)

Efficient: Less time and less rework (Cross & Lynch, 1988)

GD&T: Geometric dimensioning and tolerancing – "defining data that quantifies the variability, accuracy, and relationships of features and basic dimensions of the product" (Briggs et al., 2010)

Master model – An MBD dataset referring to one model serving as the central artifact containing all product definition (Adamski, 2010; Camba & Contero, 2015; Hoffman & Joan-Arinyo, 1998; Qunitana et al., 2010)

MBD dataset – "containing the exact solid, its associated 3D geometry, the 3D annotations of the product's dimensions and tolerances and the dataset management information" (Quintana et al., 2012b, p. 82)

Multiple models – "The existence of several models for one object, where their grouping constitutes the product models for one object. The disciplines that participate in the evolution of the product definition have the possibility to extract information from those models to achieve their functionality" (Bouikni et al., 2008, p. 63)

Product definition – "the set of product attributes, features or characteristics that coexists in a specific state of balance in order to meet physical and functional requirements as well as multidisciplinary constraints" (Quintana et al., 2012b, p. 79).

1.9 Abbreviations

The following are key abbreviations used throughout this project.

2D: Two-dimensional

3D: Three-dimensional

ASME: American Society of Mechanical Engineers

CAD: Computer-aided design

CAE: Computer-aided engineering

CAM: Computer-aided manufacturing

CAx: Computer-aided technology

ECO: Engineering change order

FT&A: Functional tolerancing and annotation

GD&T: Geometric dimensioning and tolerancing

ISO: International Organization for Standardization

MBD: Model-based definition

MBE: Model-based enterprise

MEP: Mechanical, electrical, and plumbing

NIST: National Institute of Standards and Technology

PDM: Product data management

PLM: Product lifecycle management

PMI: Product manufacturing information

TDP: Technical data package

1.10 Summary

This chapter has introduced the research for this project which is looking to find the more efficient method of MBD. It has given a problem statement, research question, and scope for the research. This research is significant because there are case studies which show that conducting ECOs in an MBD context can help improve efficiency, but no research on which MBD dataset is more efficient. Assumptions, limitations, and delimitations for this research have been given, as well as a list of definitions of key terms and abbreviations. The next chapter will be a review of literature to help better understand this research.

CHAPTER 2. LITERATURE REVIEW

The literature will cover background information on MBD, including different scenarios and variations. It will also explore CAD capabilities with MBD, and further investigate conducting ECOs utilizing MBD. There will be a summary at the end of the chapter to conclude the reviewed literature and identify any gaps.

2.1 Model-based Definition (MBD) Overview

Model-based definition (MBD) is the strategy of "moving away from paper drawings and other external means of product definition and making the CAD model the sole source for defining product and mold geometries" (Adamski, 2010, p. 39). Alemanni et al. (2011) define MBD in detail as follows:

> Model-based definition (MBD) is a new strategy of product lifecycle management (PLM) based on computer-aided design (CAD) models transition from simple gatherers of geometrical data to comprehensive sources of information for the overall product lifecycle. With MBD, most of the data related to a product are structured inside native CAD models, instead of being scattered in different forms through the PLM database. MBD aims are suppression of redundant documents and drawings, better data consistency, better product/process virtualization, and

better support for all computer-aided technologies tasks under engineering and manufacturing disciplines. (p. 1)

MBD allows design teams to provide all of their information within the 3D model, which could reduce the need to generate drawings. Previously, 2D drawings with geometric dimensions and tolerances (GD&T) were used for part definition. However, CAD software has changed the primary basis from 2D to 3D (Briggs et al., 2010). The evolution to modern MBD has gone from using 2D drawings to using 3D models along with the 2D drawings. In today's industry, 3D models are used along with 2D drawings, but one day 3D geometry will be the main source for product data (Adamski, 2010; Briggs et al., 2010).

Alemanni et al. (2011) state "[MBD] is a way of managing product data that a company has to tailor within its PLM framework" (p. 6). MBD is a way of managing different processes using 3D models as main sources of information for "design, production, distribution, technical documentation, services, and the overall product lifecycle" (p. 2). The goal of MBD is to "provide complete product definition without the use of 2D drawings or dressed-up and annotated projected orthographic views derived from 3D data" (p. 6).

2.1.1 Benefits and Impacts of MBD

There are many benefits and impacts of MBD. The evolution towards a model-based enterprise represents an "opportunity for increased performance and efficiency" (Camba & Contero, 2015, p. 35). With MBD, data will remain consistent because it is stored in a single repository (Alemmani et al., 2011). This helps lead to a reduction in design issues, which ultimately leads to increased cost savings (Briggs et al., 2010). MBD can help by "reducing time-to-market and to improve product quality. By eliminating the need to generate 2D drawings, product development costs and delays can be reduced, thus improving and accelerating the product delivery cycle" (Quintana et al., 2012a, p. 139). According to Adamski (2010) regarding MBD's impact:

> The largest impact of implementing MBD is that the manufacturing and inspection teams now have to live without drawings. Therefore, a proper MBD implementation involves finding solutions for all departments that touch the 2D and 3D data. Model-based definition data creation phase is essential for any company that will be creating design data without the use of 2D drawings. This creates the following benefits: reduced time to design and manufacture parts; reduced amount of data created, stored and tracked for a given part; increased accuracy through the use of a single object for all design, manufacturing, and inspection information; increased data re-use throughout all departments; designers no longer need to perform tedious drawing creation; reduced printed documentation which has a limited effectivity. (p. 41)

2D drawings have been the most widely used format to display information (Briggs et al., 2010; Wan, Mo, Liu, & Li, 2014). However, today's 2D drawings contain multiple views and tend to be insufficient. According to Alemanni et al. (2011) "designers and engineers require virtual prototypes and mockups to understand the complexity of their designs and verify it" (p. 2). While 2D drawings are insufficient for engineers and designers, “MBD has the capability to expedite final part inspection and verification, by utilizing solid model data such as surface finish material, plating quality, and surface roughness would be desirable” (Briggs et al., 2010, p. 4). Eliminating the need for 2D drawings can help avoid redundant information and conflicting data between the 3D CAD model and drawing. Another benefit is saving storage space due to only needing to store one file (Quintana et al., 2010). Regarding replacing 2D drawings with 3D models, Wan et al. (2014) states the “3D model maintains more complete and distinct machining semantic, and can support machining modeling, estimation and optimization more smartly when it is combined with machining annotation” (p. 537).

When utilizing an MBD dataset, no particular technical expertise is required since 3D MBD datasets provide a realistic view of objects. The geometry and GD&T can be understood by simply manipulating the model. Implicit information can also be provided by an MBD dataset because “the model can be interrogated in order to extract additional information such as taking specific measurements or making special selections” (Quintana et al., 2010, p. 499). Quintana et al. (2010) state that MBD’s greatest benefit is as follows:

> [An MBD dataset] can capture design intent very early in the product development process. Traditionally, the drafter explicitly captures the GD&T information on engineering drawings only after completing the solid model. Now this information can be captured directly on the solid model as the geometry is defined and evolves. (pp. 499-500)

2.1.2 What Goes into an MBD Dataset

At its core, MBD is "a way of gathering and managing product/process data inside of a 3D model in the form of annotations, parameters, and relations" (Huang et al., 2014). Quintana et al. (2012b) define an MBD dataset as:

> Containing the exact solid, its associated 3D geometry, the 3D annotations of the product's dimensions and tolerances (and may also include general notes and parts lists) and the dataset management information – as a means to carry the product definition and collaborate with downstream users throughout the product lifecycle, instead of relying on engineering drawings. (p. 82)

"This dataset does not contain a conventional 2D drawing. The 3D annotations are placed on planar views called annotation planes. They remain associated to the model and can be visualized within a 3D environment" (Quintana et al., 2010, p. 498).

According to Adamski (2010), "MBD includes one system file, 3D geometry, GD&T data with notes and comments such as base coordinate system, dimensions, tolerances, flag notes and technical comments concerning material, surface smoothness, weight and general notes" (p. 39). In addition to the 3D CAD model, the entire product definition can include additional information "such as part lists, part coordination documents, material specifications, etc." (p. 39). The 3D geometry contains these annotations which specify data for manufacturing and lifecycle support and can also have notes and lists (Dorriba-Camba, Alducin-Quintero, Perona, & Contero, 2013).

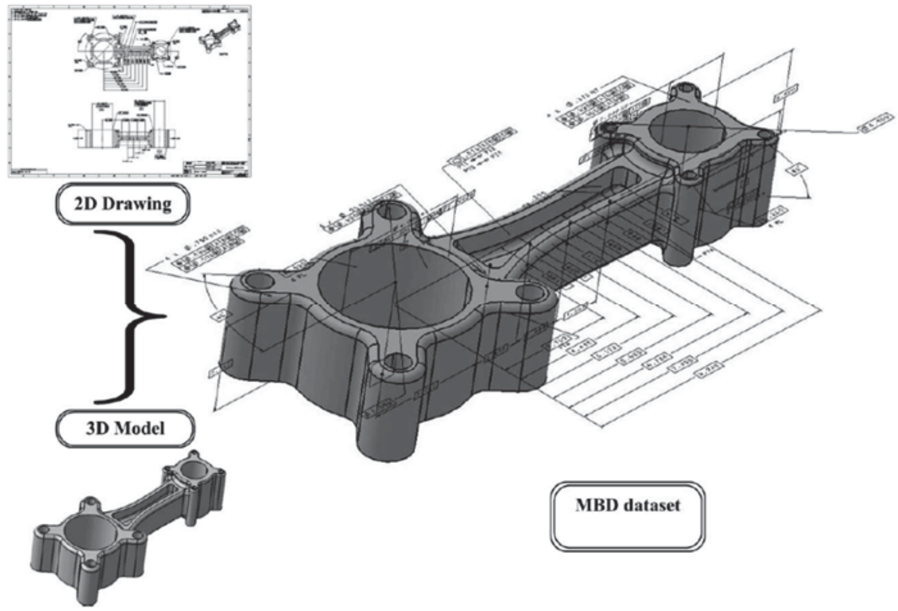

Figure 2.1 Example of an MBD Dataset (Quintana et al., 2010)

2.1.3 MBD Scenarios

There is no unique strategy of implementing MBD in industry. However, Alemanni et al. (2011) have synthesized different methods and give three scenarios. These scenarios are Product-oriented MBD, Process-oriented MBD, and Enterprise-oriented MBD. The first scenario, Product-oriented MBD, is the use of 3D as the main source of geometrical data, but 2D drawings still being used in manufacturing plants and technical documentation. However, the 2D drawings are directly generated from 3D models. No changes can be made on the drawings, but if modifications are necessary, they must be made and validated in the 3D model and the drawing is then regenerated.

The Process-oriented MBD scenario Alemanni et al. (2011) discuss “focuses primarily on 2D drawing suppression for a paper-reduced PLM where drawings are replications of data from native 3D models. They only add information about explicit dimensions, tolerances, and manufacturing annotations" (p. 4). It is possible through CAD technologies to support 3D FT&A, which could eliminate the need for drawings (Alemanni et al., 2011).

The third scenario, Enterprise-oriented MBD, is the most current. In this scenario, native 3D CAD models are the main source of product data including geometries, tolerances, materials, technology, and lifecycle data. According to Alemanni et al. (2011), this scenario is followed by most advanced aerospace companies for the following reasons: "the current generation CAx software has reached maturity: they support and promote MBD as a driver for integration and task automation" and "PLM is facing a fast growth in scope and complexity. Managing product data … is now demanding for general simplification and standardization" (p. 6).

2.1.4 Model-based Enterprise (MBE) Assessment

The MBE Assessment Tool (2014), created by NIST, looks at a company's MBE capabilities based on technical ability and business practices. The majority of the questions regard the engineering capabilities of the company. There are seven levels to the MBE Assessment Tool, starting at Level 0 and going up to Level 6, as seen in Figure 2.2. Level 0 of the MBE Assessment Tool is the foundation for all the other levels to build upon and depends on traditional 2D drawings, while Level 6 is the highest level of capability. The focus of Level 6 is automating formal delivery of a TDP while eliminating all use of 2D drawings (MBE Assessment Tool, 2014).

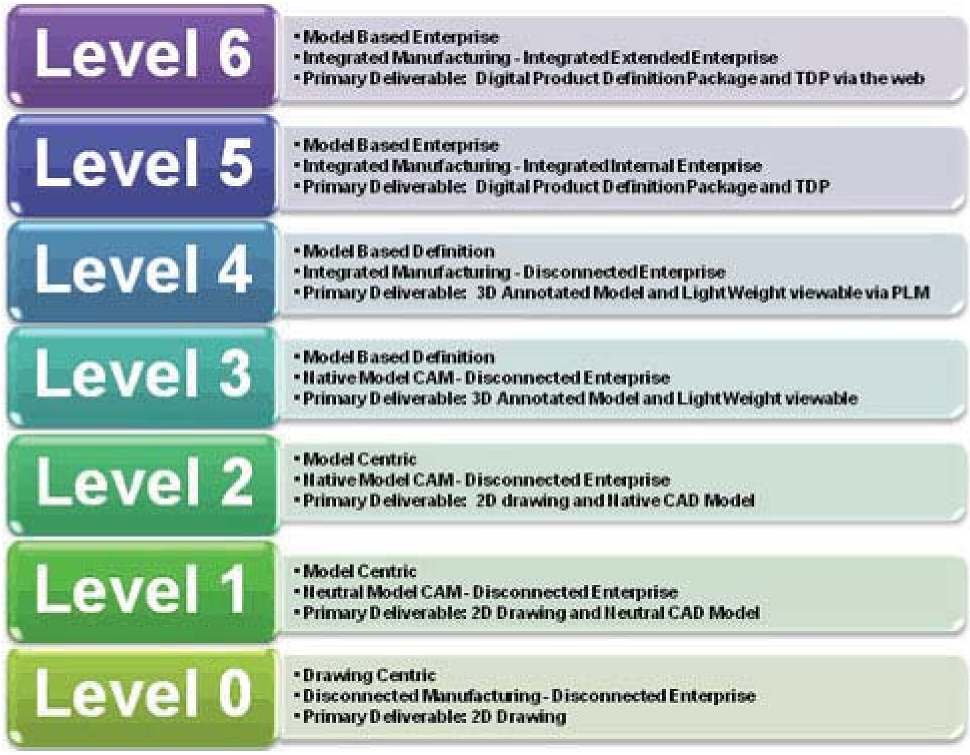

Figure 2.2 Levels of the MBE Assessment Tool (MBE Assessment Tool, 2014)

According to Whittenburg (2012), "engaging the resources of the NIST Manufacturing Extension Program (MEP), an assessment was conducted that included onsite, telephone, and web assessment tools" (p. 109). A total of 445 companies responded, and the results were as follows:

Level 1: 142 companies

Level 2: 143 companies

Level 3: 156 companies

Level 4: 4 companies

Level 5: 0 companies (p. 109)

For the purposes of this assessment, Level 6 was not used. However, this does provide a good outlook and shows "there is an appropriate MBE level for every company based on their products, processes, and customer base – not every company needs to be … at an MBE Level 4 or Level 5" (Whittenburg, 2012, p. 106).

2.1.5 Master Model Concept of an MBD Dataset

Adamski (2010) claims "the future will be MBD with one main file containing 3D geometry with dimension and tolerances" (p. 39). While not much research focuses on different strategies of MBD, much of the research into MBD and MBE refers to utilizing one central knowledge artifact as the main source of product data, or a master model (Adamski, 2010; Camba & Contero, 2015; Hoffman & Joan-Arinyo, 1998; Qunitana et al., 2010). The master model is a concept that accumulates all the information pertaining to different domains and provides that information in a compound feature, or the 3D CAD model, and is responsible for coordinating all clients. The master model coordinates the CAD system with "downstream views such as GD&T analysis, manufacturing process planning for machining, casting, forging, etc." (Hoffman & Joan-Arinyo, 1998, p. 906). Hoffman and Joan-Arinyo (1998) also point out, however, "that the question of how to organize the information as to maintain a valid master model is paradigmatic of the larger manufacturing context" (p. 912).

2.1.6 Master Model Alternatives

While the master model has been documented, not much literature exists on an alternative strategy to the master model MBD dataset. A concept of multiple views (models), however, has been documented by Bouikni et al. (2008) and Bronsvoort and Noort (2004). Bouikni et al. (2008) states:

> Actors from different disciplines working on common design models often suffer from cognitive distraction when they must interact with unnecessary design details that they do not understand and cannot change … it is important to provide to these actors only the information required to perform their tasks, in an appropriate format containing only necessary data. This working environment is favorable when the design details, depending on the information required for the task to be performed, are targeted in quantity not to contain more than is required, and in contents to be adapted to the needs of the task. (p. 61)

Bouikni et al. (2008) expand on this by stating the views are used "to define how to obtain, from the same object, different models associated with different disciplines working in collaboration" (pp. 62-63). There is an "existence of several models for one object, where their grouping constitutes the product models for one object. The disciplines that participate in the evolution of the product definition have the possibility to extract information from those models to achieve their functionality" (p. 63).

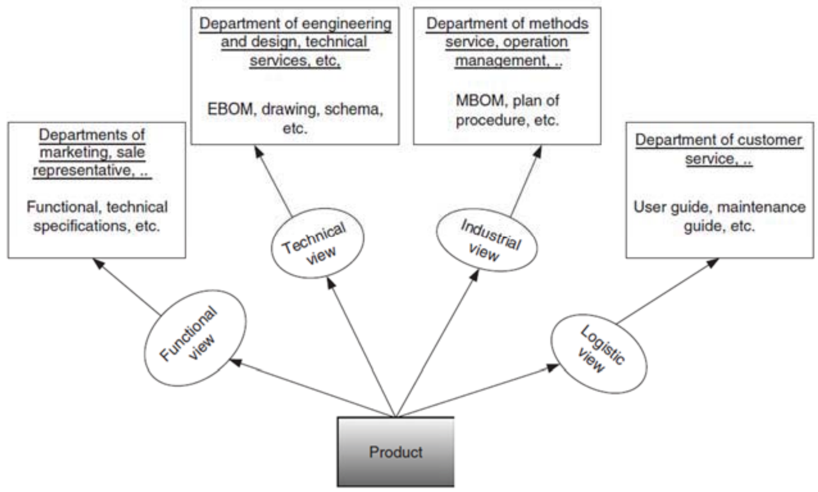

Figure 2.3 Example of Product Views (Bouikni et al., 2008)

Bronsvoort and Noort (2004) give four different phases to their multiple view (models) approach. The phases are conceptual design, assembly design, part detail design, and part manufacturing planning. The conceptual design view is "the way a product is built from functional components and of how these components are related to each other" (p. 934). The assembly design view "supports design of connections between components" (p. 936). The part detail design view and the part manufacturing planning view "are two part-oriented views that have been developed to support the part detail design phase and the part manufacturing planning phase, respectively. The feature models of both views are built from the features, mode constraints, and references" (p. 938).

The issue with these methods is they do not necessarily fall under what this research defines as "multiple models." These concepts refer to multiple models linked to a singular file, where this research refers to multiple models as individual and not linked to a singular file. This can be seen in Fig. 2.3.

2.2 CAD Capabilities for MBD

CAD and CAM systems have been used for years in manufacturing and engineering environments. CAD systems continue to evolve and new capabilities are being developed for improvement (Feng & Song, 2000). Advancements in CAD technology allow engineers and designers the ability to design and manufacture parts without the use of 2D drawings (Hartman, 2009). In digital design and manufacturing, 3D model-based has become the mainstream “due to the characteristics of visualization, digitization, and virtualization of 3D models” (Huang et al., 2014). Over the years, standards have been established in working with CAD/CAM systems. According to Adamski (2010), these standards include “layers arrangement; new projects naming and numbering rules; drawing creation rules; 3D models creation rules; notes, comments, tolerances, basic datum, local datum” (p. 45).

Modern CAD, CAM, CAE, and CAx software can already store and manage data as parameters (Alemanni et al., 2011). For years, CAD has supported simple annotations (Dorribo-Camba, Alducin-Quintero, Perona, & Contero, 2013), but with the development of digital product definition standards and the increase in popularity of MBD, the use of annotations has seen its momentum increase. Modern CAD systems now provide annotation mechanisms via product manufacturing information (PMI). These support the creation of “GD&T, 3D textual annotations, surface finishes, and other product specifications in 3D CAD models" (Camba & Contero, 2015, p. 37). Alemanni et al. (2011) go further with the capabilities by stating:

> Products can be designed, simulated, and validated directly in the virtual domain with the help of computer-aided design (CAD), computer-aided engineering (CAE), and computer-aided manufacturing (CAM) software using 3D interaction and simulation. Moreover, 3D tools may also be used for manufacturing planning, simulation-based validation, work instruction authoring, and delivery to the shop-floor workforce. (p. 1)

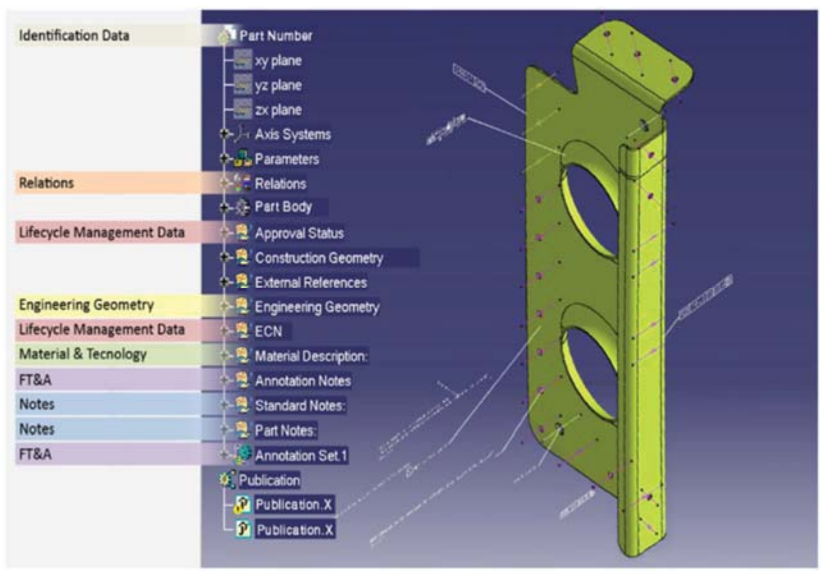

Figure 2.4 Example of an MBD Dataset in a CAD System (Alemanni et al., 2011)

In regards to MBD and the model-based enterprise, 3D CAD models can lead to improved quality, reduced development time, and improved communications. When

3D CAD models are utilized along with product data management (PDM) systems, they provide greater benefits and help the distributed development that is possible in the model-based enterprise (Camba, Contero, Johnson, & Company, 2014).

2.3 Engineering Change Orders (ECOs)

Engineering change is an important issue in industry, and is growing in prominence. Engineering change is not the same as the general concept of change in an organizational context. Change management "refers to the administration and supervision of corporate or organizational transformation," while engineering change "refers to making alterations to a product and Engineering Change Management to the organizing and controlling of this process" (Jarratt, Eckert, Caldwell, & Clarkson, 2011, p. 105). Engineering change management is a major part of PDM systems and is present in almost all new product development projects (Quintana et al., 2012b). An estimation of over 35% of resources in manufacturing are dedicated solely to managing changes to engineering drawings, plans for manufacturing, scheduling, and requirements (Angers, 2002). According to Quintana et al. (2012b):

> An engineering change is an alteration made to any parts, drawings or software that have already been released during the product design process. The change can be any size or type; the change can involve any number of people and take any length of time. (p. 80)

Engineering change orders (ECOs) are the requests for an engineering change, including "changes to parts, drawings, or software that have already been released" and "are part of almost every development process" (Terwiesch & Loch, 1999, p. 160). According to Quintana et al. (2012a), "ECOs occur because engineering is an iterative rather than a purely linear process, and traditionally ECOs are targeted toward correcting mistakes, integrating components, or fine tuning a product" (pp. 140-141). Managing ECOs solidifies integrity of the product being modified, as well as ensures tracking of engineering changes. Good change management can be a competitive tool which helps "increase product profitability via improved market responsiveness as well as greater efficiency" (Quintana et al., 2012a, p. 141).

2.3.1 ECOs Utilizing MBD

Quintana et al. (2012b) created and tested a solution for conducting ECOs without the need for 2D drawings. The solution utilized MBD for product definition. This solution was then used in a case study by Quintana et al. (2012a) in an aerospace company. The case study used the MBD context and found an "ECO process can be improved when conducted in a drawing-less environment" (p. 156). The case study quantified efficiency of utilizing MBD for ECOs with a reduction of 11% in time and an 11% reduction in average cost was achieved. Quintana et al. (2012a) estimated the annual gains for the company at about $50,000, and stated "there are clearly gains to be obtained from using the ECO process" (p. 157).

2.4 Summary

This review of relevant research has covered extensively model-based definitions and has gone into detail regarding different methods of MBD, including benefits what goes into an MBD dataset. This chapter also covered CAD capabilities regarding MBD, such as the ability to add GD&T and store parameters and annotations. A review of ECOs was also done, which showed how important engineering changes are to industry. It can be concluded that conducting ECOs in an MBD context can help improve efficiency (Quintana et al., 2012a). However, gaps have been identified in this literature. MBD datasets can improve efficiency within companies, but it is not clearly defined as to which creation and usage methods of MBD datasets are the most efficient. There is a major gap in literature when it comes to the alternate method of MBD datasets this research refers to as the Multiple Models Dataset. The next chapter of this paper will detail the methodology of the testing that will be conducted to compare two different MBD datasets.

CHAPTER 3. METHODOLOGY

This chapter introduces the methods taken to acquire data for this research. The research framework and methodology will be given, along with the sample that will be used. Also how the data will be sourced, how the data will be analyzed, and any threats to validity will be given.

3.1 Research Framework

The goal of this research is to compare two strategies of using MBD datasets to see what the more efficient method is. The term efficiency in regards to this research refers to less time on task and less rework of a process (Cross & Lynch, 1988). The first MBD dataset used for this research is the master model, which is one model containing all necessary product data, as well as any other relevant information regarding the product. The second dataset is the same data as the master model but spread amongst multiple models, or multiple models and additional non-3D CAD files. The research was a survey mechanism gathering opinions from industry professionals regarding these categories of MBD datasets to help determine which strategy is more efficient. Ideally, one strategy would prevail.

3.2 Sample

The sample used in this research targeted industry professionals from various engineering sectors including aerospace, automotive, military/defense, consumer products, heavy equipment, industrial machines, energy/utilities, and medical device/equipment. These industry professionals could be from all sizes of companies located around the world. It is imperative to use these various sectors for their knowledge and usage of MBD within their engineering processes, and it is important that the experts have different views on the subject (Uhl, 1983). The feedback from the respondents is crucial in helping understand how MBD is used in a professional engineering setting.

The sampling technique used for this research was expert purposive sampling, which is used when the researcher helps define the sample (Guarte & Barrios, 2006). Tongco (2007) defines the purposive sampling technique as “a type of non-probability sampling that is most effective when one needs to study a certain cultural domain with knowledgeable experts within,” (p. 147). According to Hasson, Keeney, and McKenna, (2000), “purposive sampling is based on the assumptions that a researcher’s knowledge about the population can be used to handpick the cases to be included in the sample,” (p. 1010). This sample of industry professionals was targeted through e-mail, along with posting the survey link on Internet sites such as LinkedIn, Facebook, as well as organizational sites such as ASME and Siemens PLM Community. The survey was administered through these sites, and the respondents could voluntarily take the survey online at their own discretion.

3.2.1 Determining an Expert

This type of research suggests the use of using "individuals who have knowledge of the topic being investigated" (Hasson, Keeney, & McKenna, 2000, p. 1010), or "a panel of informed individuals" (McKenna, 1994). This is where the term expert gets applied (Hasson, Keeney, & McKenna, 2000). An expert, as referred to in this research, is defined as an individual with enough knowledge and experience regarding the topic of research (Clayton, 1997). This is the definition used in this research, although "controversial debate rages over the use of the term 'expert' and how to identify adequately a professional as an expert" (Hasson, Keeney, & McKenna, 2000). The industry professionals used in this research are the "panel of informed individuals", as McKenna (1994) states, or the "experts" as Clayton (1997) states. However, the term "industry professionals" will be used for this research. It is assumed due to their position and work with MBD they have enough knowledge to provide adequate and valuable feedback to this research.

3.2.2 Sample Used

This research utilizing expert purposive sampling is utilizing the Delphi survey technique created by the RAND Corporation which suggests using a panel of experts for opinion data (Dalkey, Brown, & Cochran, 1969). Regarding this type of research, there is no set of rules concerning selection of participants, and the definition for subjects has remained ambiguous (Hsu & Sanford, 2007). While the recommended sample size for a study like this is unknown, some literature suggest researchers use the least adequate number of participants (Delbecq, Van de Ven, & Gustafson, 1975). To determine ideal sample for size of industry professionals for this survey, other literature such as Clayton (1997), states:

> Group size theory varies, but some general rules-of-thumb indicate 15-30 people for a homogenous population … that is experts coming from the same discipline … and 5-10 people for a heterogeneous population, people with expertise on a particular topic but coming from different social/professional stratifications. (p. 378)

Uhl (1983) suggests “more than ten experts are unnecessary for opinion data,” (p. 87). This statement was made based on accumulating multitudes of various research on the Delphi method. Based on these suggestions, the ideal size of this research would contain a sample of around ten respondents.

Figure 3.1 Sample of experts per industry sector used for this research (Other = MEP, R&D, and Student)

While industry professionals from several industry sectors were targeted, Figure 3.1 is a representation of the sample of industry professionals used for this research. There were twelve total respondents, which meets the ideal sample size of around ten.

3.3 Research Methodology

The methodology of this research is based on the research question “is the master model dataset concept of MBD more efficient than an alternative method of using multiple models?” To determine efficiency for the different strategies of MBD, a survey was administered. The respondents in the survey were asked a series of questions regarding their type of work, their work experience and experience using MBD datasets, different aspects of MBD datasets, as well as other questions targeting efficiency of using MBD within specific processes. Gathering this data of opinions on the matter of MBD efficiency can shed light on the subject and help determine if a more efficient method can be determined. At the conclusion of the survey, respondents were asked if they would be willing to participate in a follow up interview. Based on their responses, certain respondents were to be chosen for the interview.

While this research is focused on the master model dataset and the multiple models dataset, other variations of MBD datasets exist as well. When asking the respondents questions regarding which form of product definition they use, or which form best represents what they believe is the most efficient form of product definition, they were given more than just the two options. However, they were later asked to distinctively pick between either the master model dataset or multiple models dataset, specifically. The options of forms of product definition given to the respondents were:

- One singular 3D CAD file
- One singular 3D CAD file with supplemental drawings
- Multiple 3D CAD models linked to one singular 3D CAD file
- Multiple 3D CAD models not linked to a singular 3D CAD file
- Traditional 2D drawings with accompanying 3D CAD file
- Traditional 2D drawings only
- Other

The “one singular 3D CAD file” is essentially the master model dataset in this research, and the “multiple models not linked to a singular 3D CAD file” is essentially the multiple models dataset. The options “one singular 3D CAD file with supplemental drawings” and “multiple 3D CAD models linked to one singular 3D CAD file” are either variations, or slight combinations of the two MBD datasets in question during this research.

The question in the survey asking “which of the following best represents the form of product definition data you utilize to perform your job?” could possibly end the respondent’s survey depending on their answer. This can be seen in the survey questions in Appendix B. Before the survey was administered, it was concluded that any respondents who selected either “traditional 2D drawings only” or “traditional 2D drawings with accompany 3D CAD file”, or Level 0 or Level 1 on the MBE Assessment

Tool (2014) would be sent to the end the survey because of their lack of using 3D CAD files as their main source of product data would deem their responses to the forthcoming questions insignificant to the research. Although these individuals may be able to provide potentially valuable feedback, this research is focused on more 3D CAD centric MBD datasets, or Levels 2-6 on the MBE Assessment Tool (2014). It was also determined that if the respondent selects “on singular 3D CAD file,” “one singular 3D CAD file with supplemental drawings,” “multiple 3D CAD models linked to one singular 3D CAD file,” or “multiple 3D CAD models not linked to a singular 3D CAD file,” their responses would be used in the analysis.

3.4 Data Sources

The data sources for this research consisted of a survey mechanism distributed to the respondents, as well as a follow up interview which will be conducted with only certain respondents based on their responses.

3.4.1 Survey Mechanism

The survey mechanism was created using Qualtrics Survey Software. This tool was used because it is easily accessible, and the researcher has experience creating surveys in the tool. This tool made the survey easy to administer to industry professionals around the globe (Snow & Mann, 2013). The survey consisted of multiple choice questions for the respondent to answer as well as some potential short answer responses set up by the researcher to gage the opinion of the respondents when it comes to MBD datasets. The survey asked the respondent's primary job, industry sector, years of professional experience, years of experience with MBD, MBD proficiency, opinion on each MBD dataset used in this research, and which method they believe is more efficient. At the conclusion of the survey, the respondent was asked if they would be willing to participate in a follow up interview. A list of the survey questions can be found in Appendix B.

3.4.2 Interview

At the conclusion of the survey, certain respondents who finished the survey and selected they would be willing to participate in a follow up interview were interviewed based on their responses. Since only three of the respondents were willing to participate in the follow up interview, all three were chosen. The breakdown of the three selected can be seen in Table 3.1.

The respondents who volunteered for the interview were contacted via e-mail and offered the options of doing a phone call interview, or having the questions sent to them for them to fill out at their leisure. All three interviewees asked for the questions and filled them out themselves. These follow up questions will still be referred to as the interview and interview questions throughout this research. The interview provided a way to further investigate the opinions of the respondents on a deeper, more personal level and give more insight to how MBD is viewed in industry. The interview questions asked the respondent specifics from the survey responses they provided and had the respondents elaborate on their reasoning. Questions targeting the two different MBD datasets were asked to get the respondents opinion on both. The interview questions can be found in Appendix C, and results in Chapter 4.

Table 3.1 Demographics and Experience Levels of the Respondents Selected for the Interviews

		Interview 01	Interview 02	Interview 03
Q1	Industry Sector	Defense/Military	Aerospace	Other - Student
Q2	Number of employees in your company	500+	500+	500+
Q3	Primary role within the company	Systems Engineer	Management	Systems Engineer
Q4	Years of professional industry experience	0-5 years	20+ years	0-5 years
Q5	Years of experience with MBD	1-3 years	10+ years	1-3 years
Q6	Extent your job role involve the use of MBD (1-10)	2	8	5 - sometimes
Q7	Form of Product Definition You Utilize	One singular 3D CAD file with supplemental drawings	One singular 3D CAD file with supplemental drawings	One singular 3D CAD file

3.5 Data Analysis

At the conclusion of the survey and interviews, the data was analyzed based on a number of categories. The respondents' data was analyzed as a whole, and then all the data was broken down by industry sector for comparison and analysis. This helped compare the similarities and differences between the various sectors. This data was analyzed using one-way tables in the form of frequency distributions and relative frequencies. According to Groebner, Shannon, Fry, and Smith (2011), frequency distribution is "a summary of a set of data that displays the number of observations in each of the distribution's distinct categories or classes" (p. 33) and relative frequency is "the proportion of total observations that are in a given category" (p. 33). Data will also be put into bar graphs and pie charts for display purposes.

3.6 Threats to Validity

The following are threats to validity for this research:

- The respondents provided incorrect or false information
- Subjects had a bias towards a specific method based on how their company handles a process
- Subjects lack of expertise or knowledge on the subject
- Subjects not able to share information
- Differences between CAD tools leading to inconsistency in the results

3.7 Chapter Summary

This chapter introduced the research framework and methodology of this experiment. The sample targeted industry professionals from various sectors to help gather information and opinions of data. All the data from the survey has been analyzed and graphed. After analyzing the data as a whole, the data was broken down by industry sector for comparison. After analyzing the survey responses, the interviews were analyzed individually, and then compared and contrasted. The results and analysis of this survey and interviews will be explained in Chapter 4.

CHAPTER 4. RESULTS

This chapter will present the data collected during this study. First, the results from the survey will be discussed and then broken down by industry sector. At the completion of the survey analysis, the results from the interviews will be assessed. The data will be displayed in various graphs, charts, and tables along with an accompanying analysis.

4.1 Survey Mechanism

The survey consisted of fourteen questions that can be found in Appendix B. Based on how the respondents answered, some respondents did not have to answer all of the questions. There were twelve respondents to the survey for this research study which met the ten participants suggested by Uhl (1983) and Clayton (1997). However, only 7-8 respondents answered all the questions. This was due to certain responses to Question 7, specifically. Question 7 in the survey asked "which of the following best represents the form of product definition data you utilize to perform your job?" As mentioned in Chapter 3, it was concluded that any respondents who selected either "traditional 2D drawings only" or "traditional 2D drawings with accompany 3D CAD file" would be sent to the end the survey because of their lack of using 3D CAD files as their main source of product data would deem their responses to the forthcoming questions insignificant to the research. The sample was smaller than desired due to the fact that not all respondents were able to answer all the questions to the survey, as well as not every industry sector being represented.

4.1.1 Time to Complete Survey

Before looking at the results of the survey, the amount of time that elapsed while the participant took the survey will be discussed. Times will be referred to in seconds for consistency. The average amount of time it took the participants to complete the survey was 1108.92 seconds. The quickest response was 83 seconds, and the longest took 7218 seconds. In Table 4.1, there is a breakdown of each respondent's time to complete the survey. The time taken to finish the survey is given in "hour:minute:second" formatting for easier understanding, along with a column listing the time in seconds.

The respondents highlighted in light blue are the respondents who only made it to Question 7 in the survey, and their response to this question ending their survey. Obviously, these respondents would have the quickest times as they did not have to complete the entire survey. With exception to Defense/Military 02 who took 7218 seconds. This may be because the respondent left the survey open for an extended period of time before finishing. If you exclude the four respondents who did not complete the survey, the average actually goes down to 842.24 seconds for those respondents who completed the entire survey. This is mostly due to Defense/Military

02 being such an outlier. Another note, since Aerospace 02 and Other 03 took longer than average, it is also believed that these two respondents may have left the survey open before finishing it. None of these times are believed to have posed a problem with the results of the survey, with the exception of Aerospace 03, which will be discussed later in this chapter.

Table 4.1 Time to Complete Survey

Respondent	Time (hour:min:sec)	Time (sec)
Other 01	0:03:12	192
Defense/Military 01	0:07:30	450
Other 02	0:09:35	575
Aerospace 01	0:05:54	354
Defense/Military 02	2:00:18	7218
Aerospace 02	0:27:17	1637
Aerospace 03	0:02:49	169
Aerospace 04	0:01:23	83
Other 03	0:34:09	2049
Anonymous 01	0:03:08	188
Other 04	0:03:09	189
Other 05	0:03:23	203
Total Average:	*0:18:29*	*1108.92*
Average of Those Who Took the Whole Survey:	*0:14:02*	*842.24*

4.1.2 Demographics

The first few questions in the survey regarded the demographics of the respondents. These questions were to gather information about the person taking the survey to grasp an understanding of the various industry sectors and positions represented in the survey results.

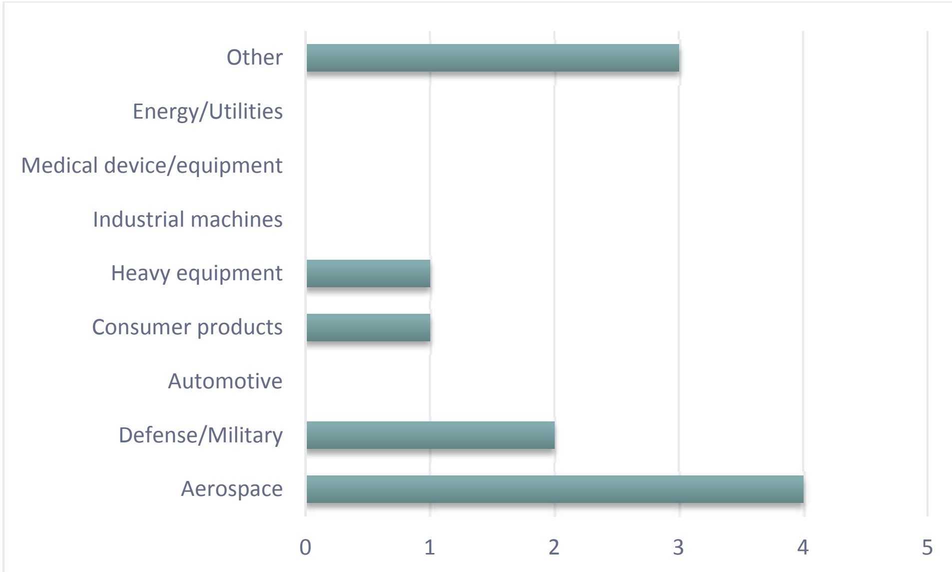

Figure 4.1 Which industry sector best represents your company or division of the company where you work? (n=11)

There were several sectors represented, however four of the major sectors were not represented at all. These sectors included energy/utilities, medical device/equipment, industrial machines, and automotive. The majority of respondents were from the aerospace sector with four selections. The defense/military sector had two respondents, and heavy equipment and consumer products were represented with one respondent each. Three respondents selected "other" with their selections being electrical engineering, student, and MEP (mechanical, electrical, and plumbing). The breakdown of responses can be seen in Figure 4.1.

The next question in the survey was regarding the size of the company the respondents worked for. This is important to see if there are differences in how MBD datasets are used in regards to the size of the company. Out of twelve responses, eleven selected that their company contained over 500 employees, and the only other response saying their company was less than ten. This is a large separation as the majority of respondents are from a large company and one respondent is from a much smaller company.

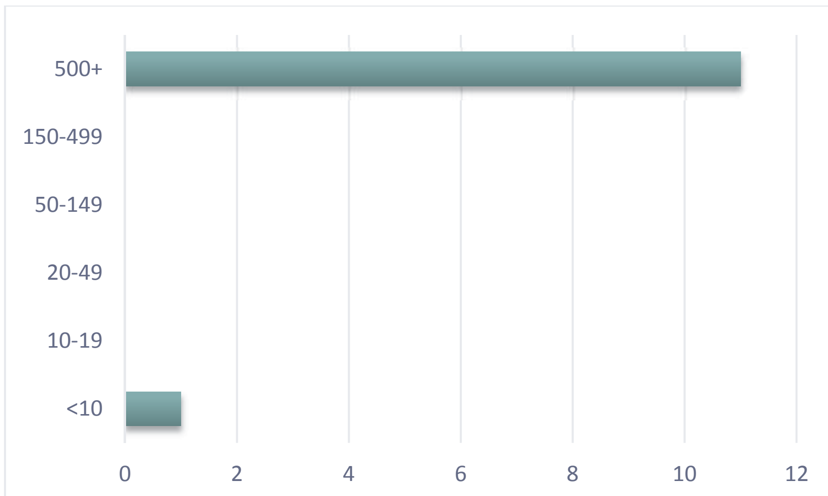

Figure 4.2 How many employees are there in your company? (n=12)

To gather more insight and background into the respondents of the survey, they were asked to give their primary role within their company. The positions selected by respondents ranged from management with four selections, engineer/systems engineering with three selections, and engineer/designer with two selections. Three respondents selected “other” and their responses were R&D (research and development) scientist, research, and systems administrator. This is another section where it would have been nice to have more variety among the respondents. While valuable information can be attained from the few positions selected, a wider range would have helped provide greater quality of data. The breakdown of these selections can be seen in Figure 4.3.

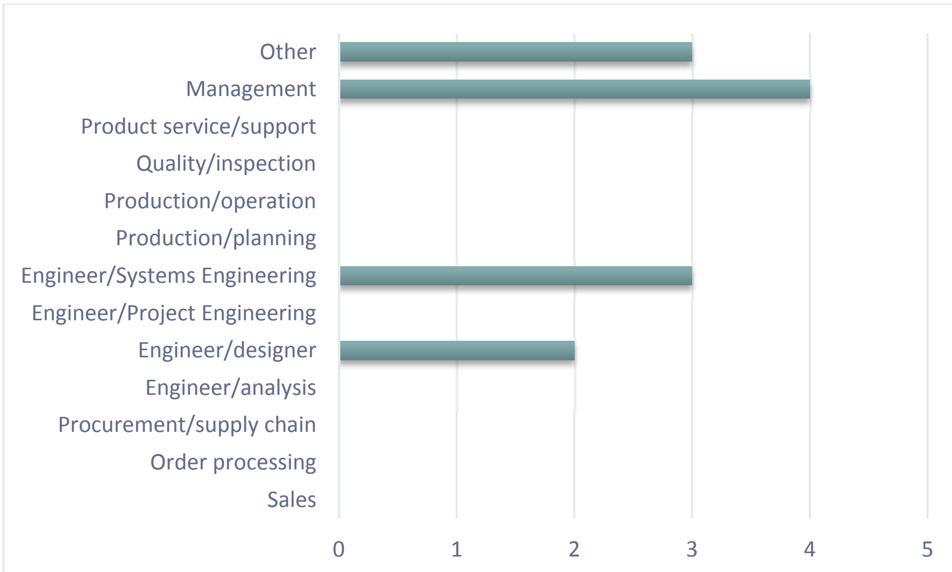

Figure 4.3 Which of the following best represents your primary role within the company? (n=12)

4.1.3 Experience Level of the Respondents

The next section of questions in the survey regarded the respondents level of experience. Not only how many years of experience they had professionally, but also their experience with MBD and MBD datasets. This information is crucial to the research as the respondents need to be proficient with MBD and MBD datasets for the results to be substantial.

The breakdown of professional industry experience can be seen in Figure 4.4. Six of the twelve, or 50%, of the respondents had over twenty years of professional experience, while a combined 82% have over eleven years of experience. This is important because the majority of the respondents have much experience and will be proficient in their role.

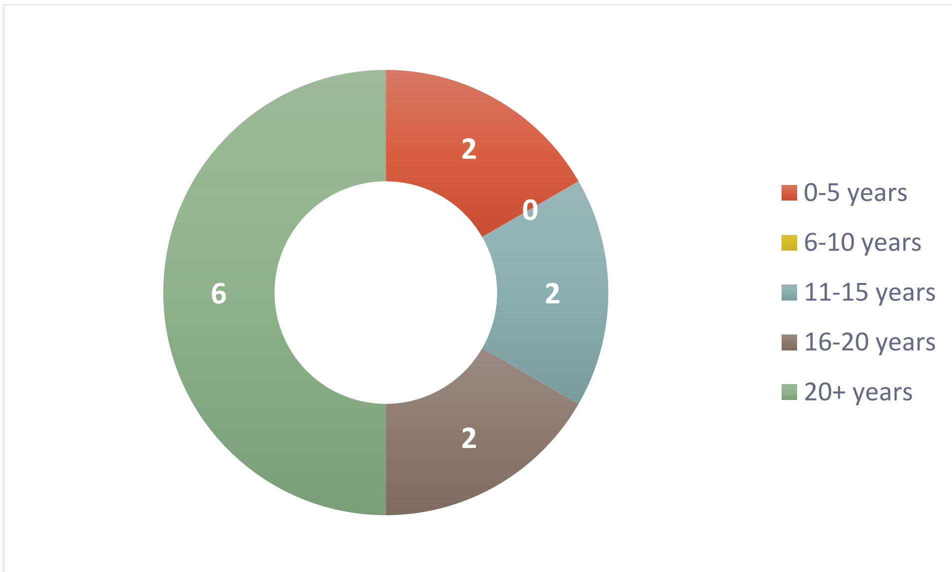

Figure 4.4 How many years of professional experience do you have? (n=12)

Now that there is an idea of the respondents' experience level, the next survey question targeted the respondents' experience level with MBD and MBD datasets. The majority of respondents had experience using MBD and MBD datasets, with most of the respondents having over ten years of experience. Only two of the respondents claimed to have no experience working with MBD or MBD datasets.

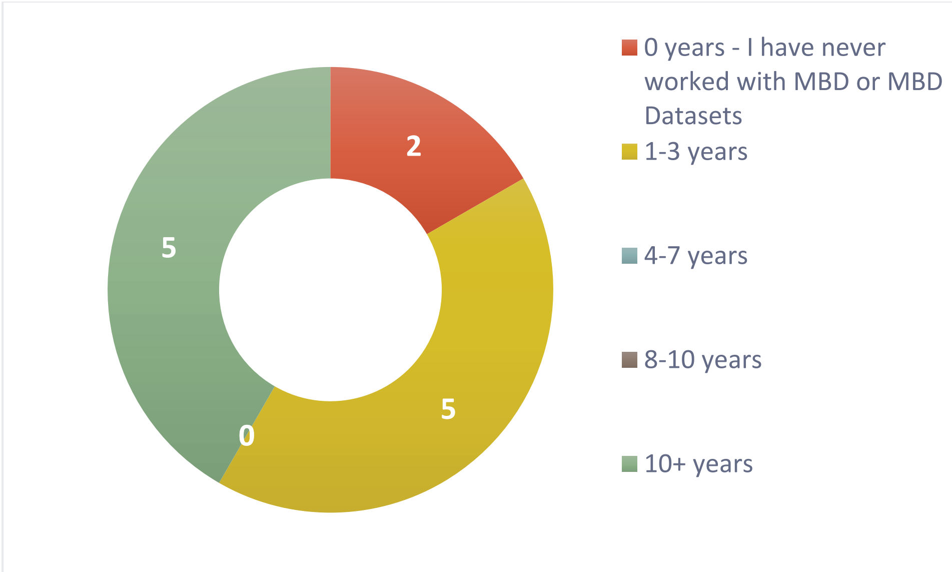

Figure 4.5 How many years of experience do you have working with model-based definition (MBD) or MBD datasets in a professional industry environment? (n=12)

The respondents were then asked to what extent their job role involved the use of MBD to complete their jobs effectively on a scale of 1-10, one being "I never use MBD", five being "I sometimes use MBD", and ten being "I use MBD daily." Only one respondent selected they never use MBD, and a total of six respondents were in the 1-3 range. The other six respondents were in the 5-10 range, meaning they at least sometimes use MBD. This breakdown can be seen in Figure 4.6.

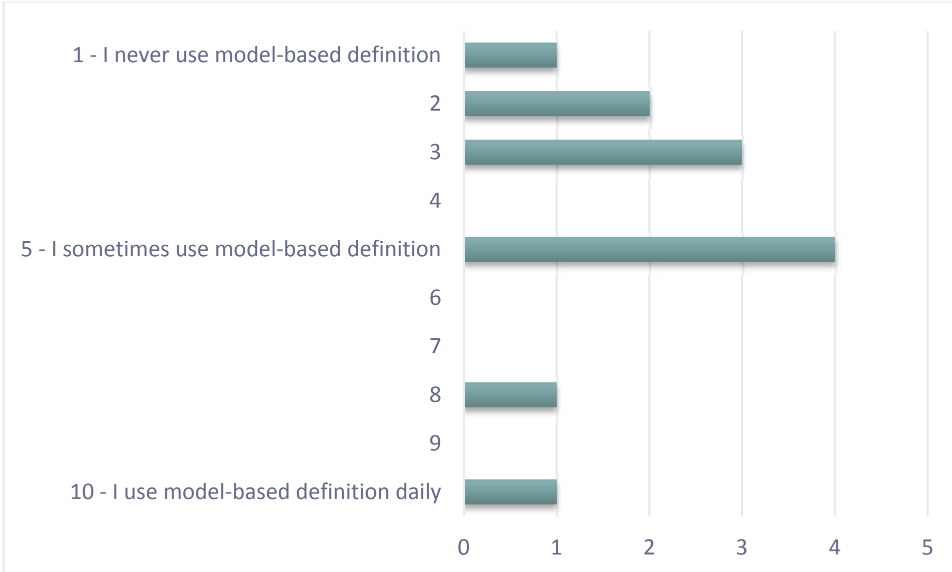

Figure 4.6 To what extent does your job role involve the use of model-based definition to complete your job effectively? (n=12)

4.1.4 MBD Usage and Opinions

Now that the experience levels of the respondents are known, as well as the extent they use MBD, they were then asked about the form of product data in which they utilize to complete their job. Only one respondent selected traditional 2D drawings only, which means the other ten respondents at least use some variation of 3D CAD files as a form of product definition. However, if the respondent selected either "traditional 2D drawings only" or "traditional 2D drawings with accompanying 3D CAD file", they were sent to the end of the survey and unable to complete any more of the survey questions. This is because their use of mainly traditional 2D drawings instead of 3D CAD models deemed their potential answers to the oncoming questions in the survey insignificant.

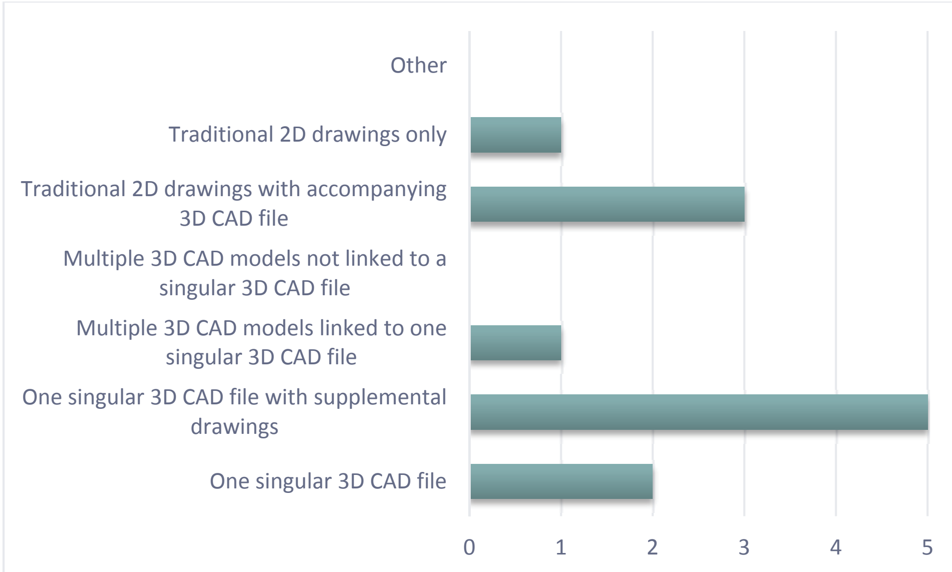

Figure 4.7 Which of the following best represents the form of product data you utilize to perform you job? (n=12)

The next two questions in the survey were fairly general, but were asked to gain an understanding of where the remaining respondents stood when it came to the research and research question. The respondents were given two definitions, one for the master model concept, and one for the multiple models concept. The definitions were "Master Model Dataset: A singular 3D CAD model containing all product definition acting as the central knowledge artifact," and "Multiple Models Dataset: Product definition spread amongst multiple 3D CAD models and/or other electronic files not linked to a singular 3D CAD model."

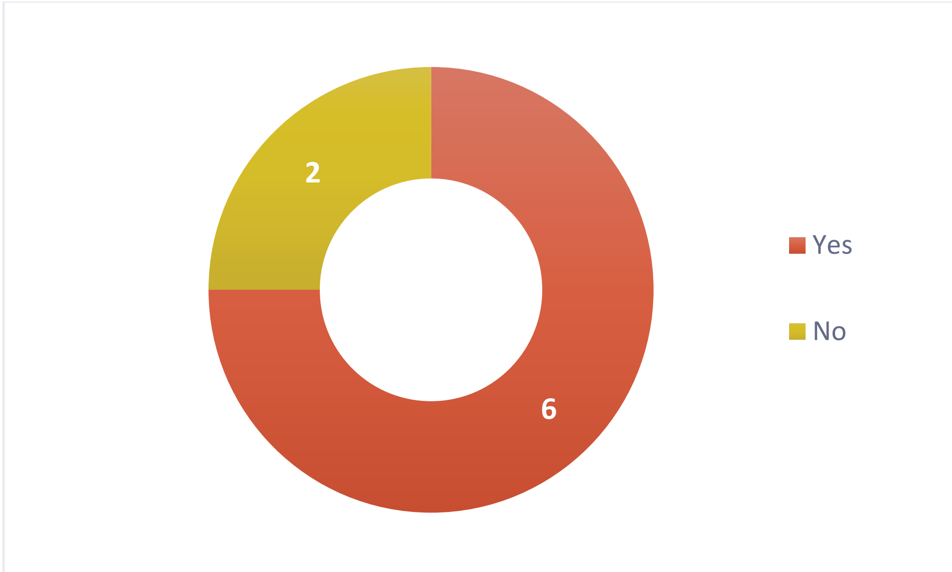

Figure 4.8 Do you believe there are benefits to utilizing the Master Model MBD dataset? (n=8)

The respondents were asked if they believed there are benefits to using the Master Model MBD dataset followed by if they believed there are benefits to using the Multiple Models MBD dataset. The results can be seen in Figure 4.8 and Figure 4.9. Only two respondents stated that there were no benefits to utilizing the master model concept, and only two respondents stated there were no benefits to utilizing the multiple models concept.

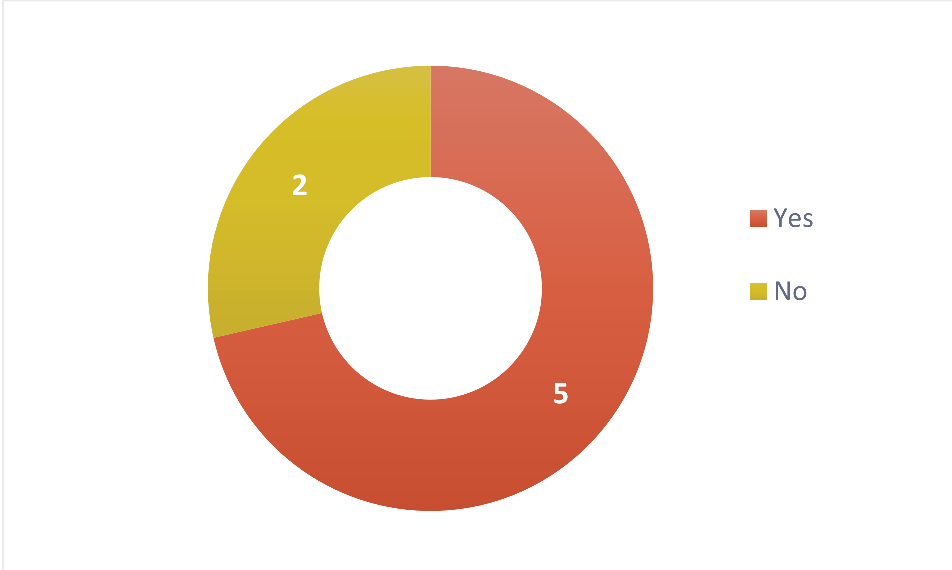

Figure 4.9 Do you believe there are benefits to utilizing the Multiple Models MBD dataset? (n=7)

With an understanding that the majority of respondents believe there are benefits to both the MBD datasets in discussion, the next question asked the respondents their opinion for which form of product definition datasets is the most efficient in a production process. Three of the seven respondents, or 43%, selected "multiple 3D CAD models linked to one singular 3D CAD file." This could be viewed as a hybrid of the master model dataset and the multiple models dataset. There was only one selection for one singular 3D CAD file, which is the premise for the master model dataset. There were also no selections for traditional drawings with accompanying 3D models or traditional 2D drawings only, which was somewhat expected. It is interesting to note that two of the seven respondents, or 29%, selected "one singular 3D CAD file with supplemental drawings," showing how important drawings can be to some industries.

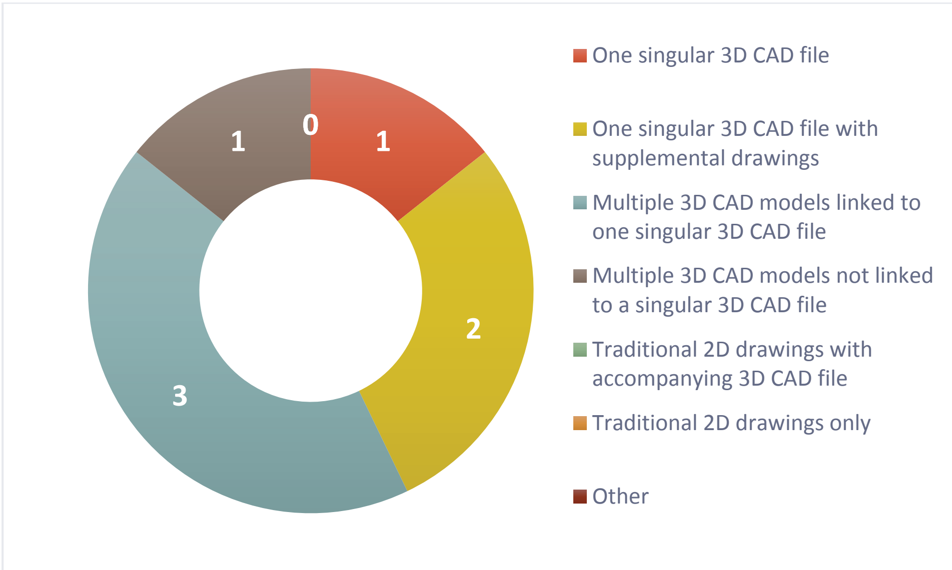

Figure 4.10 In your opinion, which form of product definition datasets is the most efficient in a product process? (n=7)

The respondents were then given three options and asked which they believed was the most true. The selections were "there is one most efficient method for utilizing MBD datasets that applies to all engineering/manufacturing processes," "efficiency of an MBD dataset depends on the situation, company, process, etc.," and "undecided." Six of the eight respondents selected that the efficiency depends on the situation, company, process, etc. This demonstrates it may be hard to determine if there is a most efficient method.

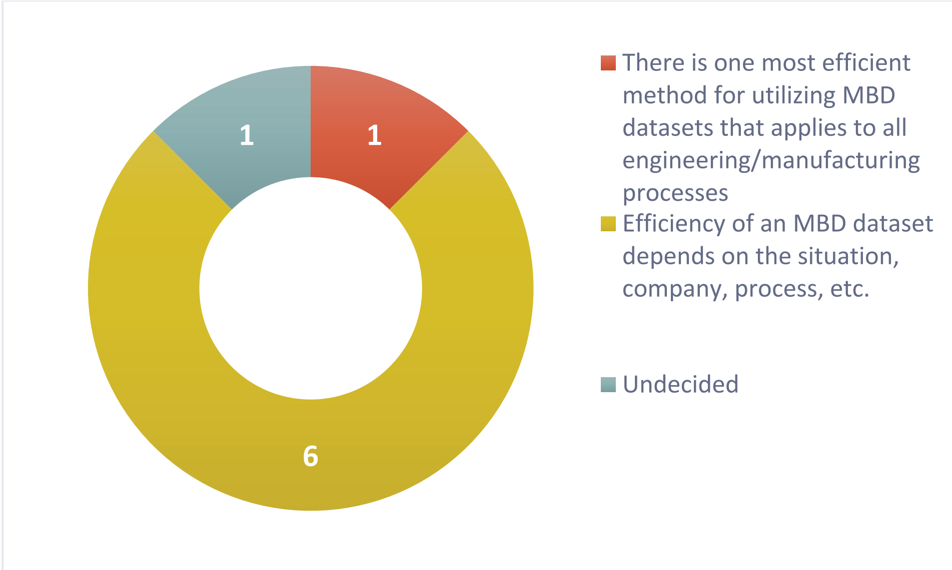

Figure 4.11 Which of the following do you believe is most true? (n=8)

The final question in the survey (excluding the question regarding participating in the interview) was another opinion question. The respondents were given three options and asked which best represents what they believed to be the most efficient MBD dataset. The options were "master model concept," "multiple models concept," and undecided. Only one respondent selected "undecided," but it was an even split between master model concept and the multiple models concept, with three selections each. The responses to this question show it may be a challenge to answer the research question due to the closeness of the results. While a larger sample may have yielded similar results, it is more likely that one method could have pulled away with a larger sample size.

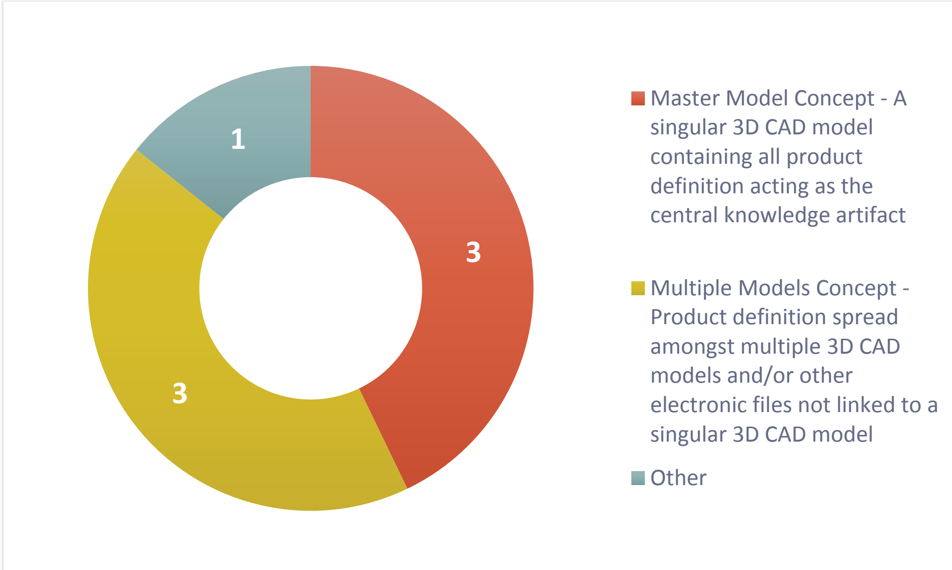

Figure 4.12 Which of the following would you say best represents what you believe to be the most efficient MBD dataset? (n=7)

4.2 Survey Breakdown by Industry Sector

After initially analyzing the results from the survey, the results were then broken down by industry sector to see if there were any common themes or interesting findings within the various sectors. Although this research could be broken down by several other factors, including job role, this research is focused on industry sector. The industry sectors represented in this survey were aerospace, defense/military, heavy equipment, consumer products, electrical engineering, MEP, and student. Since heavy equipment, consumer products, electrical engineering, MEP, and student only had one response each, they were grouped together in the "other" category to be compared.

4.2.1 Aerospace Survey Response Breakdown

There were a total of four respondents from the aerospace industry sector. To keep the identities of the respondents safe, they will be referred to here as Aerospace 01, Aerospace 02, Aerospace 03, and Aerospace 04. The breakdown of their responses is listed in Table 4.2.

Table 4.2 Aerospace Survey Response Breakdown

	ID	Aerospace 01	Aerospace 02	Aerospace 03	Aerospace 04
Q2	Number of employees in your company	500+	500+	500+	<10
Q3	Primary role within the company	Management	Other - Systems Administrator	Systems Engineer	Other - Research
Q4	Years of professional industry experience	20+ years	20+ years	20+ years	11-15 years
Q5	Years of experience with MBD	10+ years	10+ years	10+ years	1-3 years
Q6	Extent your job role involves the use of MBD (1-10)	8	10 - daily	3	5 - sometimes
Q7	Form of Product Definition You Utilize	One singular 3D CAD file with supplemental drawings	One singular 3D CAD file with supplemental drawings	One singular 3D CAD file	Traditional 2D drawings with accompanying CAD file
Q8	Benefits to Master Model?	No	Yes	Yes	N/A
Q9	Benefits to Multiple Models?	Yes	No	N/A	N/A
Q10	Which Form of Product Definition is Most Efficient in a Production Process	Multiple 3D CAD models not linked to one singular CAD file	One singular 3D CAD file with supplemental drawings	N/A	N/A
Q11	Which of the following do you believe to be most true?	Efficiency of an MBD dataset depends on the situation, company, process, etc.	Efficiency of an MBD dataset depends on the situation, company, process, etc.	Undecided	N/A
Q12	Which of the following would you say best represents what you believe to be the most efficient MBD dataset?	Multiple Models Concept - Product definition spread amongst multiple 3D CAD models and/or other electronic files not linked to a singular 3D CAD model	Master Model Concept - A singular 3D CAD model containing all product definition acting as the central knowledge artifact	N/A	N/A

While the aerospace sector was represented by the largest number of the respondents, two of the respondents' answers were not useful. Aerospace 03 did not answer most of the questions, including the most important questions targeting MBD within the survey. This is unfortunate because they stated they had over ten years of experience with MBD which could have brought better insight to the research. Looking at the elapsed time to complete the survey, Aerospace 03 finished the survey in 169 seconds. This is one of the quickest times of all the respondents, including the respondents were not able to answer all the questions in the survey. This may mean Aerospace 03 was rushed through the survey, or was forced to quickly finish the survey for some reason. This may be due to something important coming up while responding to the survey which forced Aerospace 03 to end rapidly. Either that, or Aerospace 03 found an issue or had an issue with using the Qualtrics Survey Software. Aerospace 04 selected traditional 2D drawings with accompanying CAD file as their main form of product data which ended their survey, leaving the rest of the survey questions unanswered.

While two of the aerospace sector respondents' answers were not useful, comparing Aerospace 01 and Aerospace 02's answers can shed light on a few things. Aerospace 01 and Aerospace 02 had much in common and agreed on several key elements. They both have over twenty years of professional industry experience, use one singular 3D CAD file with supplemental drawings as their form of product definition, and both suggested there is not one most efficient method of MBD datasets that efficiency depends on the situation, company, process, etc. Where Aerospace 01 and

Aerospace 02 differed was when it came to the master model against multiple models. Aerospace 01 said there were no benefits to the master model, but believed there were benefits to the multiple models concept. This is the exact opposite of how Aerospace 02 responded. It is interesting to note that while both Aerospace 01 and Aerospace 02 use the same form of product data to perform their jobs, Aerospace 01 chose a different form of product data as the most efficient in a production process, while Aerospace 02 went with what they knew. Aerospace 01 and 02 also differed when selecting what they thought best represented the most efficient MBD dataset. Aerospace 01 selected the multiple models concept, while Aerospace 02 selected the master model concept. This makes sense after seeing their responses to Question 10, "in your opinion, which form of product definition is most efficient in a production process?"

4.2.2 Defense/Military Survey Response Breakdown

There were two respondents representing the military/defense industry sector. To keep the respondents' identities safe, they will remain anonymous and from now on will be referred to as Defense/Military 01 and Defense/Military 02.

Similar to Aerospace 04 in the previously discussed aerospace sector, one of the respondent's answers were not useful towards this research. Defense/Military 02's survey ended after selecting traditional 2D drawings with accompanying CAD file as the form of product definition they use.

Table 4.3 Defense/Military Survey Response Breakdown

	ID	Defense/Military 01	Defense/Military 02
Q2	Number of employees in your company	500+	500+
Q3	Primary role within the company	Systems Engineer	Engineer/Designer
Q4	Years of professional industry experience	0-5 years	11-15 years
Q5	Years of experience with MBD	1-3 years	1-3 years
Q6	Extent your job role involves the use of MBD (1-10)	2	3
Q7	Form of Product Definition You Utilize	One singular 3D CAD file with supplemental drawings	Traditional 2D drawings with accompanying CAD file
Q8	Benefits to Master Model?	Yes	N/A
Q9	Benefits to Multiple Models?	Yes	N/A
Q10	Which Form of Product Definition is Most Efficient in a Production Process	Multiple 3D CAD models linked to one singular CAD file	N/A
Q11	Which of the following do you believe to be most true?	Efficiency of an MBD dataset depends on the situation, company, process, etc.	N/A
Q12	Which of the following would you say best represents what you believe to be the most efficient MBD dataset?	Other - A singular digital system model that relies on more than CAD as the source of truth	N/A

Instead of comparing Defense/Military 01 to Defense/Military 02, the comparison will be between Defense/Military 01 and Aerospace 01 and 02. The reasoning for this is because Defense/Military 02's responses were not useful, and Aerospace 03 and 04's responses were also not useful. Adding Defense/Military 01 to the aerospace group gives the respondent's answers something to be compared to, and will help compare across industry sectors to find similarities and differences. This comparison can be seen in Table 4.4.

Table 4.4 Comparison of Aerospace and Defense/Military

	ID	Aerospace 01	Aerospace 02	Defense/Military 01
Q3	Primary role within the company	Management	Other - Systems Administrator	Systems Engineer
Q4	Years of professional industry experience	20+ years	20+ years	0-5 years
Q5	Years of experience with MBD	10+ years	10+ years	1-3 years
Q6	Extent your job role involves the use of MBD (1-10)	8	10 - daily	2
Q7	Form of Product Definition You Utilize	One singular 3D CAD file with supplemental drawings	One singular 3D CAD file with supplemental drawings	One singular 3D CAD file with supplemental drawings
Q8	Benefits to Master Model?	No	Yes	Yes
Q9	Benefits to Multiple Models?	Yes	No	Yes
Q10	Which Form of Product Definition is Most Efficient in a Production Process	Multiple 3D CAD models not linked to one singular CAD file	One singular 3D CAD file with supplemental drawings	Multiple 3D CAD models linked to one singular CAD file
Q11	Which of the following do you believe to be most true?	Efficiency of an MBD dataset depends on the situation, company, process, etc.	Efficiency of an MBD dataset depends on the situation, company, process, etc.	Efficiency of an MBD dataset depends on the situation, company, process, etc.
Q12	Which best represents what you believe to be the most efficient MBD dataset?	Multiple Model Concept	Master Model Concept	Other - A singular digital system model that relies on more than CAD as the source of truth

While Defense/Military 01 does not have as much overall experience as Aerospace 01 and 02, they have certain qualities in common. While Aerospace 01 and 02 differed on a few things, Defense/Military 01 seems to be the intermediate. All three use one singular 3D CAD file with supplemental drawings as the form of product definition they use for their job role, however Defense/Military 01 agrees with

Aerospace 01 regarding multiple models as the most efficient method, although linked to one singular 3D CAD file. It is also interesting to note Defense/Military 01's response of "other" to which they thought best represented the most efficient method of MBD datasets: "a singular digital system model that relies on more than CAD as the source of truth."

4.2.3 "Other" Survey Response Breakdown

In the survey responses there were three respondents who selected "other" for their industry sector, however for this section there will be five in the "other" category. This is due to only one respondent from the heavy equipment and consumer products industry sector, which led to having a loner needing a group. So the "other" category ends up containing respondents from multiple sectors including heavy equipment, consumer products, MEP, a student, and electrical engineering. To keep the identities of the respondents anonymous, they will be referred to Other 01, Other 02, Other 03, and Other 04, and Other 05 from now on.

The breakdown of the responses can be seen in Table 4.5. Similar to Aerospace 04 and Defense/Military 02 in the previously discussed industry sectors, Other 04's survey responses were not useful. After selecting traditional 2D drawings only as the form of product definition they used, their survey ended. Although Other 04's survey results are not useful, there are still four other respondents in this category from various industry sectors that can be compared.

Other 01 and Other 02 have a similar background. They are both from a management role with over twenty years of professional experience. The difference is Other 01 has over ten years of experience with MBD, while Other 02 said they had zero. This is somewhat confusing as Other 02 then stated their job role was a three on a scaled of 1-10 for how involved their job role was with MBD. While Other 01 and Other 02 had similar backgrounds, they differed with their opinions on MBD datasets. Other 01 and Other 03 selected very similarly, while Other 02 and Other 05 selected the exact opposite. Both Other 01 and 03 believed the multiple models concept was the most efficient and that the efficiency actually depends on the situation, company, process, etc. Other 02 and Other 05 believed the master model concept was the most efficient dataset, but only Other 02 believed that there was only one most efficient method of MBD datasets.

While Other 02 and Other 03's validity can be questioned, due to Other 02 selecting "0 years – never worked with MBD" and Other 03 being a student, their responses were left in the survey as the both met the requirement of utilizing some form of 3D CAD files as their main source of product definition. Since Other 02 selected 3 on the scale of 1-10 for the extent their job role involves the use of MBD, and the fact they use 3D CAD models with supplemental drawings, their selection for years of experience working with MBD could have been a mistake. Other 03 has graduate level research in MBD, and while not an industry professional, this adds a new perspective to the study.

Table 4.5 "Other" Survey Response Breakdown

	ID	Other 01	Other 02	Other 03	Other 04	Other 05
Q1	Industry Sector	Heavy Equipment	MEP	Student	Electrical Engineering	Consumer Products
Q2	Number of employees in your company	500+	500+	500+	500+	500+
Q3	Primary role within the company	Management	Management	Systems Engineer	Other - R&D Scientist	Engineer/ Designer
Q4	Years of professional industry experience	20+ years	20+years	0-5 years	16-20 years	16-20 years
Q5	Years of experience with MBD	10+ years	0 years - Never worked with MBD	1-3 years	0 years - Never worked with MBD	1-3 years
Q6	Extent your job role involve the use of MBD (1-10)	5 - sometimes	3	5 - sometimes	1 - never	2
Q7	Form of Product Definition You Utilize	Multiple 3D CAD models linked to one singular CAD file	One singular 3D CAD file with supplemental drawings	One singular 3D CAD file	Traditional 2D drawings only	One singular 3D CAD file with supplemental drawings
Q8	Benefits to Master Model?	No	Yes	Yes	N/A	Yes
Q9	Benefits to Multiple Models?	Yes	Yes	Yes	N/A	No
Q10	Which Form of Product Definition is Most Efficient in a Production Process	Multiple 3D CAD models linked to one singular CAD file	One singular 3D CAD file with supplemental drawings	Multiple 3D CAD models linked to one singular CAD file	N/A	One singular 3D CAD file
Q11	Which of the following do you believe to be most true?	Efficiency of an MBD dataset depends on the situation, company, process, etc.	There is one most efficient method for utilizing MBD datasets that applies to all engineering/manufacturing processes	Efficiency of an MBD dataset depends on the situation, company, process, etc.	N/A	Efficiency of an MBD dataset depends on the situation, company, process, etc.
Q12	Which of the following would you say best represents what you believe to be the most efficient MBD dataset?	Multiple Models Concept - Product definition spread amongst multiple 3D CAD models and/or other electronic files not linked to a singular 3D CAD model	Master Model Concept - A singular 3D CAD model containing all product definition acting as the central knowledge artifact	Multiple Models Concept - Product definition spread amongst multiple 3D CAD models and/or other electronic files not linked to a singular 3D CAD model	N/A	Master Model Concept - A singular 3D CAD model containing all product definition acting as the central knowledge artifact

There was also a respondent who did not select an industry sector who would have fallen into the “other” category. However, their responses were deemed insignificant due to selecting “traditional 2D drawings with accompanying CAD file” as their main form of product definition. That along with not selecting an industry sector left them out of the breakdown.

4.3 Interviews

The second portion of the research study was an interview done with select respondents from the survey. The last question of the survey asked the respondents if they would be willing to participate in a follow up interview. There were five respondents who selected they would be willing to participate, however only three left their contact information. Since these three were the only respondents to leave contact information for an interview, they were selected for the interview. The three respondents who volunteered for the interview were contacted via e-mail and offered the option of doing a phone interview, or filling out the questions at their leisure. All three opted to fill out the questions themselves.

The research would have benefited from having various opinions from different industry sectors, but due to time constraints and the lack of participation in the survey, the study continued with the three volunteers. The interviews did contain respondents from different industry sectors, however not all of the industry sectors were able to be covered. To keep the identity of the respondents safe, they will remain anonymous. They will be identified the same as in the last section comparing the survey responses of the different industry sectors. The three interviewees will be Defense/Military 01, Aerospace 01, and Other 03. Table 4.6 has a breakdown of how each of the respondents answered the questions the survey.

Table 4.6 Survey Responses of the Interviewees

	ID	Defense/Military 01	Aerospace 01	Other 03
Q1	Industry Sector	Defense/Military	Aerospace	Student
Q2	Number of employees in your company	500+	500+	500+
Q3	Primary role within the company	Systems Engineer	Management	Systems Engineer
Q4	Years of professional industry experience	0-5 years	20+ years	0-5 years
Q5	Years of experience with MBD	1-3 years	10+ years	1-3 years
Q6	Extent your job role involves the use of MBD (1-10)	2	8	5 - sometimes
Q7	Form of Product Definition You Utilize	One singular 3D CAD file with supplemental drawings	One singular 3D CAD file with supplemental drawings	One singular 3D CAD file
Q8	Benefits to Master Model?	Yes	No	Yes
Q9	Benefits to Multiple Models?	Yes	Yes	Yes
Q10	Which Form of Product Definition is Most Efficient in a Production Process	Multiple 3D CAD models linked to one singular CAD file	Multiple 3D CAD models not linked to a singular 3D CAD file	Multiple 3D CAD models linked to one singular CAD file
Q11	Which of the following do you believe to be most true?	Efficiency of an MBD dataset depends on the situation, company, process, etc.	Efficiency of an MBD dataset depends on the situation, company, process, etc.	Efficiency of an MBD dataset depends on the situation, company, process, etc.
Q12	Which of the following would you say best represents what you believe to be the most efficient MBD dataset?	Other - A singular digital system model that relies on more than CAD as the source of truth	Multiple Models Concept - Product definition spread amongst multiple 3D CAD models and/or other electronic files not linked to a singular 3D CAD model	Multiple Models Concept - Product definition spread amongst multiple 3D CAD models and/or other electronic files not linked to a singular 3D CAD model

Looking at the survey responses from the selected interviewees, it shows they are all from different industry sectors. Two of the interviewees are rather novice, and the other has a wealth of experience. All the interviewees use similar forms of product definition and had the same or similar answers to questions 8-12 in the survey. While it would be nice to have had interviewees with differing opinions, it is interesting to see the similarities between their answers.

The interview consisted of five questions which are found in Appendix C. The questions were targeting the main questions (8-12) from the survey regarding MBD and MBD datasets. The interviewers were asked to explain and elaborate on why they selected the answers they did and provide any extra insight. The following sections of the chapter will document the responses to the interviews in full. After the interviews have been documented, there will be a section that compares and contrasts the interview responses.

4.3.1 Elapsed Time Between Survey and Interviews

Before discussing the results of the interviews, the time elapsed between the respondent completing the survey and the respondent completing the interview will be discussed. All three of the respondents completed the survey on June 21, 2016. All three respondents were contacted for the follow up interview on July 7, 2016, which was a span of sixteen days. The reason they were not contacted sooner is the researcher was waiting for more responses to the survey before selecting respondents for the interviews. Defense/Military 01 and Aerospace 01 both completed the survey on July 15, 2016, which is a span of twenty-four days between survey and interview. Other 03 completed the survey on July 21, 2016, which is a span of twenty-seven days. This may have had an impact on their responses due to the respondents not remembering how they answered specific questions. Although many of the questions in the interview did refresh the respondent with their answer, they still may not remember their thought process when taking the survey. Any irregularities this may have caused will be discussed in the analysis of the interview responses.

Table 4.7 Elapsed Time Between Survey and Interviews

Interviewee	Survey Completion Date (mm/dd/yyyy)	Date Contacted for Interview (mm/dd/yyyy)	Interview Completion Date (mm/dd/yyyy)	Time Elapsed Between Survey and Interview (days)
Defense/Military 01	06/21/2016	07/07/2016	07/15/2016	24
Aerospace 01	06/21/2016	07/07/2016	07/15/2016	24
Other 03	06/21/2016	07/07/2016	07/18/2016	27

4.3.2 Interview 01

As seen in Table 4.5, the first interview is with Defense/Military 01 who is a systems engineer within the defense/military industry. Defense/Military 01 has 0-5 years of professional industry experience, and 1-3 years of experience utilizing MBD and MBD datasets. Defense/Military 01 was first asked to provide the benefits to using one singular 3D CAD file as the main source of MBD:

> *"I believe in having one single CAD file for the master part of the digital twin. The digital twin definition is 'for every single physical/serialized instance of a product, you have an exact digital instance of it.' This means that there should be more*

than just the BOM for the digital twin, it should be the actual CAD models, the analysis behind the models, the integration and testing of the parts, etc. The master 'as-built' should be one CAD file that have the rest used."

Defense/Military 01 was then asked the benefits, if any, to using multiple models not linked to one singular 3D CAD file as the main source of MBD:

"Having multiple CAD files for the physical/serialized that enable the digital twin. This is massively important due to the fact that something out in the field may get serviced and the technician makes change to the resistor of one with a different vendor. This allows for the engineering team who may notice a trend be able to go through and debug the issue."

In the survey, Defense/Military 01 selected "multiple 3D CAD models linked to a singular CAD file" as the most efficient method of MBD in a production process. When asked to elaborate on their reasoning, they stated:

"This is because of the concept of the digital twin that was described [from the previous question]."

For Question 11 in the survey, "which of the following do you believe to be most true?", Defense/Military 01 selected efficiency of an MBD dataset depends on the situation, company, process, etc." over "there is one most efficient method for utilizing MBD datasets that applies to all engineering/manufacturing processes." During the interview, Defense/Military was asked to elaborate on this selection:

"The Model-Based Definition depends on the company, if it is a product oriented company … they will definitely have a different definition and how they use CAD.

If it is a R&D company … then [the] definition of Model-based Definition/Engineering is much more holistic and [they] do not manufacture in mass like the automotive companies. Therefore, the CAD model being completely up to date is not as important as it would be for a product oriented company."

The final question in the interview was regarding Question 12 in the survey, "which of the following would you say best represents what you believe to be the most efficient MBD dataset?" Defense/Military 01 was asked to elaborate on their response which was "Other – A singular digital system model that relies on more than CAD as the source of truth":

"The reason for this is that the MBD dataset needs to take into account that there is more than just the CAD model defining the source of truth. Before CAD can even take place, a problem has to be defined. The problem definition data and the problem space around that should be associated with the MBD dataset to understand what is being solved. After that, there should not be a jump straight to CAD, there is the solution exploration phase. [Defense/Military 01's company] calls this Trade Space Exploration (TSE) and this is a major component to the MBD dataset. It allows for the exploration of massive design alternatives and is used to choose why the current technologies and designs are being done. After the base architectures are done, the requirements and the functional and logical architectures need to be captured into the MBD dataset. Before any CAD model [is] made, there should also be a 1D model of the system made with a …

tool that allows making sure the physics work. After that, CAD and FEA can start and this can be tied into the MBD dataset. The biggest thing is making sure that there is connectivity and relationships between everything from the problem definition down to the CAD and manufacturing techniques. If an issue is found that the manufacturing technique isn't working, it can be brought back into the TSE and determine how this can impact the rest of the system or if there is a new optimal solution."

Defense/Military 01 provided a great insight with some thorough responses to the interview questions. These responses will be compared to the responses from the other interviewees later in this chapter, and then again be discussed and used to help make conclusions in Chapter 5.

4.3.3 Interview 02

The second interview is with Aerospace 01 who is in management within the aerospace industry sector. Aerospace 01 has over twenty years of experience, and over ten years of experience utilizing MBD and MBD datasets. The questions asked in this interview were very similar to the questions asked in the previous interview with Defense/Military 01, however just worded differently based on how Aerospace 01 responded in the survey. Again, the first question asked in the survey was to provide benefits, if any, of using one singular 3D CAD file as the main source for MBD:

"The advantage in using a singular 3D CAD file is that the file is a single source of truth for the data … as long as all the data needed for the model-based definition

is in that file. However, over the entire product lifecycle, it is hard to imagine a single file would be able to contain all necessary data for a complex product MBD. This single file may offer convenience for use and management in the original, typically the authored, CAD application, although at some point file size may become an issue. It may even provide for less complex data interoperability and data management techniques for use by other applications. It may be more difficult when only a portion of the model data is need for a down-stream purpose."

This was an interesting response, as Aerospace 01 had stated there were no benefits to the Master Model concept in the survey, yet gave a few reasons in this response. This question was followed up by asking to provide the benefits to using multiple models not linked to a singular 3D CAD file as the main source of MBD:

"The advantage in using multiple models not linked to a one singular 3D CAD file is that there are multiple authoring systems across industry and, if ease of interoperability exists, the multiple models can be used across various tools in the product lifecycle. Many (large) companies have multiple CAD systems, even in the same domain, whether due to acquisitions or just through evolution within the same community. The ability to easily use/reuse multiple models versus constantly migrating files into a single model system is a benefit. Being able to create and use a specific MBD data set using multiple models from various authoring tools is a benefit."

In the survey, Aerospace 01 stated their opinion for which method of MBD is the most efficient in a production process was "Multiple 3D CAD models not linked to a singular 3D CAD file." They were asked to elaborate on their reasoning:

> *"Multiple models not linked to a singular 3D CAD file as the main source for MBD is consistent with the concept that as the model based definition evolves throughout the product lifecycle; different needs require different data for definition. If there is an ability to manage multiple models, each representing some element of definition; and then combine the appropriate pieces to create a particular model based definition for a particular purpose – there will be efficiency at the complex system-level of the product. This will also provide for efficiency even at the more straight-forward component level as well. For instance, creating a manufacturing work instruction assembly using models from multiple CAD systems as the components (e.g. mechanical chassis parts and electrical printed circuit board parts)."*

Regarding their answer to question 11 in the survey asking "which of the following do you believe to be most true?" Aerospace 01 selected "efficiency of an MBD dataset depends on the situation, company, process, etc." Aerospace 01 elaborated on this selection:

> *"I believe the MBD dataset is different for different points in the product lifecycle. It is also different depending on the purpose being served. Sometimes the only element of MBD that is needed might be the mechanical geometry. Other times, there might be a need for the geometry and electrical definition combined. For*

example, to validate that interconnect is the same in both the physical pin location and the electrical signal for two mating connectors. The MBD for a particular purpose will be different at different times in the product lifecycle. Therefore, the efficiency in a given situation or process will depend on the ability to combine the appropriate model based data into the necessary model based definition for the applied need at that point."

Regarding their answer to question 12 in the survey asking "which of the following would you say best represents what you believe to the be the most efficient MBD dataset?", Aerospace 01 selected "Multiple Models Concept – Product definition spread amongst multiple 3D CAD models and/or other electronic files not linked to a singular 3D CAD file." Aerospace 01 was asked to explain why they believed this is true over the Master Model Concept:

"Products are often complex systems represented by definition spanning multiple domains, [for example] mechanical, electrical, software, etc. Each domain has an application model and file format that uniquely serves its purpose. There is even need for the model based definition to include information that today is often maintained in the form of a text-based document. Enabling a model based definition that combines the relevant models from across these domains to serve a particular purpose in the product lifecycle, [such as] requirements, design intent, simulation, fabrication, assembly, inspection, test, repair, etc., is more likely possible by using [and/or] combining the appropriate multiple models for a purpose … rather than trying to create and manage a singular master model with

all of the information. Not only is a singular cross-domain model not practical, it is likely not possible. If this concept could be enabled for the complex system, then the underlying domains, [for example] 3D CAD for mechanical models, should employ the same construct."

Similar to Defense/Military 01, Aerospace 01 provided great, thorough responses to the interview questions. These provide great insight, and will be compared with the other interview responses later in this chapter.

4.3.4 Interview 03

The third interview is with Other 03 who is a graduate student/systems engineer who has 0-5 years of professional experience, but does have 1-3 years of experience working with and researching MBD and MBD datasets. Although Other 03 is not an industry professional with much experience, the insight they can provide from someone who has researched MBD can add an extra layer into this research. Similar to the first two surveys, the questions asked in this interview were almost the same, however worded differently based on how Other 03 responded in the survey. Other 03 was first asked to provide the benefits, if any, of using one singular 3D CAD file as the main source for MBD:

"Less version management and easier for the team to be on the same page."

Secondly, Other 03 was asked to provide what benefits are provided from using the multiple models concept:

"[The multiple models concept] allows for more innovation by putting only the basic compatibility constraints between separate models. Easier distribution and relevant information transfer."

Other 03's opinion for which method of MBD is the most efficient in a production process was "Multiple 3D CAD models linked to one singular 3D CAD file." Other 03 elaborated on the reasoning:

"Easier organization and easier to identify the compatibility constraints. High-level singular CAD file can just store the high-level information whereas the detailed model can be created separately. This structure will be very relevant to the design of complex products like an aircraft."

Regarding Other 03's answer to question 11 in the survey asking "which of the following do you believe to be most true?", they selected "efficiency of an MBD dataset depends on the situation, company, process, etc." Again, asked to elaborate:

"I am not an industry practitioner, so my answer might not reflect the exact situation in the industry. I feel that the efficiency will be dependent on the company policies and processes as a particular way of organizing information might be more applicable to a specific company. For example, one singular CAD file that contains all the information might be the way to go for designing a small product like a computer mouse, but it might not be suitable to have just one singular CAD model contain all information for designing a complex product like an automobile as different teams will be working separately on various parts of the automobile."

Finally, regarding Other 03's answer to question 12 in the survey asking "which of the following would you say best represents what you believe to the be the most efficient MBD dataset?", they selected "Multiple Models Concept – Product definition spread amongst multiple 3D CAD models and/or other electronic files not linked to a singular 3D CAD file." Other 03 elaborated on this:

> *"Based upon my interaction with the industry practitioners, they were not impressed with the concept of having one singular 3D CAD model to rule them all (if I may). The reason behind that the presence of different teams working on different parts makes it really difficult to keep the information consistent, [for example] reflecting the current state of the design, in the master model. Moreover, having to stick to the compatibility constraints (coming from the preliminary design of other parts) might hinder the innovation and development. Thus, having a singular 3D CAD file linked to multiple files might be a good option to represent the 'final design' but might not be the best type of dataset organization during the design phase."*

Along with Military/Defense 01 and Aerospace 01, Other 03 provided a great insight into their opinion of MBD datasets. While Other 03 is not an industry professional like Military/Defense 01 and Aerospace 01, they do have graduate level research experience in the field of MBD. This can help provide a unique perspective to the research.

4.3.5 Interview Analysis

The three interviewees provided thorough insight that will benefit this research. As previously stated, the three interviewees had a lot in common in terms of responses to the survey, as can be seen in Table 4.5. However, regarding the interview, their responses branched out and provided differences in their opinions. Although they mostly agreed on the answer in the survey, their responses to the interview questions varied. This analysis will go over each question of the interview and compare and contrast the different answers provided by the interviewees giving short excerpts from the responses for comparison.

The first question was the same for all of the interviewees. They all had selected in the interview that they believed there were benefits to the master model concept. When asked what those benefits were, all the respondents provided a different answer. Select quotes from the interviews have been selected and provided regarding the benefits to the master model concept:

- *"I believe in having one single CAD file for the master part of the digital twin … The master 'as-built' should be one CAD file that have the rest used." – Defense/Military 01*
- *"The advantage in using a singular 3D CAD file is that the file is a single source of truth for the data." – Aerospace 01*
- *"Less version management and easier for the team to be on the same page." – Other 03*

These responses help provide additional benefits for the master model concept not found in the literature review, or from the survey itself.

The second question was also the same for all the interviewees. The second question asked the interviewees to provide the benefits to the multiple models concept. All the respondents selected that there were benefits to this method in the survey. However, like the previous question, there were various responses during the interview:

- *"…this allows for the engineering team who may notice a trend be able to go through and debug the issue." – Defense/Military 01*
- *"…there are multiple authoring systems across industry and, if ease of interoperability exists, the multiple models can be used across various tools in the product lifecycle" – Aerospace 01*
- *"…easier distribution and relevant information transfer" – Other 03*

Similar to the question before, these responses provide additional benefits to the multiple models concept that were not found in the literature, and could not be deduced from the survey responses.

The third question is where the interview began to differ between interviewees. Defense/Military 01 and Other 03 were both asked why they chose "multiple 3D CAD models linked to one singular CAD file" as the most efficient method of product definition in a production process:

- *"This is because of the concept of the digital twin. [The digital twin definition is 'for every single physical/serialized instance of a product, you have an exact digital instance of it.']" – Defense/Military 01*
- *"Easier organization and easier to identify the compatibility constraints. High-level singular CAD file can just store the high-level information whereas the detailed model can be created separately." – Other 03*

Aerospace 01 had a different response to the survey question, so they were asked why they selected "multiple 3D CAD models not linked to a singular 3D CAD file":

- *"[It is] consistent with the concept that as the model based definition evolves throughout the product lifecycle; different needs require different data for definition." – Aerospace 01*

These responses help provide an insight to how product data is approached in industry. While MBD varies per industry sector and company, individuals also approach MBD datasets differently.

The fourth question in the survey was the same for all three interviewees because they all selected "efficiency of an MBD dataset depends on the situation, company, process, etc." as being more true than "there is one most efficient method for utilizing MBD datasets that applies to all engineering/manufacturing processes."

- *"The Model-Based Definition depends on the company, if it is a product oriented company … they will definitely have a different definition and how they use CAD. If it is a R&D company … then [the] definition of Model-based*

Definition/Engineering is much more holistic and [they] do not manufacture in mass like the automotive companies." – Defense/Military 01

- *"I believe the MBD dataset is different for different points in the product lifecycle. It is also different depending on the purpose being served. Sometimes the only element of MBD that is needed might be the mechanical geometry. Other times, there might be a need for the geometry and electrical definition combined." – Aerospace 01*
- *"I feel that the efficiency will be dependent on the company policies and processes as a particular way of organizing information might be more applicable to a specific company." – Other 03*

The responses to this question of the survey are rather similar. All the interviewees believe it depends on the company or the product as to which method would be more efficient. They also provide multiple responses not found in the literature review.

The final question in the interview was the same for Aerospace 01 and Other 03 as they both selected the multiple models concept as the concept they believed to be most efficient:

- *"Enabling a model based definition that combines the relevant models from across these domains to serve a particular purpose in the product lifecycle … is more likely possible by using [and/or] combining the appropriate multiple models for a purpose … rather than trying to create and manage a singular master model with all of the information." – Aerospace 01*

- *"[Industry professionals] were not impressed with the concept of having one singular 3D CAD model to rule them all … The reason behind that the presence of different teams working on different parts makes it really difficult to keep the information consistent." – Other 03*

Defense/Military 01 selected "other" and responded "A singular digital system model that relies on more than CAD as the source of truth":

- *"The reason for this is that the MBD dataset needs to take into account that there is more than just the CAD model defining the source of truth. Before CAD can even take place, a problem has to be defined. The problem definition data and the problem space around that should be associated with the MBD dataset to understand what is being solved" – Defense/Military 01*

These responses are interesting because they seem to contradict the benefits found in the literature review. This shows that the interviewees do not see these datasets the same as each other, or as the literature discusses. This opens an interesting discussion as to whether the definitions for the various concepts given to them before the interview were understood the way they were intended.

Comparing the responses from the interviews showed varying opinions. These responses also provided several elements not found during the literature review. These responses also showed how different individuals from different industry sectors understand the issue, and how they approach it.

4.4 Chapter Summary

This chapter has displayed and analyzed all the results from both the survey as well as the interview. Although there was a low number of responses to the survey and interviews, important data was collected and can be discussed. This chapter has documented the survey responses and compared and contrasted them to each other. After the survey responses were analyzed, the interview responses were documented in full individually, and then analyzed together for comparison. In the forthcoming chapter, these results will be discussed further and conclusions will be made.

CHAPTER 5. DISCUSSION AND CONCLUSION

This chapter will serve as a summation of this research and will discuss the results as well as give the final conclusions of the research. The conclusions will compare research from the literature review from Chapter 2 with the results from the survey and interview from Chapter 4. Finally, there will be a section suggesting future research and recommendations to expand this work.

5.1 Survey Discussion

As previously stated, the survey had a low number of respondents. The research could have benefited from having a larger sample size to compare data, especially if every industry sector could have been represented. The fact that four of the respondents' surveys ended due to using traditional 2D drawings as their main form of product data, along with some respondents not fully participating also hindered the results. Although the total of twelve respondents met the suggested sample size (Uhl, 1983; Clayton, 1997), the overall outcome was not ideal due to less than ten answering the most important questions (8-12) in the survey, as well as the lack of validity of expertise of the eight remaining respondents.

The survey gave insight into how industry professionals utilize MBD datasets, how involved their job role is with MBD datasets, and their opinions on the different MBD datasets. This information was critical when trying to compare the master model concept with the multiple models concept. While the results were broken down by industry sector and compared, it was difficult to find any commonalities between the different industry sectors in regards to the use of the master model or multiple models concept. With a low response from each sector, finding themes within was nearly impossible. The majority of respondents believed there were benefits to both concepts, as well as the most efficient method depends on the situation, company, process, etc. The split in opinion of which is more efficient between the master model concept and multiple models concept was dead even and much closer than expected. Based on the results, it was seemingly impossible to determine the most efficient method. With a larger sample size, it is likely one concept could have pulled away.

5.2 Interviews Discussion

As with the survey, this research could have benefited from having more of the respondents participate in the follow up interview. Ideally every industry sector would have been represented in the interviews along with a large enough pool of volunteers for the interview to pick specific respondents based on their answers to the survey. Since only three respondents were willing to volunteer, all three were selected for the interview. Although there were only three interviewees, they were a diverse group with interesting responses. While two of the interviewees were industry professionals from different sectors who could provide insight from a working environment, the other was a graduate level student who could provide a research approach to the responses.

The three interviewees provided a thorough insight into their opinions on MBD and MBD datasets. These responses helped to shed light on how industry approaches the problems in this research. While the interviewees had similar responses in the survey, they provided a variety of different responses to the interview questions. These responses added benefits and insights not found in the literature review. These responses also helped elaborate and explain in more detail the reasons the interviewees answered the survey questions the way they did.

5.3 Conclusions (Informed Opinions)

With such a small sample of respondents to the survey and interview, it is difficult to establish many concrete conclusions from this research. However, comparing the results of the research with information from the literature review, the following informed opinions have been made:

1. *The most efficient method of utilizing MBD datasets most likely varies between industry sectors, companies, etc.*

   Even with a small sample, the results of the survey had the vast majority (six of eight, or 75%) of respondents select "efficiency of an MBD dataset depends on the situation, company, process, etc." when asked, "which of the following do you believe is most true?" The other choices were "there is one most efficient method for utilizing MBD datasets that applies to all engineering/manufacturing processes" and "undecided," which received one vote each. Comparing the different industry sectors with each other also showed interesting results. While several respondents from a given sector agreed with other respondents from a different sector, there were also differing opinions. All three of the interviewees agreed and provided insight to why this is true. From the literature review, research such as Quintana et al. (2010) and Adamski (2010) suggest a one model MBD dataset, while Bouikni et al. (2008) and Bronsvoort and Noort (2004) suggest the idea that a need exists to use multiple files. The findings suggest that depending on the type of work being done in the company or industry sector, either a master model dataset or multiple models dataset could be more efficient. There is not one most efficient method that can cover all engineering and manufacturing processes.

2. *There are benefits to both the Master Model Concept and the Multiple Models Concept.*

   Even with respondents selecting one concept or the other in the survey, they were asked if there were benefits to each. Each question had the majority of respondents answering "yes." Also, the interviews provided even more insight to benefits of both concepts, and reasons why either could be used depending on the situation. Research and literature such as Hedberg et al. (2016), Quintana et al. (2010, 2012a, & 2012b), Adamski (2010), and others show that there are many benefits to MBD. The findings in this research agreed with the literature, however did not conclude which is more efficient in a specific production process.

3. *The opinion of industry professionals is a close split when it comes to the Master Model Concept or Multiple Models Concept being more efficient.*

   Since the most efficient method of MBD datasets depends on several factors, it is clear that different industry sectors are going to have differing opinions as to which method is more efficient. Neither choice had a landslide of votes, and ended up being dead even. While the interviewees leaned toward the multiple models concept, they still wanted these models to be linked to one singular CAD file. This closely resembles the master model file, although there are multiple models being used. Research such as Alemanni et al. (2011) and Huang et al. (2013) state current MBD is heavily software driven and extremely customized, which means that different industry sectors most likely have different ways of using MBD datasets based on their specific needs. This, along with Conclusion 1, shows that depending on the type of work the company or industry is doing, one method may be more efficient than the other. Some companies or industry sectors will use the master model concept because that works best for their processes, and other companies or industry sectors will use the multiple models concept because it works best for their processes.

4. *More work, research, and testing needs to be done to establish which MBD dataset is more efficient (per industry sector and/or company).*

This research was based on the research question "is the master model MBD dataset more efficient than an alternative method of using multiple models?" This research was not able to concretely answer this question and more information will be needed to resolve. While the research concluded that most likely the most efficient method of MBD datasets varies depending on industry sector and/or company, the research question could be altered for future research targeting the most efficient method per industry sector. Targeting the research towards a specific company or industry sector may yield more concrete results.

These informed opinions have been made based on the review of literature along with the results of the research. Comparing the literature to this research has shown many similarities, however much is still unknown. More work and research into the field of MBD and MBD datasets will be needed to answer several of the unanswered questions from this research, especially to determine the most efficient method of using MBD datasets.

5.4 Recommendations and Future Work

While the survey and interviews conducted during this research shed light on some of the important issues faced regarding the research question, the results are just the beginning of potential future work into the discussion of MBD datasets. The survey and interviews helped gather various opinions from industry professionals and even a student who has studied MBD, however more work needs to be done to help establish the most efficient method of MBD datasets.

Recommendations to improve this research would let the survey run for a longer period of time to possibly add more respondents. Another suggestion would be to personally connect and reach out with people to get them to take the survey. While many potential respondents were e-mailed, and the survey was posted through Internet sites such as LinkedIn and the Siemens PLM Community web page, the small number of respondents really hurt the results of the research. More respondents could have led to a larger separation of opinion between the master model concept and multiple models concept. A larger number of respondents also could have led to more volunteers for the survey which could have provided even more insight. Also, better definitions of the datasets are needed. It seems many of the respondents would select one dataset for a given question, then contradict themselves later in the survey. The definitions must be more clear to avoid this. To help with this, providing examples of the different datasets along with the definition would help the respondents understanding.

Recommendations for the survey questions themselves would be to alter the options for “years of professional experience” and “years of experience using MBD and MBD datasets.” Instead of giving ranges, have them choose an exact number of years. This would make the data clearer, and allow for an average to be calculated. This would help rid of the inconsistency of the ranges in the options. Another recommendation would be to alter the logic of the survey. Instead of ending the respondent’s survey due to their response to a question, let them finish the entire survey. Responses can be deemed insignificant by the researcher after the fact, but this at least allows the collection of the data in case it is ever needed. In hindsight, some of the respondents whose surveys ended could have provided valuable feedback, however this was missed because they were not capable of finishing the survey. Also, instead of relying on the form of product definition the respondent uses, rely on their years of experience with MBD and how often they utilize MBD in their job role. Again, allow all respondents to finish, and then deem certain responses insignificant after the fact. This is a way to better gather “expert” opinions. Again, in hindsight, this research should have altered the method for determining an expert before administering the survey. While Other 02 and Other 03 made it through the whole survey, the validity to their responses is skeptical due to their lack of experience.

Another recommendation would be to administer an experimental test using industry professionals. As stated in the conclusions, the most efficient method of MBD datasets depends on several factors including the company, product, workflow, etc. To help identify which method is most efficient in a given production process, a test could be set up and initiated on the various industry sectors. The test would contain three groups per industry sector: one group utilizes the master model dataset, the second utilizes the multiple models dataset, and the third utilizes the hybrid of the two where multiple models are linked to one master model. The testing would initiate an ECO or some other task using the specified MBD dataset, and the testers would be timed and the amount of errors would be recorded. Initially the test could be administered in one industry sector to start, and then followed up in other industry sectors. Results from the various industry sectors could then be compared. For this testing to be effective, more research would need to be conducted to understand what all must be contained within an MBD dataset per the various industry sectors, as well as how ECOs are conducted in the given field. Training may also need to be provided if the company used for the testing is not comfortable with the different MBD datasets. This would require a large time commitment, as well as willingness to participate from companies within these industries, for this research to be conducted.

5.5 Chapter Summary

This chapter has provided an overall summary of the research, along with four conclusions based on the findings of the research compared with the literature review. With the small number of responses, along with some very close results, no concrete conclusions could be made. However, this research provided an insight to how industry approaches the problems faced in this research. A section providing recommendations for future work to help improve this work further has also been given. There is a potential for future work to further this research and to help identify the most efficient method of MBD datasets, and improve the efficiency of engineering and manufacturing processes overall.

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APPENDICES

Appendix A Survey Introduction

This research study will gather information regarding Model-based Definition (MBD) within engineering/manufacturing environments to help identify efficiency when using MBD datasets in the production process. The research defines MBD as:

> **Model-based Definition (MBD) –** a strategy involving the move from two-dimensional (2D) traditional drawings to three-dimensional (3D) computer-aided design (CAD) models, with the 3D CAD model acting as the central knowledge artifact.

This research will analyze two different MBD datasets in an attempt to see which is more efficient. The term "efficiency" for this research refers to utilizing less time and less rework in the production process when using MBD datasets. Before utilizing resources to conduct a test of the two different modeling methods, a survey of industry professionals will be done to collect their opinions about which technique is better.

The two datasets involved are the "Master Model" and the "Multiple Models" MBD datasets. Most MBD research refers to the "master model" concept, which is a singular 3D CAD model containing all product definition acting as a central knowledge artifact. However, some companies may not be able to afford to utilize the master model concept, or they have multiple disciplines which utilize the same models but need different data from the models. This is where using multiple models could come into play. The definition for these datasets are as follows:

Master Model Dataset - A singular 3D CAD model containing all product definition acting as the central knowledge artifact.

Multiple Models Dataset – Product definition spread amongst multiple 3D CAD models and/or other electronic files ***not*** linked to a singular 3D CAD model.

Your feedback for this survey is greatly appreciated. Please answer the questions honestly and to the best of your ability. This survey is completely optional, and the participant may end the survey at any time with no penalty. All answers will remain confidential, with results only reported in aggregate form. At the end of the survey, the participant will be asked if they are willing to participate in a follow up interview where the researcher will attempt to gather a more personal opinion from the participant on the subject. The interview is completely optional, as well.

This research is being conducted through Dr. Nathan Hartman and Purdue University's Product Lifecycle Management Center. Your answers will be kept confidential, and you may end the survey at any time with no penalty. If you have any questions, please contact Nathan Hartman at nhartman@purdue.edu or by phone at 1-765-496-6104.

a. I have read the introduction and am willing to participate in the survey
b. I do not wish to participate in this survey

Appendix B Survey Questions

1. Which industry sector best represents your company or division of the company where you work?
    a. Aerospace
    b. Defense/Military
    c. Automotive
    d. Consumer Products
    e. Heavy Equipment
    f. Industrial Machines
    g. Medical Device/Equipment
    h. Energy/Utilities
    i. Other
2. How many employees are there in your company?
    a. <10
    b. 10-19
    c. 20-49
    d. 50-149
    e. 150-499
    f. 500+
3. Which of the following best represents your primary role within the company?
    a. Sales

b. Order Processing
c. Procurement/Supply Chain
d. Engineer/Analysis
e. Engineer/Designer
f. Engineer/Project Engineering
g. Engineer/Systems Engineering
h. Production/Planning
i. Production/Operation
j. Quality/Inspection
k. Product Service/Support
l. Management
m. Other

4. How many years of professional industry experience do you have?
   a. 0-5 years
   b. 6-10 years
   c. 11-15 years
   d. 16-20 years
   e. 20+ years
5. How many years of experience do you have working with model-based definition (MBD) or MBD datasets in a professional industry environment?
   a. 0 years – I have never worked with MBD or MBD datasets
   b. 1-3 years

c. 4-7 years

d. 8-10 years

e. 10+ years

6. To what extent does your job role involve the use of model-based definition (according to the definition provided at the beginning of the survey) to complete your job effectively?

    a. 10 – I use model-based definition daily

    b. 9

    c. 8

    d. 7

    e. 6

    f. 5 – I sometimes use model-based definition

    g. 4

    h. 3

    i. 2

    j. 1 – I never use model-based definition

7. Which of the following best represents the form of product definition data you utilize to perform your job?

    a. One singular 3D CAD file

    b. One singular 3D CAD file with supplemental drawings

    c. Multiple 3D CAD models linked to one singular 3D CAD file

    d. Multiple 3D CAD models ***not*** linked to a singular 3D CAD file

e. Traditional 2D drawings with accompanying 3D CAD file

f. Traditional 2D drawings only

g. Other

If "e" or "f", go to END

8. Do you believe there are benefits to utilizing the Master Model MBD dataset?

    a. Yes

    b. No

9. Do you believe there are benefits to utilizing the Multiple Models MBD dataset?

    a. Yes

    b. No

10. In your opinion, which form of product definition data is the most efficient in a production process? (Efficiency meaning less time and less rework in the production process)

    a. One singular 3D CAD file

    b. One singular 3D CAD file with supplemental drawings

    c. Multiple 3D CAD models linked to one singular 3D CAD file

    d. Multiple 3D CAD models ***not*** linked to a singular 3D CAD file

    e. Traditional 2D drawings with accompanying 3D CAD file

    f. Traditional 2D drawings only

    g. Other

11. Which of the following do you believe is most true?

a. There is one most efficient method for utilizing MBD datasets that applies to all engineering/manufacturing processes
b. Efficiency of an MBD dataset depends on the situation, company, process, etc.
c. Undecided

12. Which of the following would you say best represents what you believe is the most efficient MBD Dataset?
    a. Master Model Concept – A singular 3D CAD model containing all product definition acting as the central knowledge artifact
    b. Multiple Models Concept – Product definition spread amongst multiple 3D CAD models and/or other electronic files ***not*** linked to a singular 3D CAD model
    c. Other
13. Thank you for completing this survey. Would you be willing to participate in a follow up interview so the researcher can collect more in depth information on the subject? (This is completely optional and all responses are confidential)
    a. Yes
    b. No

If "a" go to Q14, if "b" go to END

14. Thank you for your willingness to participate in a follow up interview on the subject of MBD and efficiency of MBD datasets. Please provide your name and

e-mail address below. If you are selected, you will be contacted by the researcher by Friday, July 8, 2016.

Name: ____________

E-mail:_____________

END: Thank you for your participation in this survey. Your time and feedback are greatly appreciated as it will provide the researcher vital information towards this research project. All of your responses will be kept completely confidential.

Appendix C Interview Questions

This interview will be 5 questions and should not take more than 20 minutes. Your answers will be kept confidential, and you may end the interview at any time with no penalty.

1. What benefits, if any, are provided by using one singular 3D CAD file as the main source for MBD?
2. What benefits, if any, are provided by using multiple models not linked to one singular 3D CAD files as the main source for MBD?
3. In your opinion, which method of MBD is the most efficient in a production process? Why do you believe this is so?
    a. One singular CAD file
    b. One singular 3D CAD file with supplemental drawings
    c. Multiple 3D CAD models linked to one singular 3D CAD file
    d. Multiple 3D CAD models ***not*** linked to a singular 3D CAD file
    e. Traditional 2D drawings with accompanying 3D CAD file
    f. Traditional 2D drawings only
    g. Other
4. Regarding your answer to question 11 in the survey, you selected (A, B, or C). Why do you believe this is true over the others?
5. Regarding your answer to question 12 in the survey, you selected (A, B, or C). Why do you believe this is true over the others?

Thank you for your time and participation in both the survey and interview. Your feedback is greatly appreciated and will benefit this research.