EVALUATING THE POTENTIAL BENEFITS OF CONVERTING TO MODEL-BASED DEFINITION METHODS IN ENGINEERING

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ABSTRACT

EVALUATING THE POTENTIAL BENEFITS OF CONVERTING TO MODEL-BASED DEFINITION METHODS IN ENGINEERING

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The world is shifting to the new industrial era of Industry 4.0. This new era includes modern manufacturing principles such as standardized data formats, cloud-based computing, product-life cycle management, big data, internet of things, cybersecurity, and smart factories. The Model-Based Definition (MBD) approach reformats the 3D model to include all model properties such as part geometry, material, dimensions, annotations, and tolerance. Because the MBD model contains all the necessary part information, the need for an additional 2D drawing is questioned. This research examines the feasibility of implementing the MBD approach through a case study in collaboration with a local industry partner. The ultimate goal is to determine if MBD models are more effective at conveying part details than traditional 2D drawings. MBD model templates were created for several parts of various sizes and complexities. A study was conducted to determine the time needed to complete a standard quality inspection using the new MBD method compared to the traditional method of using 2D drawings. All participants had a lower average inspection time using MBD than 2D drawings, but the differences were not statistically significant. When used by more experienced quality inspectors, MBD was shown to be significantly faster than the traditional approach. Moreover, using MBD eliminates process steps. These factors could lead to substantial cost savings, reduction of data translation errors,

and improved time to market. Overall, this new approach has the potential to reduce many production inefficiencies. Some large engineering companies have already begun implementing MBD in their production processes.

CHAPTER 1: INTRODUCTION

Technical drawings have historically been used to portray design intention and detail. The use of technical drawings can be traced back to the creation of the pyramids and to the development of the Parthenon (Quintana et al., 2010). Drafting by hand takes time to master, requires a multitude of skills, and has been replaced by computer-generated 2D drawings in business and industry. Digitalizing technical drawings has made procuring graphics more efficient and utilizes the skills and techniques used in manual 2D drafting processes in the new digitalized drafting and manufacturing era (Mclaren, 2008).

The world is shifting into a new industrial era known as Industry 4.0. An aspect of Industry 4.0 is improving the transfer of digital information by linking computer systems so they can communicate more effectively. One of the outcomes of Industry 4.0 is the creation of the MBD (Model-Based Definition) approach, which has the potential to impact the drafting and design community. At its core, MBD aims to gather and manage product/process data inside the 3D model through annotations, parameters, and relations (Alemanni et al., 2011). While most companies still use 2D drawings for their ease of use and simplicity, using MBD may lead to many benefits in the design and production processes. Some of the benefits of using MBD include the following: reductions in manually produced data, reduced errors in design, better communication, quicker response time, fewer files, and cost reductions (Ruemler et al., 2016). MBD has already been used in the automotive, aerospace, and defense industries (Quintana et al., 2010). The MBD approach can lead to the creation of MBEs (Model-Based Enterprises), which use MBD to define product requirements and specifications instead of 2D documents as the data source for all engineering activities (Jin & Price, 2019). While many potential benefits exist, implementing MBD requires time, money, and patience. Technical, certification, and management issues can be expected when implementing MBD (Jin & Price, 2019). However, through fast-paced technological growth and implementation, some of these issues can be avoided or fixed before they are encountered.

This research examines the feasibility of implementing the Model Based Definition approach through a case study in collaboration with a local industry partner. The ultimate goal of the research is to determine if the MBD models are more efficient in portraying product data and information than the existing method of 2D drawings.

CHAPTER 2: LITERATURE REVIEW

2.1 Industry 1.0 to Industry 4.0

Over the past 250 years, industry has rapidly grown through technological advancements and process improvements. Through each industrial era, improvements have been made to help further industrial processes for better production and productivity. The first industrial era began in the late 1700s and has been defined as Industry 1.0. Prior to this industrial revolution, human labor and animal power had been the driving force for all productivity. The introduction of water and steam-powered machines in manufacturing improved the manufacturing world. With this increased productivity, small family-owned businesses began transforming into large organizations that needed proper management and more space to use these new systems (Thangaraj & Narayanan, 2018).

The second industrial era, Industry 2.0, started by introducing electricity and using the assembly line in industrial processes. Electricity made it easier by allowing special machinery to aid in the production process (Yavari & Pilevari, 2020). Henry Ford, founder of Ford Motor Company, used these newly powered machines to help drive the production of his Model T assembly lines. The assembly line produced products in larger quantities while reducing the overall costs needed to produce them (Yin et al., 2018). Assembly lines are still used around the world today.

Industry 3.0 began with implementing automation and reduced human involvement in the manufacturing process. In this industrial era, computers and programming are used extensively in product development and operations. While human operators are still needed, human involvement in production has decreased significantly (Show et al., 2021). Processes that were initially completed by multiple people could easily be accomplished by a single computer program embedded into a machine. Industry 3.0 shows improvements in production processes by using automated production machinery and process steps to remove human involvement throughout production. Industry 3.0 may also be associated with transitioning from analog and mechanical systems to electrical and digital systems that utilize automated production lines for full production operations.

Today, a new industrial revolution is underway, Industry 4.0. While most still use the technologies and methods introduced in the last revolution, some have begun transitioning into a 4.0 mindset and structure. This new industrial era focuses on integrating manufacturing operations systems and information and communication technologies (Dalenogare et al., 2018). The idea of reduced human involvement created in Industry 3.0 is further pursued and improved upon in Industry 4.0. Interconnected computers, smart materials, and intelligent machines communicate with one another, interact with the environment, and eventually make decisions with minimal human involvement (Ghobakhloo, 2020). Various techniques and software are introduced in Industry 4.0 that build off the accomplishments achieved in Industry 3.0

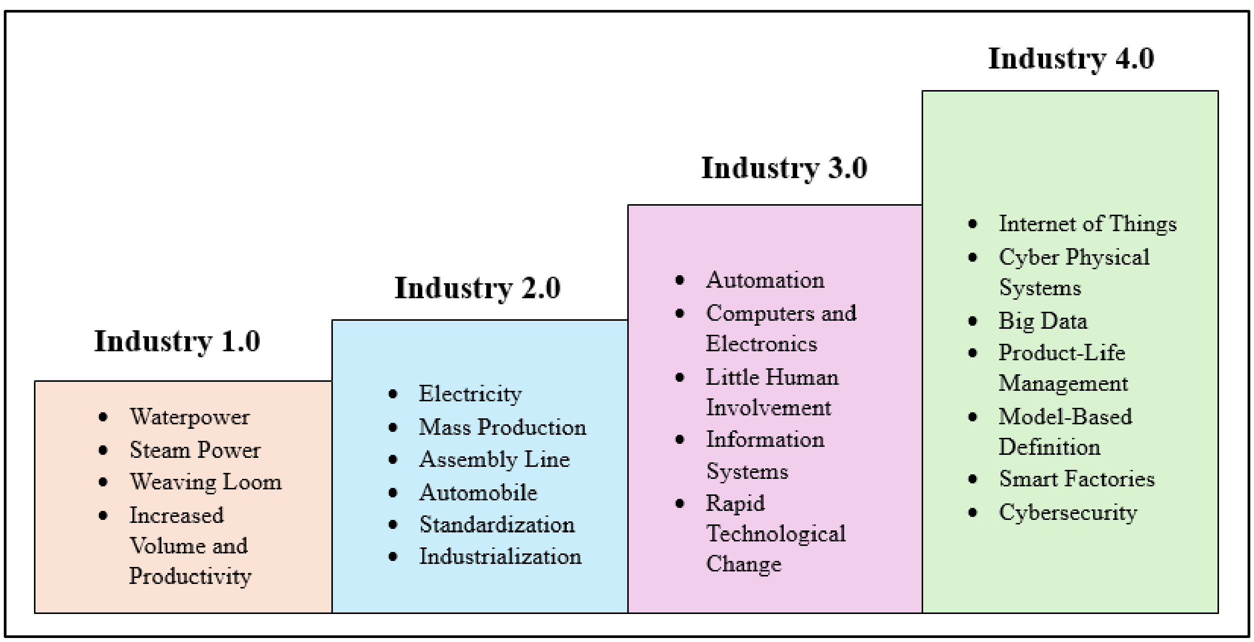


Figure 2.1 – The development of industry from 1.0 to 4.0.

2.2 Development of Industry 4.0

Countries around the world have already begun making the transition into an Industry 4.0-based infrastructure. More developed countries have had little issues making the transition over to an Industry 4.0 system, while less developed countries struggle to push out of Industry 3.0 and choose to postpone advancement. However, some believe that Industry 4.0 would push less developed countries to update their underachieved industrial development to accelerate economic growth within the country (Ghobakhloo, 2020). Attempts are being made to revitalize many of the technologies that were used throughout Industry 3.0. Advancements are being made to accomplish this task while new technologies are being created to help push past current technologies used in Industry 3.0. Scholars claim that the technological frontier is rapidly moving ahead, making the concept of Industry 4.0 closer to complete development (Laffi & Boschma, 2022). Many opinions have been stated about how a company can transition to Industry 4.0. Modernizing an existing Industry 3.0 production company or building a new 4.0 company from scratch are two views on transitioning (Zakoldaev et al., 2019).

Industry 4.0 is the foundation for the growth and widespread use of advanced methods in manufacturing and processing. Its development has brought a new industrial age of emerging technologies that provide digital solutions to various problems (Frank et al., 2019). These innovative technologies have allowed for ease of manufacturing and faster transfer of information from one area to another. The term “smart factory” describes the industry that has transitioned into this new industrial era. Significant components that can be associated with the development are IoT (Internet of Things), Big Data, and PLM (Product Life-Cycle Management) (Frank et al., 2019).

IoT (Internet of Things) is a concept that covers the autonomous exchange of useful information between different devices via the internet (Farooq et al., 2015). Besides the collection of information, IoT focuses on the communication of devices and machinery for data and information exchange. IoT can be used to monitor production processes for potential points of failure and areas where production may be lacking. Some of the other improvements found through IoT are cost savings, data management, and improved efficiency.

The concept of Big Data commonly refers to the collection and analysis of larger data sets that are usually more thorough and detailed than what is seen in more standard data sets. Big Data sets are known for having three common characteristics that depict the layout of information: variety, volume, and velocity (Sagiroglu & Sinanc, 2013). Big Data works along with the implementation of IoT since Big Data creates more opportunities to have data and information available. At the same time, IoT focuses on analyzing the newly found large data sets. More specifically, IoT focuses on the volume of information produced by Big Data by increasing the amount of data from process operations and decisions. The goals of Big Data and IoT are to provide more information and opportunities to gather information; the usage of PLM helps monitor what has been gathered by these other tools from process start to process end. More details on PLM will be explained in section 2.10.

The components of Industry 4.0 listed in the prior paragraphs push for Industry 4.0 development and focus on advanced and smart manufacturing. Points of interest within the manufacturing process (product development, planning, preparation, and quality) are treated with special attention. Product development is being reimagined into a more collaborative form that focuses on bringing more people into the development cycle while reducing error and increasing efficiency. Certain product development pieces are being inspected to see if there is a potential improvement that Industry 4.0 can remedy. One focus area is engineering drawings, a tool used for years to help depict product/part dimensions and specifications.

2.3 The State of Engineering Drafting/Drawings Today

Engineering drawings have been used for decades as the primary form of information and data for manufacturing and production. Creating 2D engineering drawings is considered to be an essential skill that all engineers should have (Wang et al., 2012). The following properties are commonly found in engineering drawing: dimensions, tolerances, surface conditions, heat treatment, material type, manufacturing process information, and assembly information (Quintana et al., 2010). The information previously listed is important when procuring a proper 2D engineering drawing. CAD (Computer Aided Design) software packages makes creating these drawings easier by allowing for a quick and smoother conversion of information from 3D model to digital 2D drawing. The progress of information technology has made the 3D definition of geometry a reality, and engineers can construct the solids with computer software and display them easily on their screens (Wang et al., 2012). As time goes on, new methods and software will begin to replace the traditional methods of drafting by hand, and drawings will be digitized or removed entirely. According to the US Bureau of Labor Statistics, engineering drafting jobs are expected to decrease by 3% from 2021 to 2031 (*Drafters*, n.d.). While a decrease can be seen between 2021 and 2031, the need for drafters does not disappear and will remain like this for an extended period.

2.4 Using CAD Software Packages in Drafting

Most CAD software packages can produce digital 2D drawings from the created 3D models. Having these digital 2D drawings helps reduce waste and allows for a safer approach to storing the documentation in a secure server. Drafting CAD packages offer the tools needed to create drawings that fully represent the models and all the required information. Digital CAD drawings have proven that paper storage is no longer needed and other options are available (McCullouqh, 2022). Putting engineering drawings into an electronic database can save time, money, and much aggravation (Shelley, 1990). Digitizing the design process helps improve collaborative capabilities. The ability to quickly transfer these documents from one to another helps reduce waiting periods. More collaborative capabilities allow for feedback to be sent from person-to-person much faster. The accelerated feedback loop can spur iterative cycles at all levels of engineering design, which are fundamental to design ideation, exploration, and optimization (Xie et al., 2018). Using CAD simulations has enabled the ability to analyze specific features on 3D models. Critical information for tolerancing and specifications can be used from these simulations and applied directly to the drawing. In recent years, traditional and digital 2D drawings have both been questioned for their conciseness, and some have looked towards using the 3D model as a master document.

2.5 The Concept of Model-Based Definition (MBD)

MBD, or Model-Based Definition, is creating a fully defined 3D model that contains the aspects of what would be found in a traditional engineering drawing. Initially, the drawings would be made using the 3D models, and PMI (Product Manufacturing Information) would be added to the drawing. These drawings are pushed to downstream operations (manufacturing), which can lead to communication issues between the original designer and the manufacturer (Mohammed et al., 2021). MBD removes the drawing step and uses PMI on the 3D models, eliminating the need for two separate documents. The needed PMI is applied to the model during the design phase and stays with the models throughout the remainder of the project. A unique feature of working with MBD models is that the MBD dimensioning changes as features are changed on the model. If feature dimensions were to be changed, the dimensions on the MBD model would change along with it, reducing the time it would take to fully prepare the MBD model for manufacturing. Several groups/organizations have begun to standardize MBD. The International Organization for Standardization (ISO), The American Society of Mechanical Engineers (ASME), and the United States Department of Defense have all standardized MBD (Križaj & Vukašinović, 2019). Standards for 2D drawings have been developed and improved upon for years; these standards helped create a base for what is being done for MBD standards today. Many of the standards designed so far for MBD focus on adequately applying information to the model itself. Some also go into detail on what is and is not allowed.

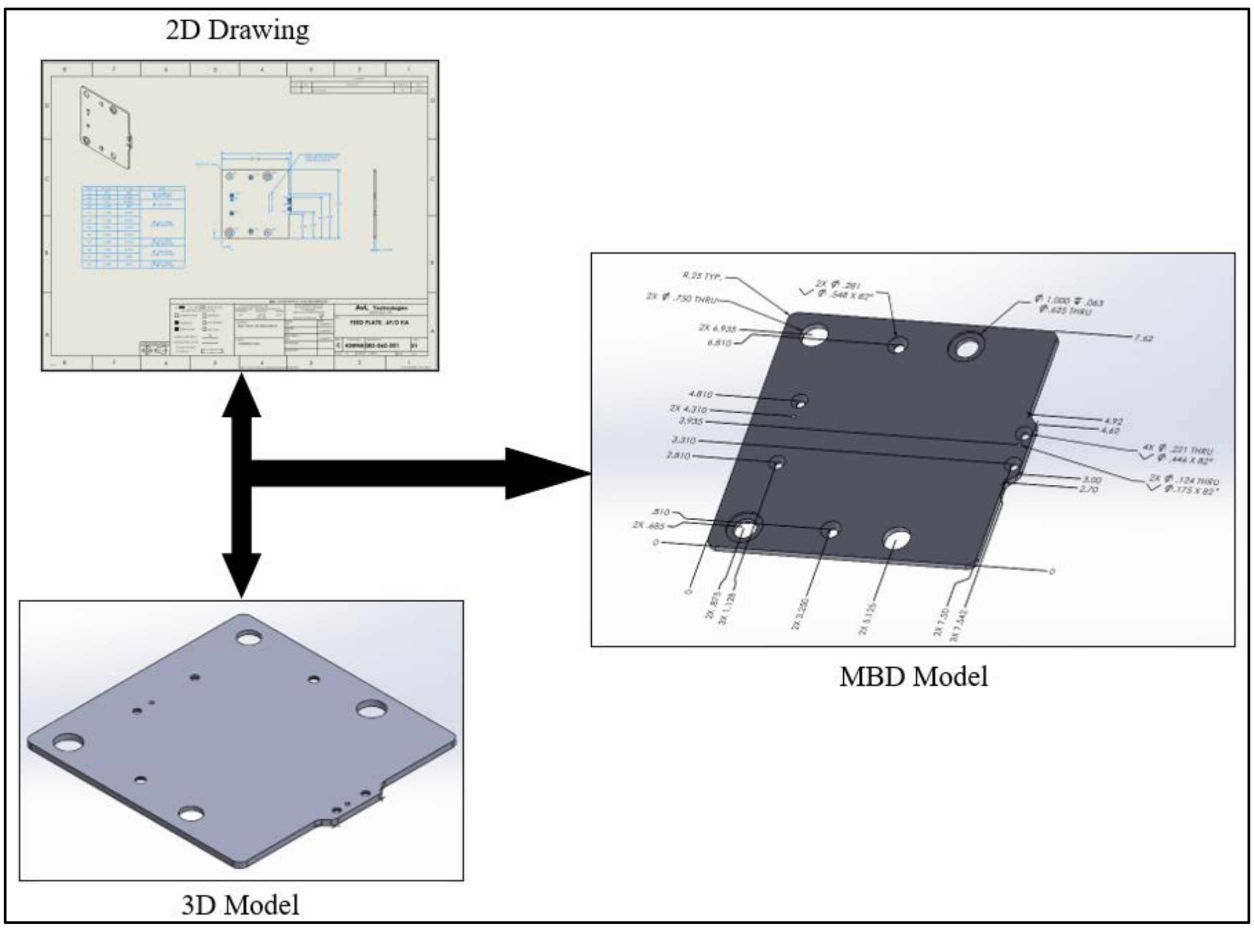


Figure 2.2 – Combination of 2D drawing and 3D model into an MBD model.

2.6 Process Improvement through MBD

Traditionally, creating a product or idea takes numerous steps and flows throughout the company. However, disconnection between areas (design, manufacturing, procurement, planning, etc.) can confuse design and manufacturing intent. This disconnection is due to using multiple systems, languages, and techniques in the industrial process. Engineering and design (a.k.a. Design engineering) creates the 3D model, leading to the 2D drawing containing all the necessary PMI (Product Manufacturing Information). The machinist then takes the drawing and manually enters the information from the drawing into a CAM (Computer-Aided Manufacturing), CMM (Coordinate-Measuring Machine), or CAI (Computer-Aided Inspection) software. Two points throughout the process can cause failure or error: the transfer of information manually and interpreting the data.

When MBD is implemented, these errors can be reduced or eliminated. The intentions behind implementing these models into the process are meant to cover a wide area of aspects (clear interpretation, reusability, merging of information from different sources, and a possibility to describe the reality better) (Hick et al., 2019). These annotated models can easily be transferred from one place to another and offer collaboration so that misinterpretation is less likely to happen. The information no longer needs to be pulled from the drawing and entered by the required software; it can be uploaded through the model, which contains all the required PMI and eliminates the need to make a drawing. A production process based on MBD looks towards having a highly efficient and rational process design system using the three-dimensional model and MBD data (Song et al., 2018).

2.7 MBD Industrial Application

There are multiple perspectives on how the application of MBD will appear in the industrial layout. While MBD pushes to remove the 2D drawing, the drawing could be used as a secondary source of information that can be referenced at various points. The tables below describe some potential approaches that can be investigated in developing MBD in a product, enterprise, and process scenario.

Table 2.1: Product-oriented MBD

Product-Oriented Scenario
The 3D model has become the primary (master) source of geometrics for the product.
Associative 2D drawings will accompany the model for the manufacturing and maintenance departments.
No modifications can be applied to the drawings.

Table 2.2: Enterprise-oriented MBD

Enterprise-Oriented Scenario
The 3D model has become the only source of information for any geometrics, tolerances, material, technology, and lifecycle data.
Manufacturing and Maintenance notes can now be found in the model.

Table 2.3: Process-oriented MBD

Process-Oriented Scenario
The 2D drawing becomes suppressed.
The 3D model becomes the only master source of geometrics and tolerance.
3D FT&A (Functional Tolerancing and Annotations) is applied.
The addition of manufacturing lines accompanied by LEV (Low-End Viewer) systems for visualization and mark-up.

Examining Table 2.1, the use of 2D drawings is still available and accompanies the models for manufacturing. However, it is no longer the primary source of information for the manufacturing process. The drawing is treated as a reference document in case issues arise with the model (technological issues, licensing issues, etc.). Table 2.2 presents the straightforward application of MBD, where the MBD model is the only source of information and is used throughout the project's lifecycle. This approach focuses on creating a bridge of information transmission between 3D design and manufacturing (Jing et al., 2020). Notes and information that could pertain to manufacturing applied to the model for the benefit of manufacturing. The final scenario in Table 2.3 provides more for manufacturing by giving more annotative capabilities on the model. Around 35% of manufacturing resources are estimated to be spent on managing changes to engineering drawings, manufacturing plans, and scheduling requirements during the manufacturing process (Quintana et al., 2012). Suppose notes, mark-ups, and suggestions can be applied to the model. In that case, it reduces the time and waste created by having another form of documentation in the pool of manufacturing items. Furthermore, if there were to be a standard template that manufacturing companies could follow, it would help reduce confusion between designer and manufacturer. There has been some development towards making this standard template a reality.

2.8 ASME Standard Y14.41 – 2019

The American Society of Mechanical Engineers (ASME) has already taken steps toward standardizing MBD. Y14.41, known as Digital Product Definition Data Practices, develops a series of practices and applications in which technical data is applied directly to the model. It has formalized how product information is presented and interpreted in a three-dimensional model and supported many manufacturing companies' adoption of MDB(D. Camba et al., 2013). There are two methods that the standard depicts throughout the text: the use of an annotated model or an annotated model accompanied by a drawing graphic sheet (ASME, 2019). The standard discusses the requirements applicable to both methods and the individual requirements. Furthermore, it pushes to develop better annotation and modeling practices for engineering and CAD-related disciplines. Fourteen sections are found in Y14.41; some of these include data set requirements, model requirements, model values and dimensions, geometric tolerances, and surface texture (ASME, 2019). The information and data attached to these models should be clear and understandable when given to another person for reading or manufacturing. It is important to remember that the point of adding this information to the model is to specify manufacturing and life cycle support data (D. Camba et al., 2013). When done correctly, the model captures what a drawing could accomplish and has the same value as traditional 2D drawings.

2.9 Combining MBD with STEP AP 242

CAD formats have been used to help better represent information found in 3D models, making it easier to transfer information to other people and systems. STEP (Standard for the Exchange of Product Data) is a neutral file format developed by ISO (International Organization for Standardization) to help make information through models more accessible. Usually, the STEP files are followed by an AP (application protocol) that helps determine which industry the STEP format should pertain to (Križaj & Vukašinović, 2019). For product definition through the 3D model, a new protocol was created for the manufacturing industry. STEP AP 242 or ISO 10303-242 is a format that allows 3D models to capture important semantic data, which can be helpful for automating various downstream modules, mainly manufacturing (Venkiteswaran, 2016). The 242 standard was created by combining pieces of two other STEP standards that had been formed in the past: the STEP AP214 (automotive industry) and STEP AP203 (aviation industry) (Wardhani

& Xu, 2016). The use of STEP AP 242 will make transferring model details and manufacturing details throughout industry more efficient. The practice of using both MBD and STEP AP 242 within manufacturing falls within PLM (Product Life Cycle Management).

2.10 The Adaptation of Product Life Cycle Management (PLM)

PLM is the business activity of managing, in the most effective way, a company's products across their lifecycles, from the first idea for a product to product is completion or retirement (Stark, 2016). It is a method of tracking product information to help assist in future development and decisions. PLM software helps to move the information and data form process planning and development to a digital format that unifies product planning and development. The five phases of product development (design, manufacturing and assembly, service, maintenance, and recycling), product information and data are collected within the steps to help analyze the current state of the product and any future outcomes (Ji et al., 2013). PLM takes all this data collectively and keeps track of it for the teams involved in the design, planning, manufacturing processes, etc. Various companies have developed PLM programs and tools to layout process and product information that can be viewed and edited by participants involved with the project. While not created by PLM, Model-Based Definition is a tool utilized by the process to help maintain the models and designs used throughout the life cycle. Regarding manufacturing, PLM represents the missing link between CAD, digital manufacturing, and simulation (Alemanni et al., 2011). While effective, there are issues with getting PLM started within a process. The scope of PLM implementations is large and takes numerous resources and time to complete. This can make it hard to keep to a schedule with current projects and manage a budget. PLM should be studied and prepped before establishing and using the PLM style within the product development environment (Batenburg et al., 2006).

CHAPTER 3: METHODS

The methods are divided into three separate sections. Add some lines here to introduce the methods section and explain why it was organized into three sections.

- Selecting the software package to use - Section 3.1
- Development of Testing Protocol - Section 3.2
- Conducting the Tests - Section 3.3

3.1 Evaluating and Selection of CAD Software Packages for MBD

A standard recommendation in the MBD field is having a common template/format that can be used for any modeling done throughout the production process. Along with this recommendation, it is also safe to research which CAD software packages are suitable for the company and provide all the needed tools for company operations. To gain a better understanding of MBD capabilities, different modeling software packages were researched and investigated to determine which had made the most progress toward developing a usable MBD package and how user-friendly it appears.

Creo Parametric (Parametric Technology Corporation (PTC), Boston, MA) is a CAD program that can be used to develop models, assemblies, and 2D drawings. PTC is one of the leading CAD innovators in the world of CAD software and has made considerable advancements in pushing towards creating a CAD software package that fully encompasses the goals and techniques of MBD. Creo Parametric version 9.0(2022) was used to create MBD models. A test part was created in Creo that included dimensions, tolerances, datums, and notes. ASME standard Y14.41 was referenced throughout the process. While completing the test part to evaluate the capabilities of Creo, auto dimensioning, annotation tools, view creation tools, tolerancing schemes, and other tools were used to help apply the information to the part to see if there were other ways of creating MBD models faster. These tools proved to not be efficient and standard dimensioning methods were used to complete the part(s).

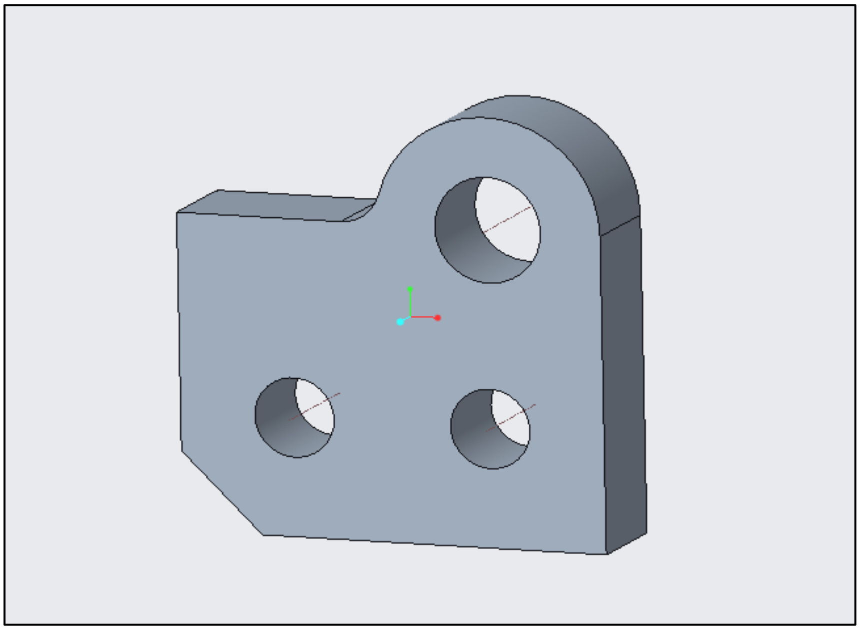


Figure 3.1 – Isometric view of a part created using Creo Parametric.

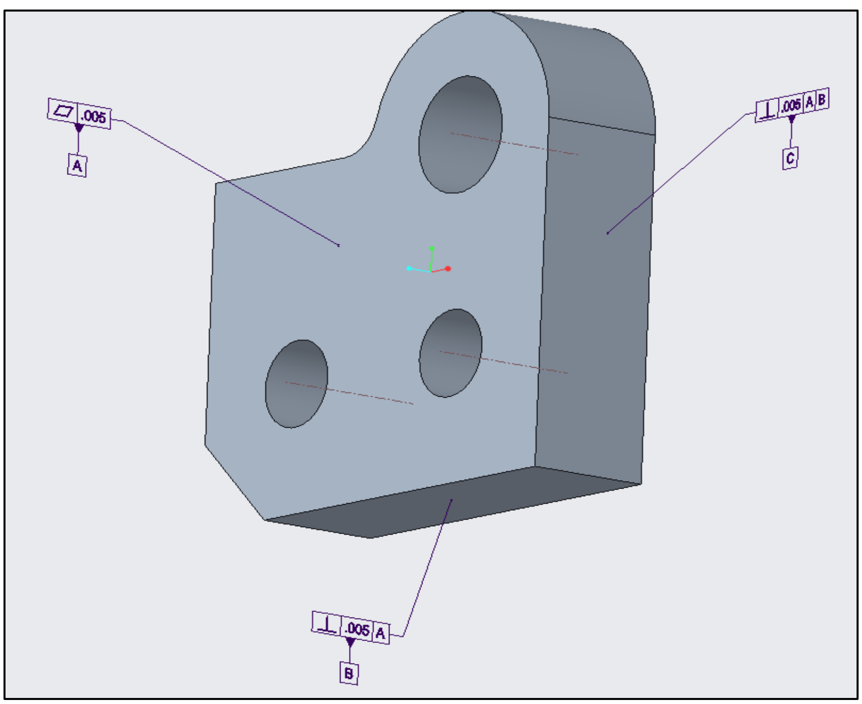


Figure 3.2 – Creo Part Model, showing datums and GD&T callouts.

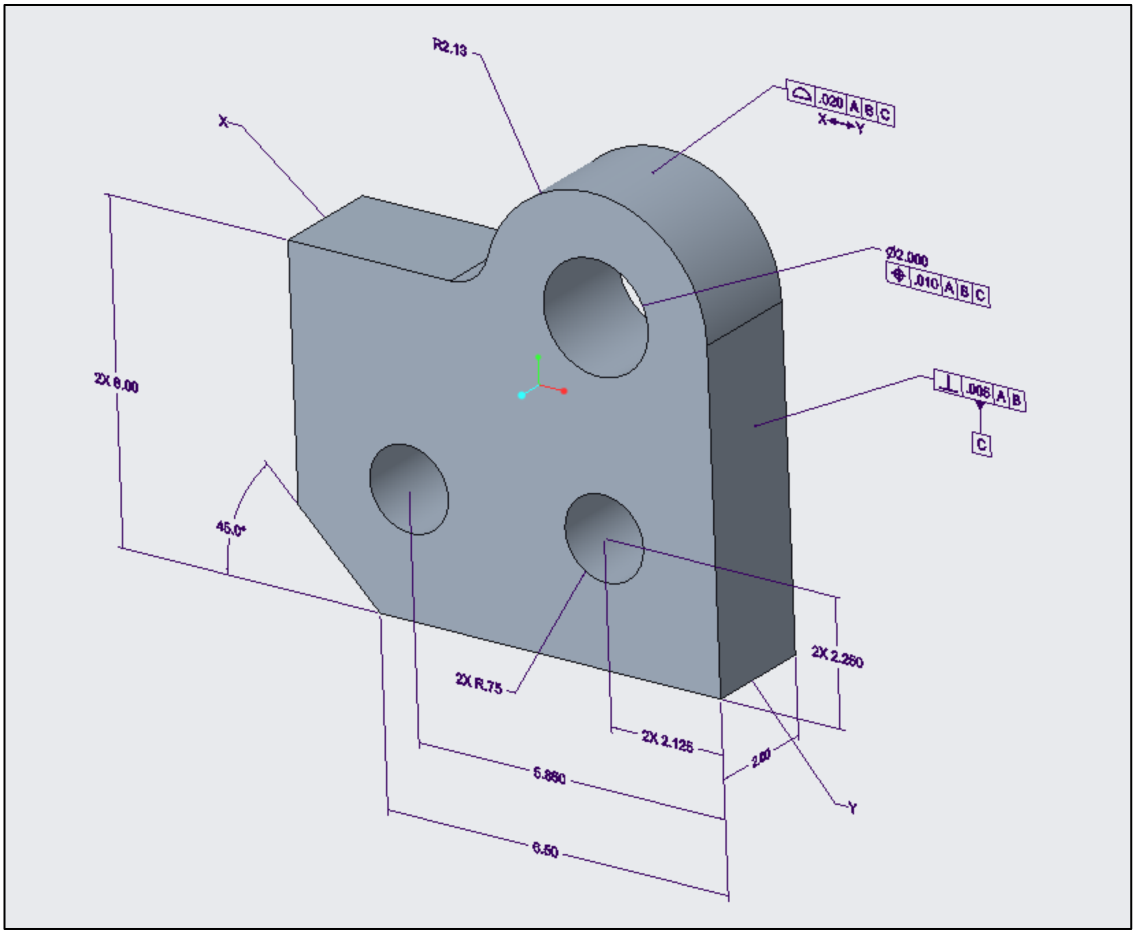


Figure 3.3 – Creo Part Model, showing dimensions based on the ASME Y14.41 standard.

SolidWorks (Dassault Systèmes SolidWorks Corporation, Waltham, MA) version SP03.1 (2022) was also investigated and an MBD model was created. When using SolidWorks, it is best to create a template for MBD that utilizes features that pertain to annotations and dimensions. SolidWorks allows for views (known as 3D views) to be created for models where specified PMI is shown and hidden when not needed. 3D views were created, and settings were applied to display only the PMI information that pertained to the specific view. This option was useful with some of the views created in the test models that contained large amounts of dimensions that could have been easily applied to other views.

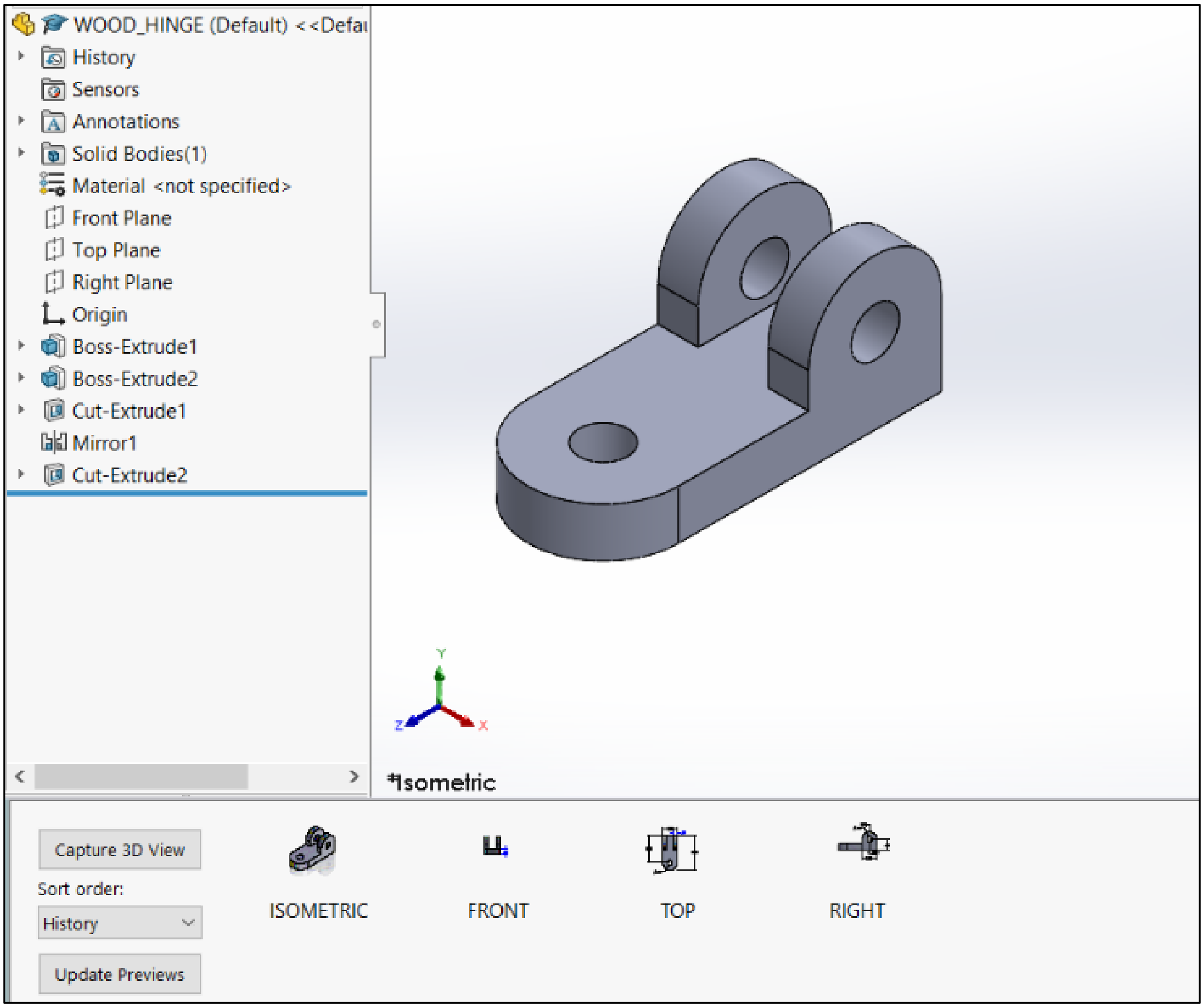


Figure 3.4 – Isometric view of MBD model in SolidWorks.

SolidWorks offers many creative features that make the modeling process comfortable and easy to navigate. One of the helpful features in SolidWorks is the dimensioning and annotating pop-up window that appears when selecting PMI on the model. It allows for easy manipulation of details and providing for quick tolerancing and changing of dimensions on the parts. Furthermore, if the features are changed on the model at any point, the PMI placed on the model will change automatically to the new dimensions applied (except for notes, manually entered dimensions, and geometric callouts).

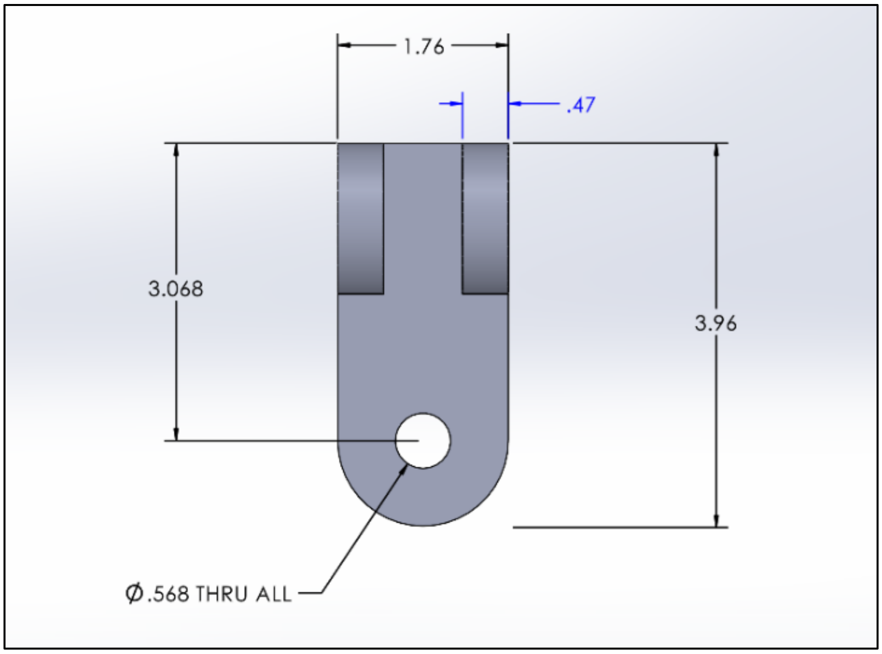


Figure 3.5 – TOP view of MBD model in SolidWorks.

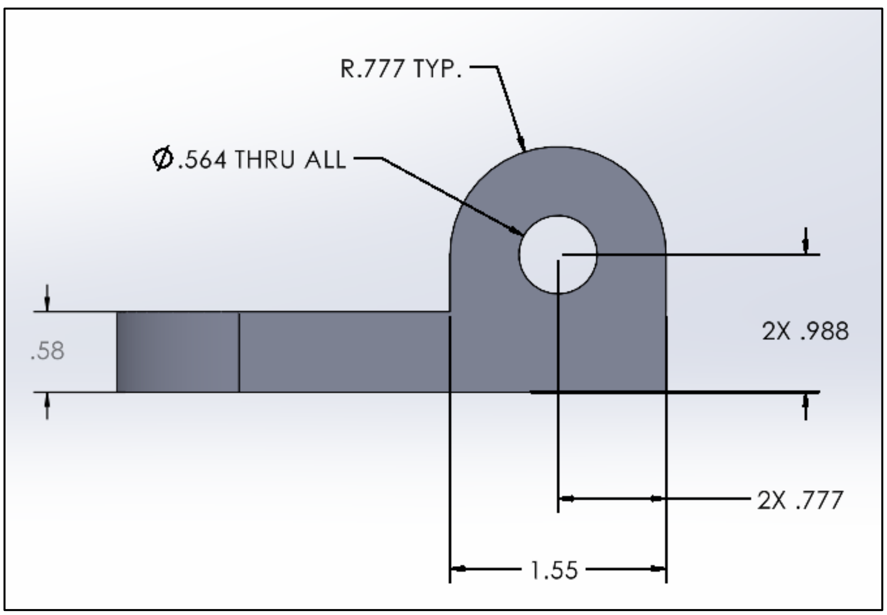


Figure 3.6 - RIGHT view of MBD model in SolidWorks.

Comparing the two-modeling packages, it was much easier to convert models to MBD using SolidWorks than Creo. SolidWorks provided a multitude of templates to choose from and it was faster to bring views of models into the drawing than using Creo. Applying dimensions to the models was different between the two software packages. Automatic dimensioning tools that applied dimensions to the entire model and individual dimensioning tools for applying singular dimensions were investigated in both software packages. SolidWorks dimensioning options were much easier to use and provided various options for applying dimensions in both drawings and 3D models. SolidWorks dimensioning tools made it easy to select and manipulate the dimensions as they were being applied to the models. Creo did provide a larger variety of dimensioning editing options when applying the dimensions to the model, but when using and researching what these options were, many were unneeded and provided unnecessary detail. Various notes were applied to the models to see how notes would attach and appear, Creo was much easier to use when applying these notes to the models. Both Creo and SolidWorks had an easy system for creating these views, but navigating the tools and views area in SolidWorks was much clearer and easier to follow. Additional views could be created slightly faster using SolidWorks, but nothing substantial. For the reasons stated above, SolidWorks was selected for use in this study.

3.1.1 Developing an MBD Template

To start the template, various annotation views were created to explain and layout the MBD model. Early template work was completed in the model tree found on the left side of the modeling area. The work focused on creating areas within the model that would hold certain types of information. Note areas were applied to the model tree to separate the two forms of text information in the MBD models. The "general info" note area contains all information that pertains to the title block area while the "model annotations" note area contains all notes and text that apply to the model's features. Dimensions and other GD&T operations are applied in this note area. Additional note areas were applied to the model tree in the beginning to callout specific notes and information applicable models, but this was removed and replaced by the two note areas presented in Figure 3.7. Having established the note areas, the next step was to create view areas for the different model views that would be presented in the template. In figure 3.7, a section labeled "unassigned items" can be seen, the created view areas will be applied under this section. All the standard orthographic views were used to provide a selection in the template for the MBD models and the following views were created in the template: Top, Front, Right, Left, Bottom, Back, and Isometric. The applied view areas can be seen in Figure 3.8 under the "unassigned items" section previously mentioned.

Completing the note and view areas finalizes the work needed in the 3D model tree template. The next task was creating the needed 3D views for the model template. The 3D views tab, located at the bottom of the modeling area, contains all created 3D views and allows the user to select these at any point. A 3D view was created for all the areas listed in the previous paragraph. The process of creating the 3D views required options to be selected before finalizing the views. For example, when capturing the isometric 3D view, the modeling area had to be oriented into the proper state before completion. The model planes were activated for this process to ensure the correct view was being set. When going to capture the view, the proper view area needed to be selected before the 3D view was finalized. Selecting the correct 3D view area ensures that only annotations pertaining to that view will appear. This process was repeated for all view areas and was applied to the 3D views tab. Having the 3D views created, the user can now go to the 3D views tab and see all available options. Additional 3D views can be added by orienting the modeling area into the state needed and following the same operations described above. The created 3D views can be seen in Figure 3.9 on the following page. The capture tool in SolidWorks allows the 3D view to be captured again if changes are needed. Many created 3D views were excessively zoomed in when the 3D views were selected. These were zoomed out so the modeling planes could easily fit within the modeling area, and the capture tool was used to update the 3D views.

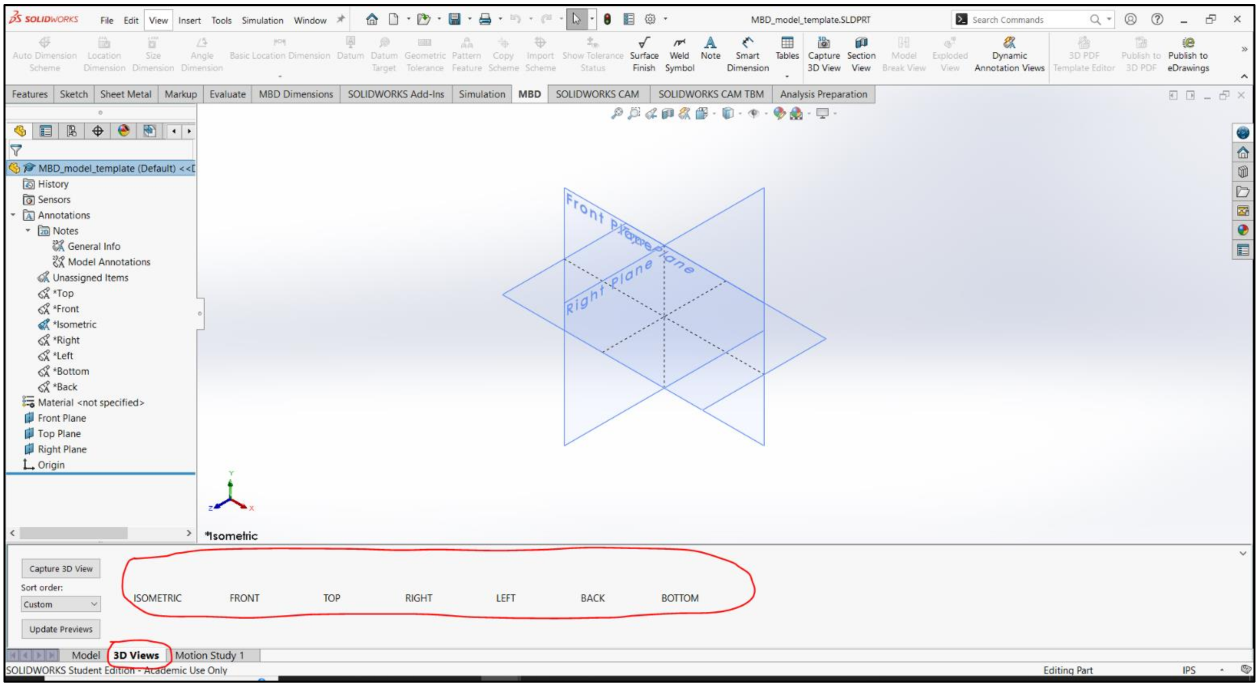


Figure 3.7 – Newly created note areas added to the model tree.

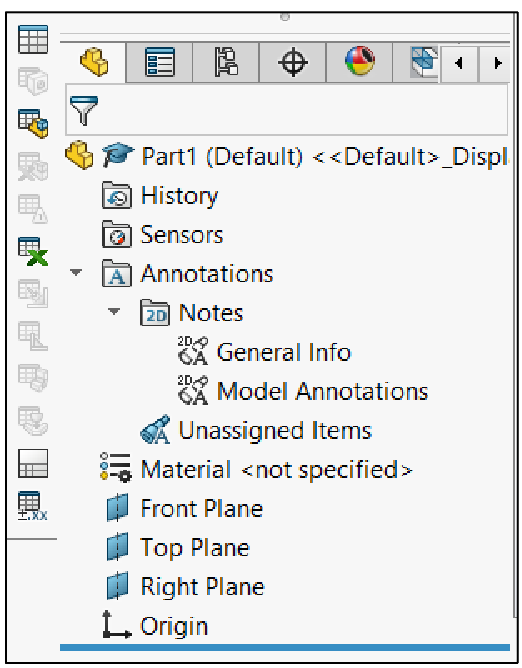


Figure 3.8 – Default annotation views for template.

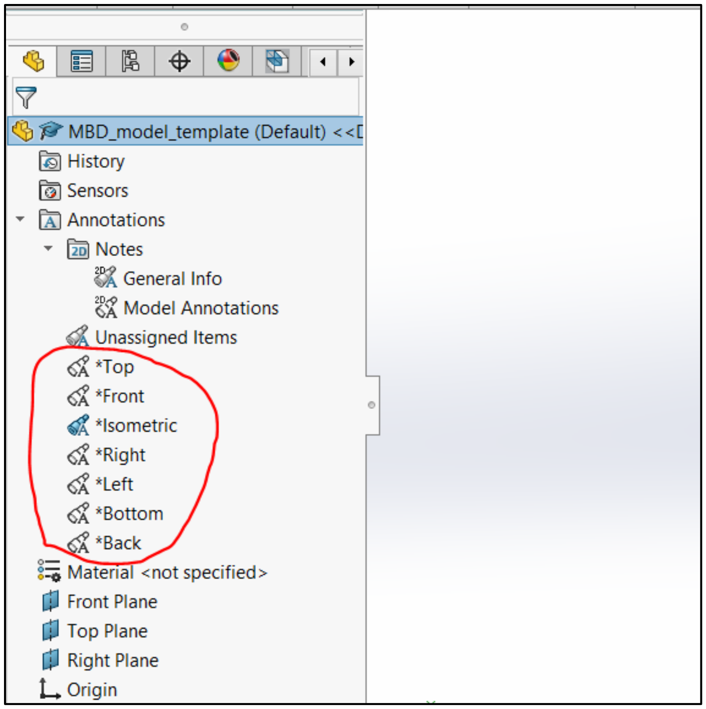


Figure 3.9 – Default 3D views for template.

Different tolerancing schemes were investigated and applied to practice model dimensions to view how the appearance would change from the drawing to model, there were no significant differences. SolidWorks allows for the option of setting automatic tolerancing styles to dimensions when applying tolerances. This was investigated but not applied to the template, it was determined that it would be best to allow the user to decide what tolerancing style they would want to use instead of restricting to a singular style. If someone wanted to change the style, it can be done during the modeling process. The local production company participating in this study uses a particular tolerancing standard for drawings and models. To help keep familiarity with their drawings, the same tolerancing standard was applied to the model template. Figure 3.11 is the tolerancing scheme that was used throughout the template. These values were applied within the document properties of the template and can be referenced at any point throughout the modeling process. This information was not represented as a note in the modeling area but could have easily been applied. The 3D PDF created later would capture the tolerancing standard in the top of the 3D PDF along with the other title block information needed to give full model definition. After the tolerancing had been applied, the template was moved into a usable state for MBD models. One of the options mentioned earlier was the possibility of using and creating a 3D PDF. When the concept was brought up to local production company, they believed it could be worth investigating and using throughout testing because they had received insufficient 3D PDFs in previous projects. SolidWorks provides the ability to create 3D PDFs directly from the model. Templates are provided in the PDF menu with sections to keep up with revisions and add title block information. The templates' appearance lacks detail, and many areas that should be filled with necessary information pertaining to the model are missing.

A secondary PDF editing software is needed to edit the 3D PDF templates. When creating the 3D PDF from the MBD model, the only options available for modifying the 3D PDF are which template to use and what views are needed on the template. At this time, there are no ways to edit the PDF through the modeling software. Having PDF editing software installed allows a person to create tables and designated areas for part information. Some editing tools used to create the PDF template were the annotation and geometry tools. The annotation tools allow for adding note areas and places where text can be manually entered when applying the model to the PDF. The geometry tools were used to create the different boxes of the title block containing the required information from the model. To successfully create a compelling 3D PDF that captures part information and mimics the drawing appearance, these tools are excellent options to consider.

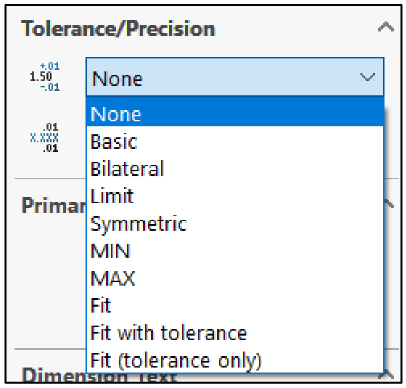


Figure 3.10 – Tolerancing options in SolidWorks.

UNLESS OTHERWISE SPECIFIED		
DIMENSIONS ARE IN INCHES-TOLERANCES ON:		
FRACTIONS	DECIMALS	ANGLES
±.03	.X± .1 .XX± .02 .XXX± .005	±1/2°

Figure 3.11 – Local production company's block tolerancing.

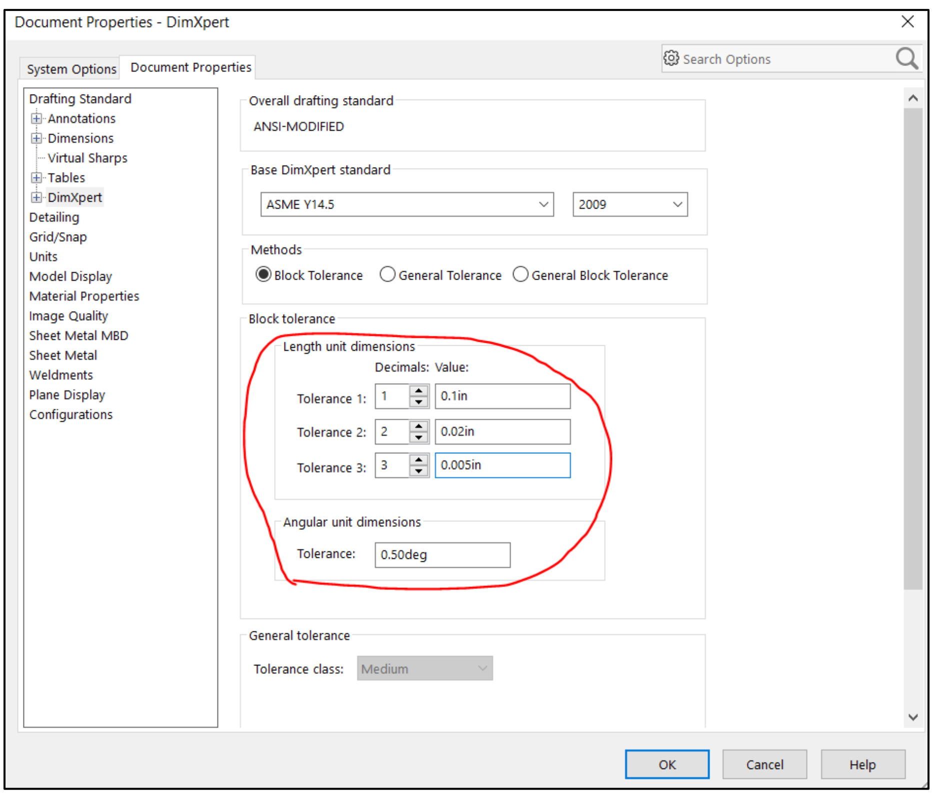


Figure 3.12 – Block tolerances applied to the model template.

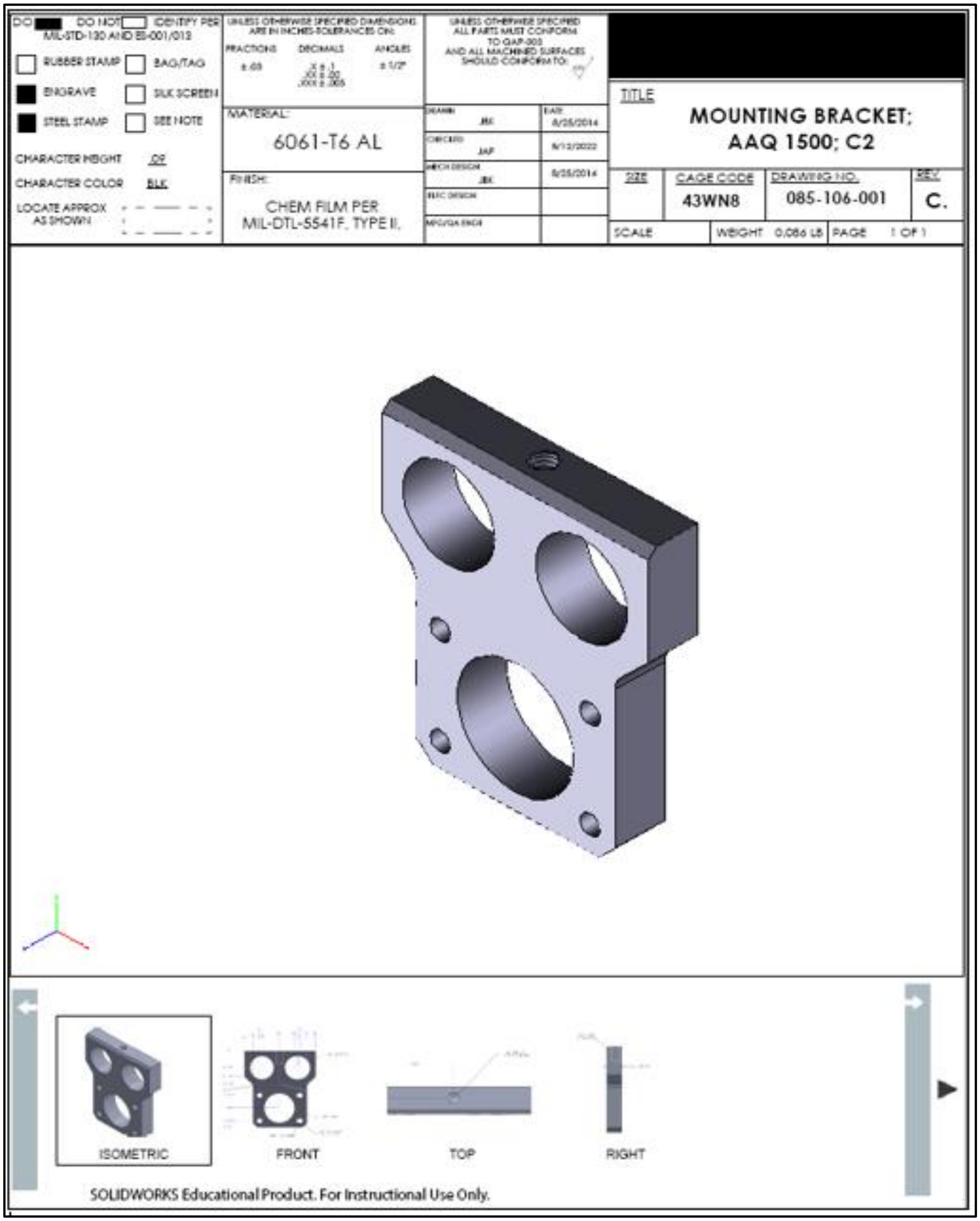


Figure 3.13 – Approved part converted to MBD and applied to created 3D PDF template.

3.2 Study Design

Testing was conducted at a local production company that specializes in engineering and manufacturing a variety of products that scale from large too small and change in complexity depending on customer need. This type of company was targeted due to their large database of various parts and involvement with product design and modeling throughout many of their production and design process steps. They will be known as the local production company throughout the earlier and later sections of this study. The quality department of the local production company was the targeted area for this study. This department was selected because of its frequent use of 2D drawings and exposure to different types of part representations. Drawings and models are continuously circulating throughout the quality inspection, and sometimes, these drawings can be lacking in detail; therefore, the models are sometimes referenced for inspection instead of the drawings. IRB approval was obtained prior to beginning testing. A testing script was prepared along with the process of gaining IRB approval. An informed consent form was created to inform participants about the thesis study, what they would experience during testing, and their rights as study participants. Four people from the quality department were recruited for the study. Information pertaining to what was expected during the testing was withheld from the participants to ensure the data collected was not skewed by prior knowledge of the study objectives. All four people agreed to participate in the testing and signed the consent forms. Each person was assigned a participant number to help keep their personal information confidential, and the signed consent forms were given to Dr. Tanaka (thesis advisor) and stored in a locked cabinet.

3.2.1 Selection of Parts

There were limitations to what could be included within the thesis. Customer requests and company policy keep many of their produced parts confidential. Most of the stock room parts were available for selection and were readily available whenever they would be needed for testing. Parts recommended by the local production company included brackets, supports, spacers, plates, and weldments. To make sure the parts selected were not under any confidentiality agreements, all parts were examined by production engineering before proceeding.

Ten parts were selected for testing. These parts spanned a wide range of different sizes and styles. Some parts had few details, such as a few holes on the surface and chamfers applied to the edges. More complex parts such as weldments, brackets, and plates required detailed dimensioning and annotations to be captured.

Figure 3.14 – Potential parts approved by the local production company (Photo by Carson Pardue)

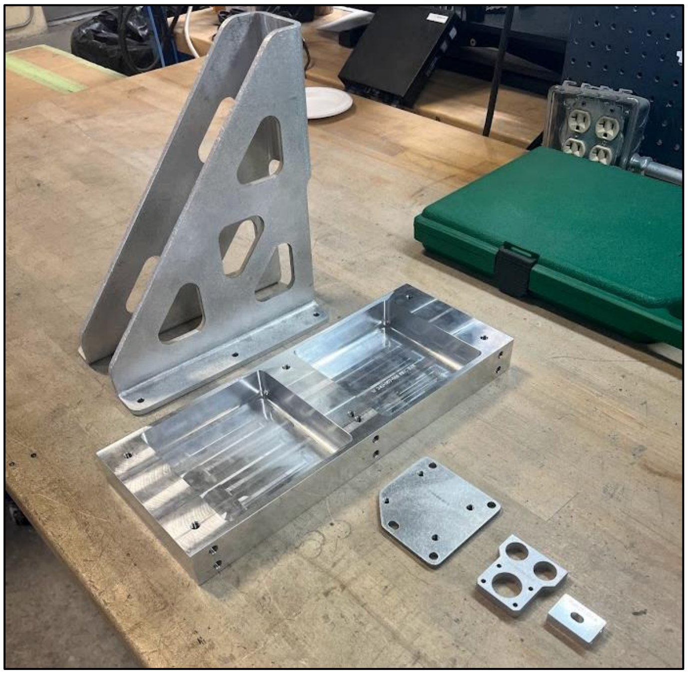


Figure 3.15 – First set of testing parts used (Photo by Carson Pardue)

Figure 3.16 – Second set of testing parts used (Photo by Carson Pardue)

3.2.2 Converting the Models to MBD

MBD models were created for each of the ten parts. Smaller parts took less time to convert to an MBD model. They contained few dimensions and annotations; most tolerances were standard, so there was little to no tolerancing on the features. The MBD models were created from the original 3D models provided by the local production company. When models were being created within the template, the 3D views were updated to show the models like mentioned earlier. The smaller models were completed easily and didn't require any intricate dimensioning techniques. For a majority of the smaller models, dimensions were edited one-by-one as they were pulled from the model. This helped reduce error throughout the modeling process by making sure each dimension was accurate to the drawing and model before proceeding to the next dimension. Some of the bigger models exposed problems with the template and changes were made to correct the template. One of the discoveries was that in lager models zooming out was needed to show all dimensions within the 3D views. However, when this was done for the 3D views, the annotations became small and harder to read. Thus, the text sizes were increased for all large parts to help with reading of dimensions and text.

In addition, holes on the models required special attention to make sure they were capturing the proper information. SolidWorks provides a dimensioning tool that assisted in applying the proper dimension style to the holes. The only thing lacking from this tool was the proper screw size and drill callouts needed to capture the hole information accurately. The needed information only needed to be applied within the text areas found in the dimensioning window when a specific dimension is selected. Hole dimensions and callouts were selected, and the needed text was added. The top and right side of Figure 3.19 show some examples of hole callouts and the text that should be presented when doing a proper hole callout. When applying dimensions to the model template, there were areas where the dimensions were bunched up and unclear of what they were calling out. A different dimensioning scheme, known as ordinate dimensioning, was used that was favored by the local production company. While ordinate dimensioning can make manufacturing easier, it is not a preferred dimensioning approach for product design because it creates tolerances stack up errors. An example of this dimensioning scheme can be seen in Figure 3.19. This dimensioning scheme was mainly used throughout the larger models, the smaller models had enough space for clear dimensioning. Many of the rounded edges were edited to have intersection lines so that the edges of the part could easily be recognized and dimensioned. When the models were prepared and contained all the needed annotations, the 3D views were examined again to see what 3D views were not being used or what 3D views didn't provide any benefit to product definition. These views were deleted and the views that contained needed information were kept. Any dimensions that were calling out multiple instances or features, such as holes or slots, had text applied within their dimensions text boxes to help callout all instances. If a feature was being used across the model frequently, text was applied to the dimension to indicate that it was typical for that type of feature.

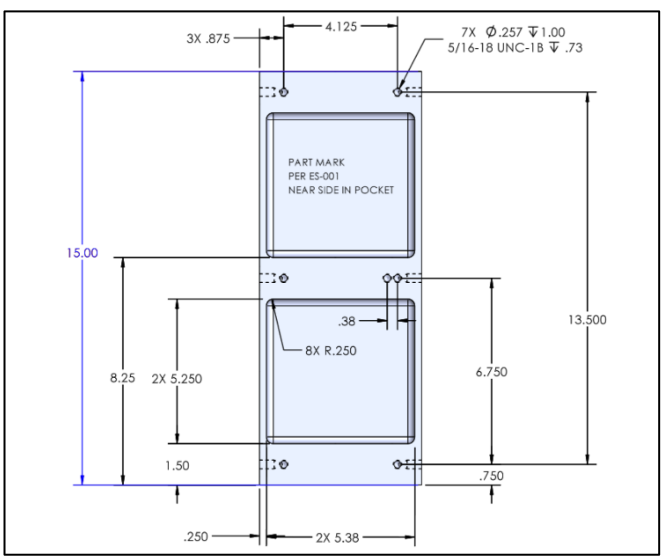


Figure 3.17 – Model with PMI applied.

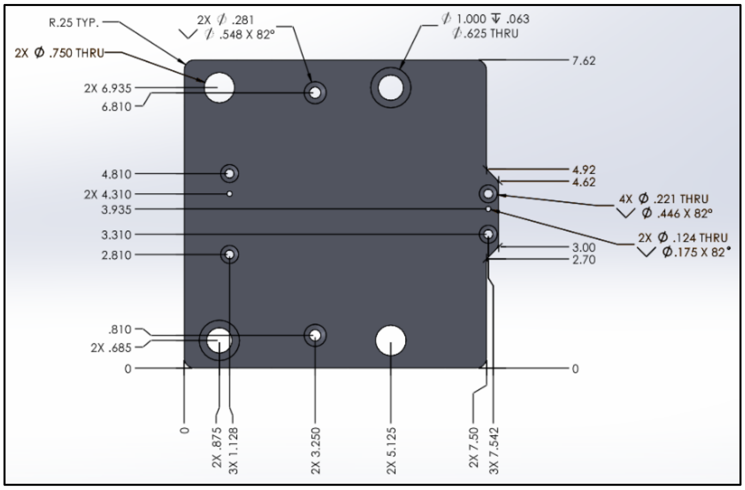


Figure 3.18 – Example of ordinate dimensioning.

3.2.3 Moving the MBD model to the 3D PDF

All models were transferred into a usable MBD model for testing.The MBD models were checked against the 3D models and the orginal 2D drawings to check for accuracy and to make sure they were ready. Only a few issues were found with some of the dimensions and notes; they were fixed and then checked once again against the original model and drawing. In addition, a 3D PDF was prepared for all models to accompany them. Due to issues getting the PDF connected to the model, the information was entered manually. Specific title block areas were applied to the top of all of the 3D PDFs for model information to be applied to them. When the model was sent to the PDF format, the information from the title block on the 2D drawing was manually entered into the created title block areas. This process did take extra time to complete, and causes some setbacks in time. The participants had both options open to them during the testing phase. All 3D views containing any information about the model are presented in a section at the bottom of the PDF. If any section views or detailed views were created during the modeling process, they can be selected for this section when the PDF is being made from the MBD model. The PDF also provides the option for editing text information if seen fit during the inspection.

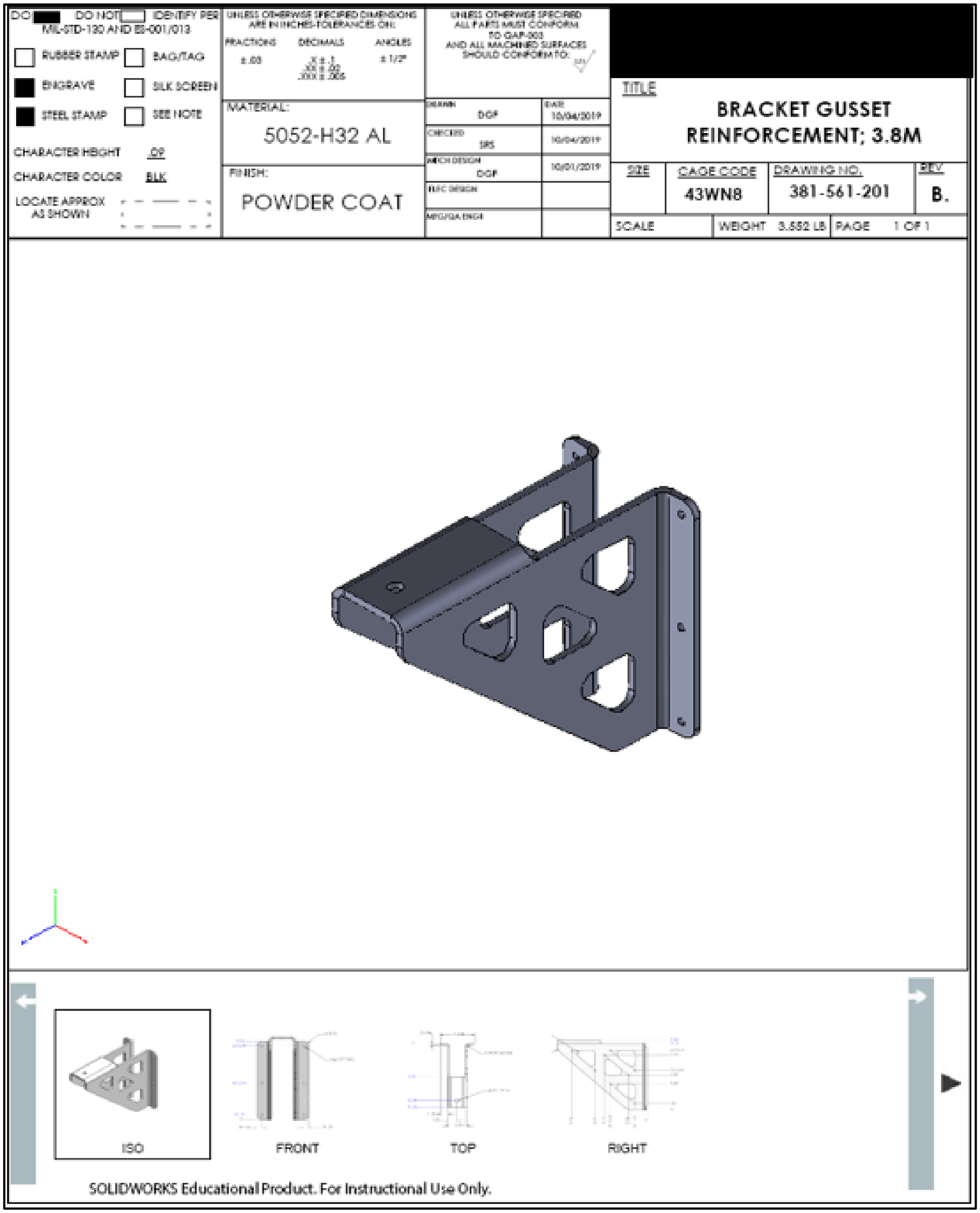


Figure 3.19 – Finalized MBD model applied to 3D PDF.

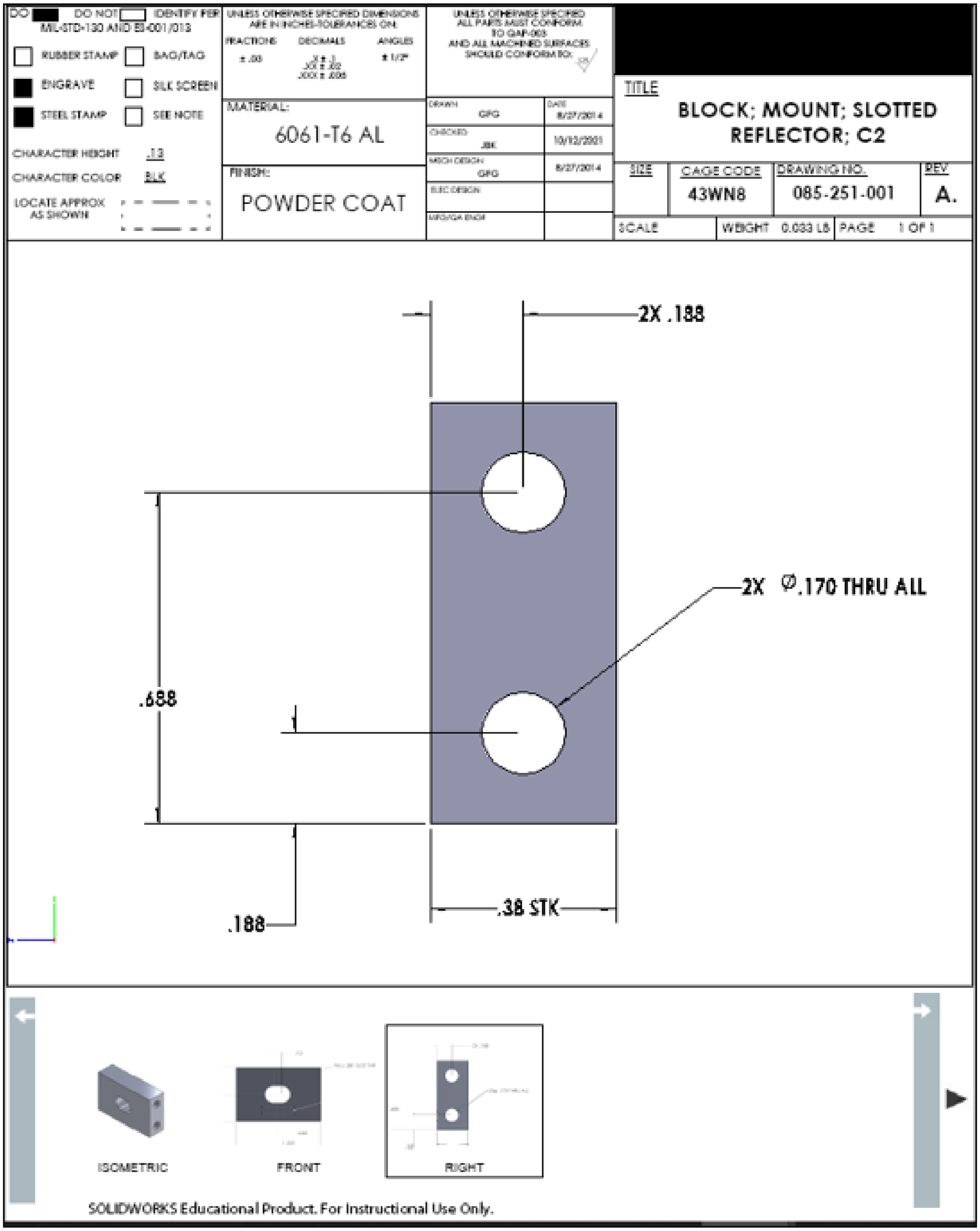
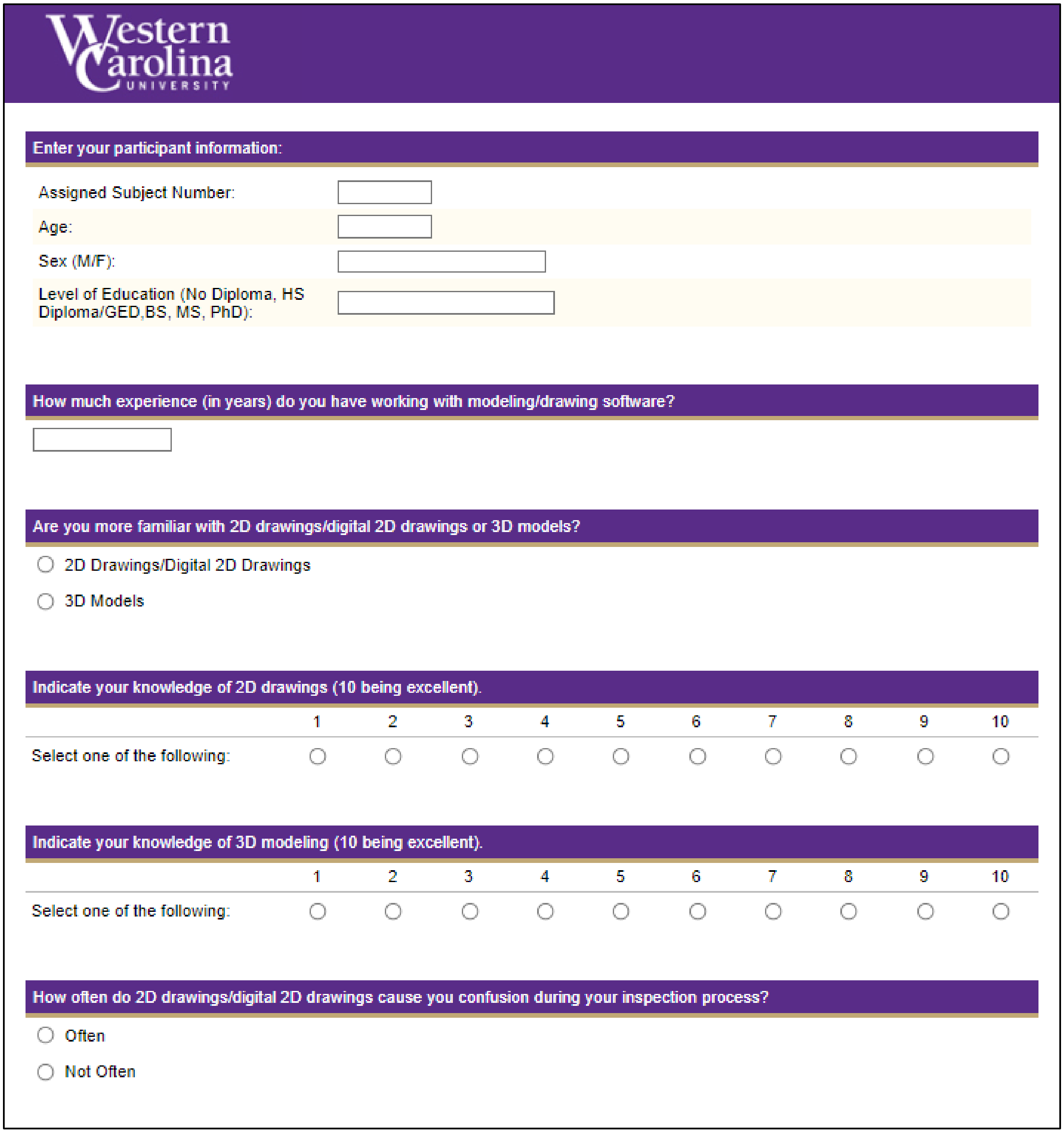


Figure 3.20 – Finalized MBD model applied to 3D PDF.

3.2.4 Creating the Post-Testing Survey

A post-test survey was created to obtain information from study participants after they finished measuring the parts. The beginning of the survey asked the participants for demographic information such as age, sex (M/F), level of education, and the assigned participant number given to them when the consent forms were signed. The information listed would be used later on to help find trends in collected data and to help back up any statements made. The following questions asked participants how much experience they have working with 2D drawings and modeling software and their level of knowledge of drawings, GD&T, and 3D modeling software. These questions are used to help gauge the experience of the participants. The answers to these questions wouldhelp show whether these participants perform better or worse when exposed to a new method outside their traditional style. Some questions about their knowledge of MBD and 3D PDFs mainly aimed to determine if they had heard of the concept before exposure to the study. Their responses could be linked to what is found later on after testing. The remainder of the questions asked about their experience during the testing phase and whether the models/PDFs adequately captured all of the model details. The participants also had a chance to express their opinions about what was completed during the testing phase at the end of the survey. Information about what they liked, did not like, and recommended was collected to talk about future improvements in the discussion and conclusion of this thesis.



Western Carolina University

Enter your participant information:

Assigned Subject Number:

Age:

Sex (M/F):

Level of Education (No Diploma, HS Diploma/GED,BS, MS, PhD):

How much experience (in years) do you have working with modeling/drawing software?

Are you more familiar with 2D drawings/digital 2D drawings or 3D models?

- 2D Drawings/Digital 2D Drawings
- 3D Models

Indicate your knowledge of 2D drawings (10 being excellent).

	1	2	3	4	5	6	7	8	9	10
Select one of the following:	○	○	○	○	○	○	○	○	○	○

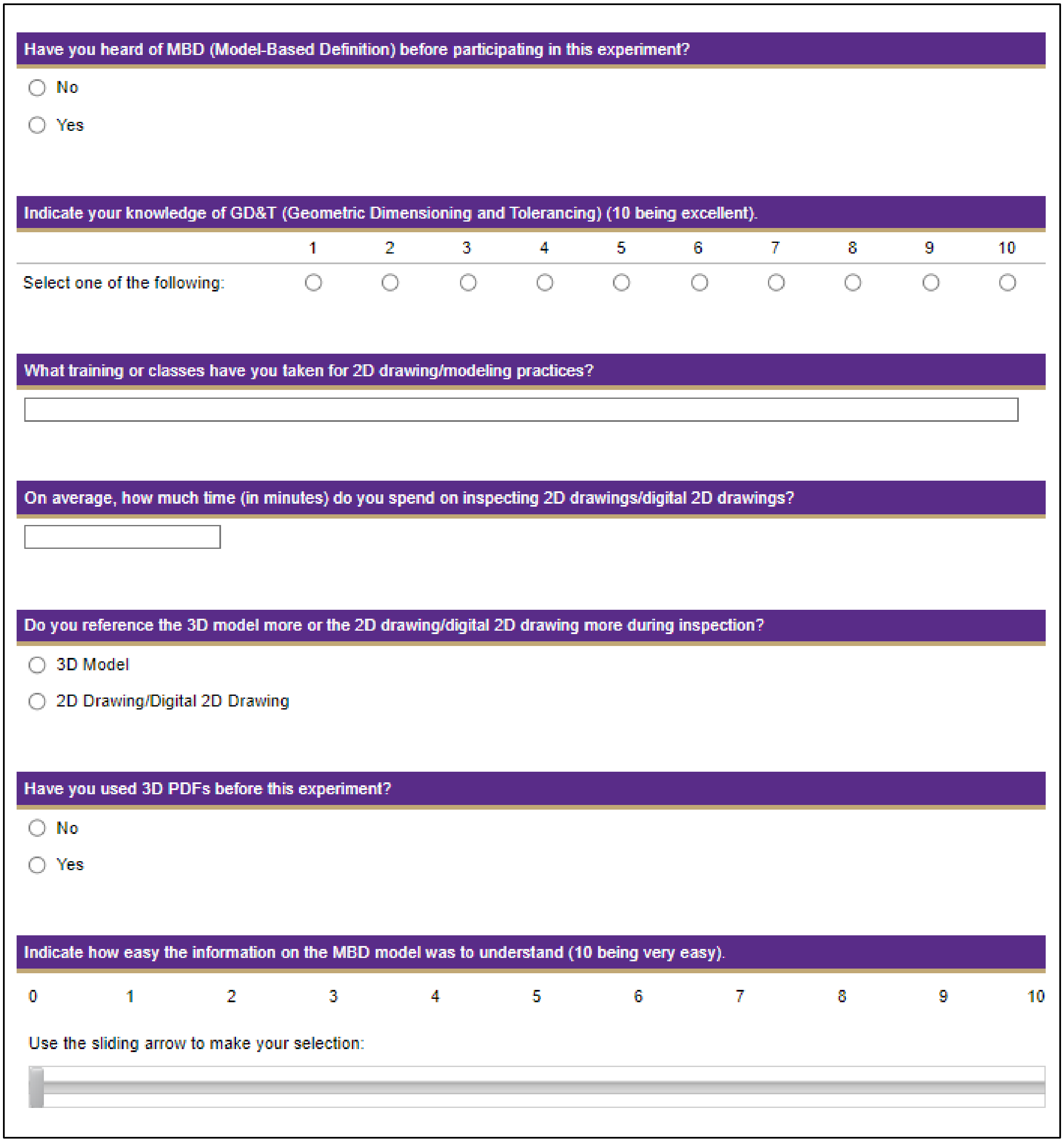
Indicate your knowledge of 3D modeling (10 being excellent).

	1	2	3	4	5	6	7	8	9	10
Select one of the following:	○	○	○	○	○	○	○	○	○	○

How often do 2D drawings/digital 2D drawings cause you confusion during your inspection process?

- Often
- Not Often

Figure 3.21 – Post-testing survey questions.



Have you heard of MBD (Model-Based Definition) before participating in this experiment?

- ○ No
- ○ Yes

Indicate your knowledge of GD&T (Geometric Dimensioning and Tolerancing) (10 being excellent).

	1	2	3	4	5	6	7	8	9	10
Select one of the following:	○	○	○	○	○	○	○	○	○	○

What training or classes have you taken for 2D drawing/modeling practices?

On average, how much time (in minutes) do you spend on inspecting 2D drawings/digital 2D drawings?

Do you reference the 3D model more or the 2D drawing/digital 2D drawing more during inspection?

- ○ 3D Model
- ○ 2D Drawing/Digital 2D Drawing

Have you used 3D PDFs before this experiment?

- ○ No
- ○ Yes

Indicate how easy the information on the MBD model was to understand (10 being very easy).

0 1 2 3 4 5 6 7 8 9 10

Use the sliding arrow to make your selection:

Figure 3.22 – Post-testing survey questions cont.

Which of the two methods did you prefer?

- ◯ MBD
- ◯ 2D Drawing/Digital 2D Drawing

Did the MBD model capture all part information properly?

- ◯ No
- ◯ Yes

Was the 3D PDF easy to understand and did it contain all the required information?

- ◯ No
- ◯ Yes

What aspects of the 3D PDF did you like? Write 2-3 sentences.

What aspects of the 3D PDF did you not like? Write 2-3 sentences.

If you could make any changes to the 3D PDF, what would they be? Write 2-3 sentences.

Figure 3.23 – Post-testing survey questions cont.

3.3 Testing

Participants were instructed not to ask for help from anyone inside or outside of the study. To refresh the memory of all participants, the testing protocol was explained again prior to beginning testing. Any questions that arose after the testing protocol was explained were answered. A common question was if preparation could be done before starting the inspection. They explained that typically they inspect the drawing briefly before the inspection to find what measurement tool will be needed to complete the inspection on a particular feature.

3.3.1 Conducting the Experiment

Each participant was handed the physical part before starting each inspection. They were allowed to inspect the drawings or models to determine the measuring tools needed to complete the inspection. Each participant had a different layout for testing; the methods used for the first five parts would not be the same for the other participants, and the order would be rearranged.

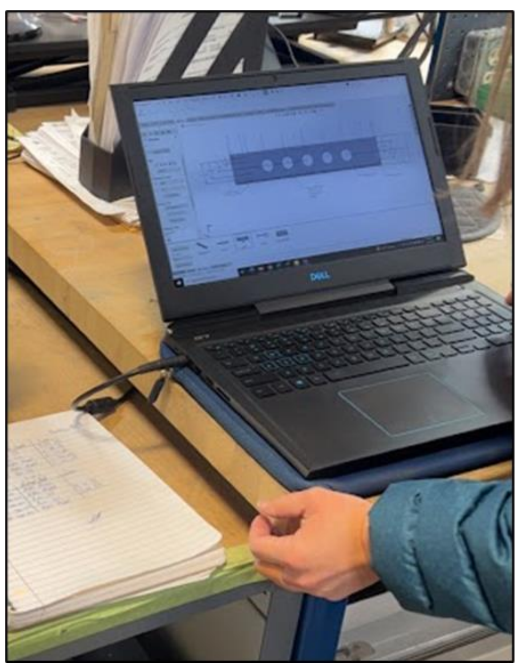


Figure 3.24 – Participant inspecting part using MBD model (Photo by Carson Pardue)

Figure 3.25 – Participant inspecting part using MBD model (Photo by Carson Pardue)

3.3.2 Collecting the Data & Analysis

As each inspection was completed, the time it took to complete the entire process was recorded. The data was put into an Excel sheet so that the test results could be analyzed and reviewed. The data were plotted onto a graph to show the differences between the two methods during each test. Several comparisons were made and used to compare different pairs of participants. Experience, age, education, and training are the four primary comparisons used to evaluate the results obtained from the testing phase. The mean value and standard deviation of each participant and pair are calculated to show improvements in time and the spread of the data relevant to the mean value. A paired samples t-test is run to compare the drawing and model data to determine if the data being examined is statistically significant or if the event being examined is random. Inspecting the different comparisons and evaluating the calculated values mentioned above shows the different conditions that affect the understanding and ability of a participant to utilize MBD.

CHAPTER 4: RESULTS

This section includes the data that was collected from the testing procedure. The representations group the data into different comparisons, showing the raw and graphical data. Following the data representation will be images of the process maps created for the current production process that the local production company uses and the revised process with MBD implementation.

4.1 Individual Participant Data

Section 4.1 shows the testing participants' data collected in a single table. Means, standard deviations, and t-test values are calculated at the bottom of the table for all participants. These values will be used for other comparisons throughout the results section.

	Participant #1		Participant #2		Participant #3		Participant #4	
Part #	2D Drawing (min)	MBD (min)	2D Drawing (min)	MBD (min)	2D Drawing (min)	MBD (min)	2D Drawing (min)	MBD (min)
1	0.7063	0.6800	1.3408	1.4328	2.9122	3.3483	0.9425	1.3096
2	1.0202	0.5800	2.0857	0.9182	3.8910	3.8317	2.1856	2.0716
3	1.8278	1.1205	1.8692	1.5095	4.2650	4.2045	2.1086	2.5295
4	3.3880	3.2663	3.6275	3.5015	10.3545	8.2553	7.4358	5.9696
5	3.2093	3.3837	4.5965	4.5632	4.6970	5.5930	5.8815	6.2963
6	1.2500	0.9688	5.9288	6.0690	N/A	N/A	7.0772	4.3997
7	3.0518	3.0097	4.1897	3.7512	N/A	N/A	2.5960	2.0978
8	2.0742	2.1423	1.7287	1.0260	N/A	N/A	4.6927	6.2327
9	4.3445	4.4170	10.1728	9.9273	N/A	N/A	3.1622	2.5680
10	3.9735	3.8437	3.8200	3.8652	N/A	N/A	4.0042	4.2145
Mean	2.4846	2.3412	3.9360	3.6564	5.2239	5.0466	4.0086	3.7689
SD	1.2811	1.4232	2.6411	2.7891	2.9428	1.9789	2.2157	1.9031
P Value	0.1238		0.0588		0.7466		0.5322	

Table 4.1: Collected testing data for all participants with calculated values.

Examining the data shown in Table 4.1, average inspection times appear to improve across all participants when moving from 2D drawings to MBD. Participants 1 and 2 keep average inspection times under 4 minutes for 2D drawings and MBD methods. Participant 4's average inspection times were similar to what was found with Participant 2. The high standard deviation values shown in the table indicate large variance/variability within the collected data. Calculated p-values for the participants show that statistically, there is no difference between using the two methods when compared to the predetermined value of alpha = 0.05.

4.2 Data Grouped Based on Level of Experience

Data were grouped based on the level of experience. The participants were grouped based on their experience within their positions and how often they completed inspections. Participants 1 and 2 both completed inspections regularly and have 5 or more years of experience with this process. Participants 3 and 4 have been in their positions around the same amount of time as 1 and 2, but complete inspections infrequently and only when needed due to a high volume of parts. The values shown in Table 4.1 are used to calculate average inspection times for the pairs. The same values were used to calculate the p-values shown in Table 4.2. The calculated p-values will help show if there is statistically significant data that support the claim that MBD performs better than 2D drawings.

	More Experienced				Less Experienced			
	2D Drawing (min)		MBD (min)		2D Drawing (min)		MBD (min)	
	#1	#2	#1	#2	#3	#4	#3	#4
Mean	2.4846	3.9360	2.3412	3.6564	5.2239	5.0466	4.0086	3.7689
SD	1.2811	2.6411	1.4232	2.7891	2.9428	2.2157	1.9789	1.9031
Mean	3.2103		2.9988		4.4137		4.1948	
SD	2.1531		2.2582		2.4458		1.9585	
P Value	0.0126				0.4611			

Table 4.2: Experience data comparison.

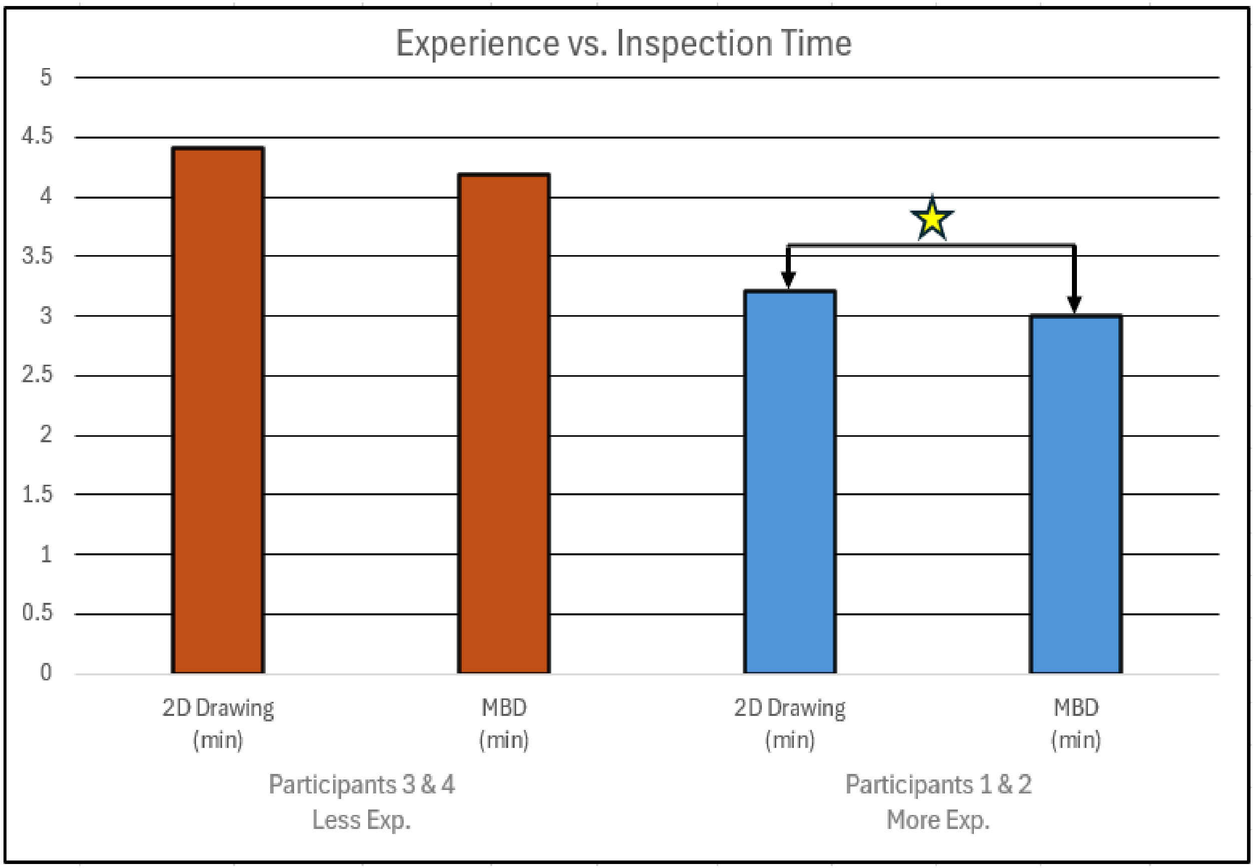


Figure 4.1 – Average inspeciton times for less and more experienced participants.

The average inspection times for experienced and less experienced participants show a decrease in time when using the MBD method to complete the inspection process. For the more experienced participants, the average inspection time decreased by 0.2115 minutes, while the less experienced participants saw a decrease in time by 0.2189 minutes. While the less experienced participants had a slightly larger decrease in time, their calculated p-value shows that the data being examined has a 46.11% chance that the data being analyzed is random and is considered statistically insignificant. The p-value for the more experienced participants indicates that the analyzed data has only a 1.26% chance of being arbitrary, indicating that the difference was statistically significant. This supports the conclusion that experienced workers can complete an inspection using the MBD method faster than 2D drawings.

4.3 Grouped Based on Age

The data in Table 4.3 shows two pairs of participants grouped according to their age. At the time of the study, two participants were both 46 years old, their birthdays were used to determine which of the two was older. For the older group of participants, their ages were 49 and 46. The younger group of participants were aged at 46 and 34. Each participant's calculated mean and standard deviation are provided at the top of the table. This data was used to create the average inspection times for the combined times of the two pairs. The calculated p-values from the t-test are provided at the bottom of the table for each pair.

	Older N > 46				Younger N ≤ 46			
	2D Drawing (min)		MBD (min)		2D Drawing (min)		MBD (min)	
	#2	#4	#2	#4	#1	#3	#1	#3
Mean	3.9360	4.0086	3.6564	3.7689	2.4846	5.2239	2.3412	5.0466
SD	2.6411	2.2157	2.7891	1.9031	1.2811	2.9428	1.4232	1.9789
Mean	3.9723		3.7127		3.3977		3.2430	
SD	2.3730		2.3246		2.3057		2.0405	
P Value	0.1885				0.3715			

Table 4.3: Age data comparison.

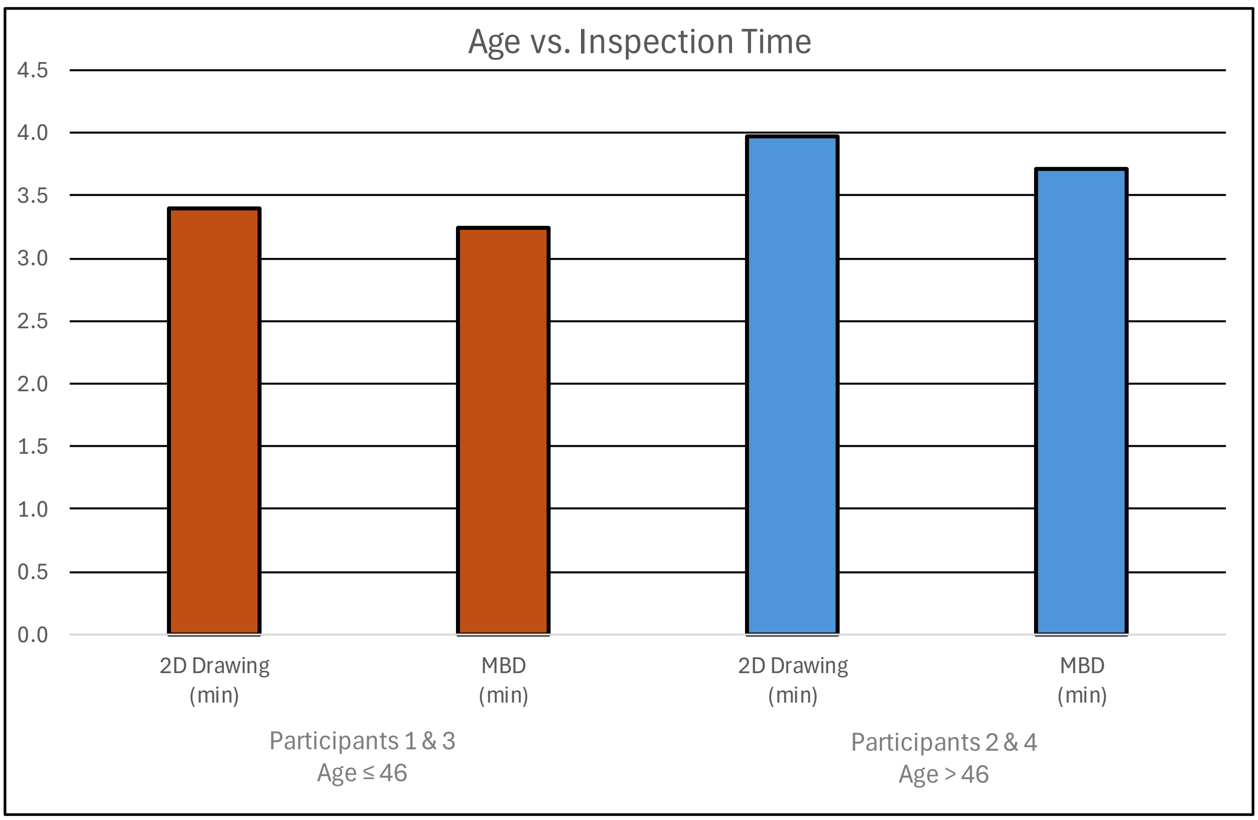


Figure 4.2 – Average inspection times for younger and older participants.

Similar to what was seen in the comparison done in section 4.2, the MBD method continues to show a decrease in average inspection times when compared to average inspection times using the traditional 2D drawing for older and younger participants. A reduction of .2596 minutes is seen in the older participants, while a decrease of .1547 minutes is seen in the younger. The older participants save slightly more time than the younger participants. When analyzing the calculated p-values for both pairs, neither of the examined data sets achieved a p value less than 0.05, so these differences were not statistically significant.

4.4 Grouped Based on Education

Two groups were created with varying educational ranges based on the participants' educational background. The first group of participants consist of lower educational backgrounds, one participant having a high school diploma and the other having a bachelor's degree. The second group of participants contains higher educated participants, one having a bachelor's degree followed by certifications within the same field their degree was obtained and the other having both a bachelor's and associate degree. The average inspection times and the standard deviations for the paired data sets are provided. The p-values calculated from the t-test are provided at the bottom of the table.

	Education (N > BS)				Education (N ≤ BS)			
	2D Drawing (min)		MBD (min)		2D Drawing (min)		MBD (min)	
	#2	#3	#2	#3	#1	#4	#1	#4
Mean	3.9360	5.2239	3.6564	5.0466	2.4846	4.0086	2.3412	3.7689
SD	2.6411	2.9428	2.7891	1.9789	1.2811	2.2157	1.4232	1.9031
Mean	4.3653		4.1198		3.2466		3.0551	
SD	2.7118		2.5651		1.9272		1.7921	
P Value	0.1936				0.3125			

Table 4.4: Education data comparison.

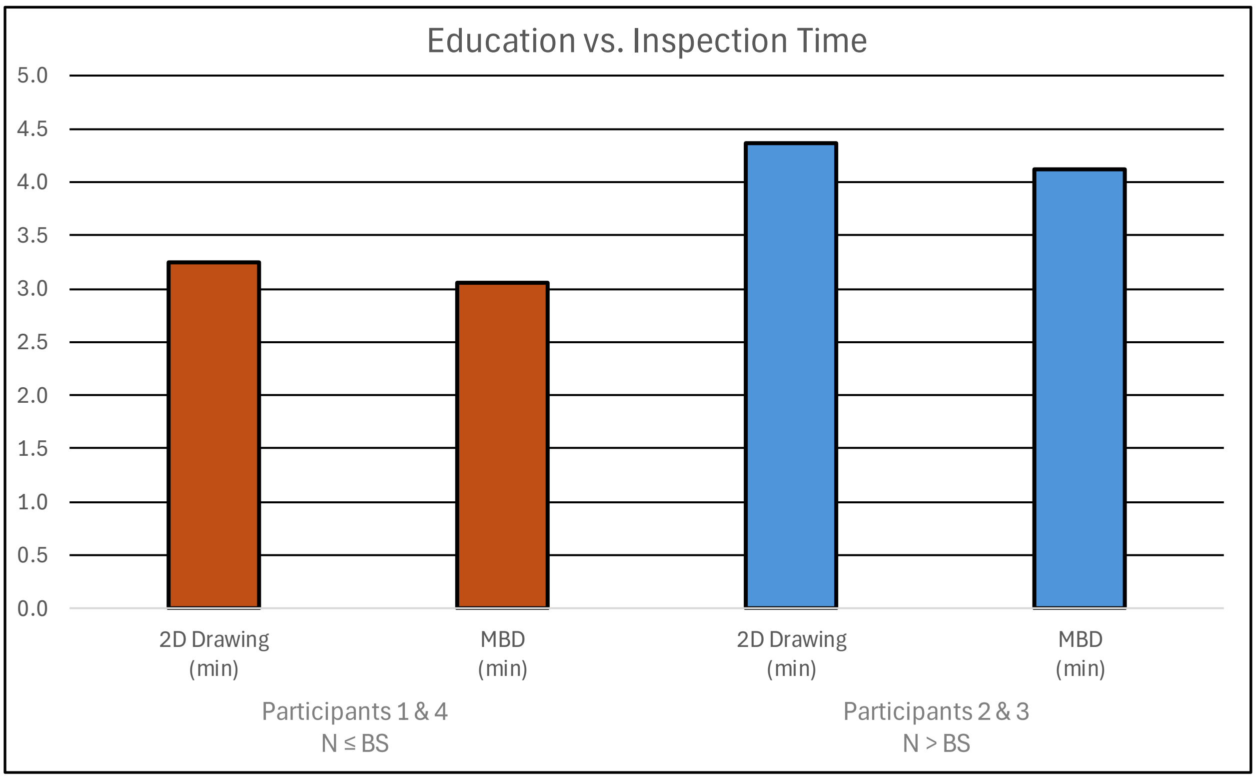


Figure 4.3 – Average inspection times for lower education and higher education.

Average inspection times show that using the MBD method over the traditional 2D drawing decreased the time needed to inspect the parts for both lower and higher educated participants. The participants with lower educational backgrounds show a decrease of 0.2455 minutes was found between the two methods. For the higher educated participants, a reduction of 0.1915 minutes was seen between the two methods. Calculated p-values at the bottom of the table show the trend of the data. Lower education shows the analyzed data has a 19.36% chance of being random. Higher education shows the analyzed data has a 31.25% chance of being random. Both calculated values show that the data being examined is not statistically significant due to it not reaching an acceptable value of .05.

4.5 Grouped Based on CAD/Design Training

The final table shown below is an examination of two classifications of participants. Three participants are classified as having no CAD/design training and put into a group. The other group consists of one participant, participant 2, who received training in CAD/design. These two groups are compared in the table and figure shown below. The collective average inspection time and standard deviation for the first group are provided in the table, while Participant 2's independent average inspection time and standard deviation are provided. The p-value for the first group is shown at the bottom of the table, along with the p-value created for the solo participant.

	No CAD/Design Training						CAD/Design Training	
	2D Drawing (min)			MBD (min)			2D Drawing (min)	MBD (min)
	#1	#3	#4	#1	#3	#4	#2	#2
Mean	2.4846	5.2239	4.0086	2.3412	5.0466	3.7689	3.9360	3.6564
SD	1.2811	2.9428	2.2157	1.4232	1.9789	1.9031	2.6411	2.7891
Mean	3.6421			3.4534			N/A	N/A
SD	2.2440			1.9637			N/A	N/A
P Value	0.2893						0.0588	

Table 4.5: Training data comparison.

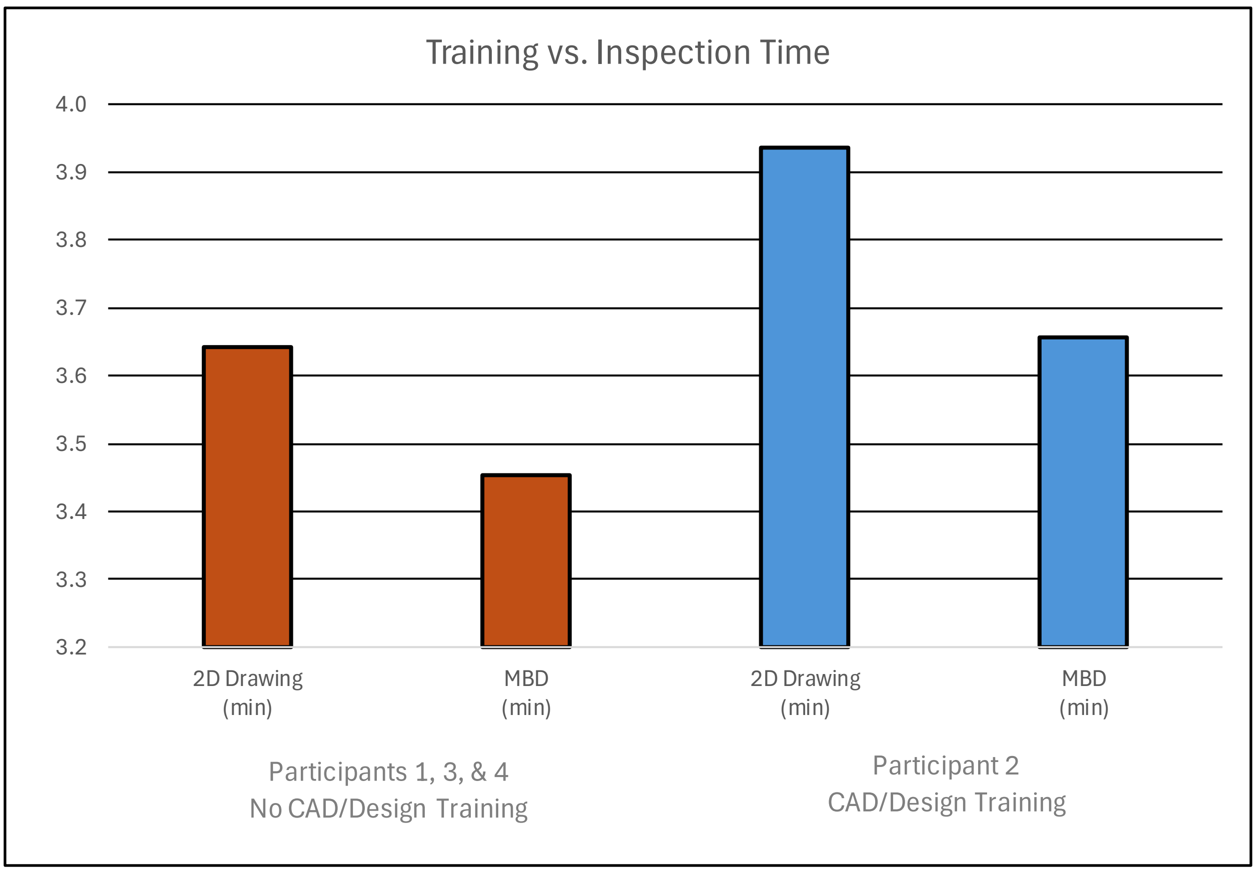


Figure 4.4 – Average inspection times for untrained and trained participants.

The data shown in Table 4.5 shows improvements in inspection times for both groups when using the MBD method rather than the 2D drawing. More specifically, the group with CAD/Design training performed the inspection better using MBD than the other. The average inspection time for the participants with no CAD/design training decreases by 0.1887 minutes when using MBD, and the opposite group decreased by 0.2796 minutes. The p-values calculated for both data sets show that the first set of analyzed data has a 28.93% chance of being random, while the second only has a 5.88% chance. Both values dictate that the analyzed data sets examined are not statistically significant. However, the data collected shows potential for further testing and investigation.

4.6 Current Production Process Map (Traditional 2D Drawing)

The following figures (4.5 – 4.10) represent the current production process used at the local production company. The map contains five separate stages that break down the different areas of the production process. The current production process utilizes the 2D drawing from beginning to end, not referring back to the 3D model as a master source of information at any point. The current process map is used later in the results to create a base for the newly designed production process.

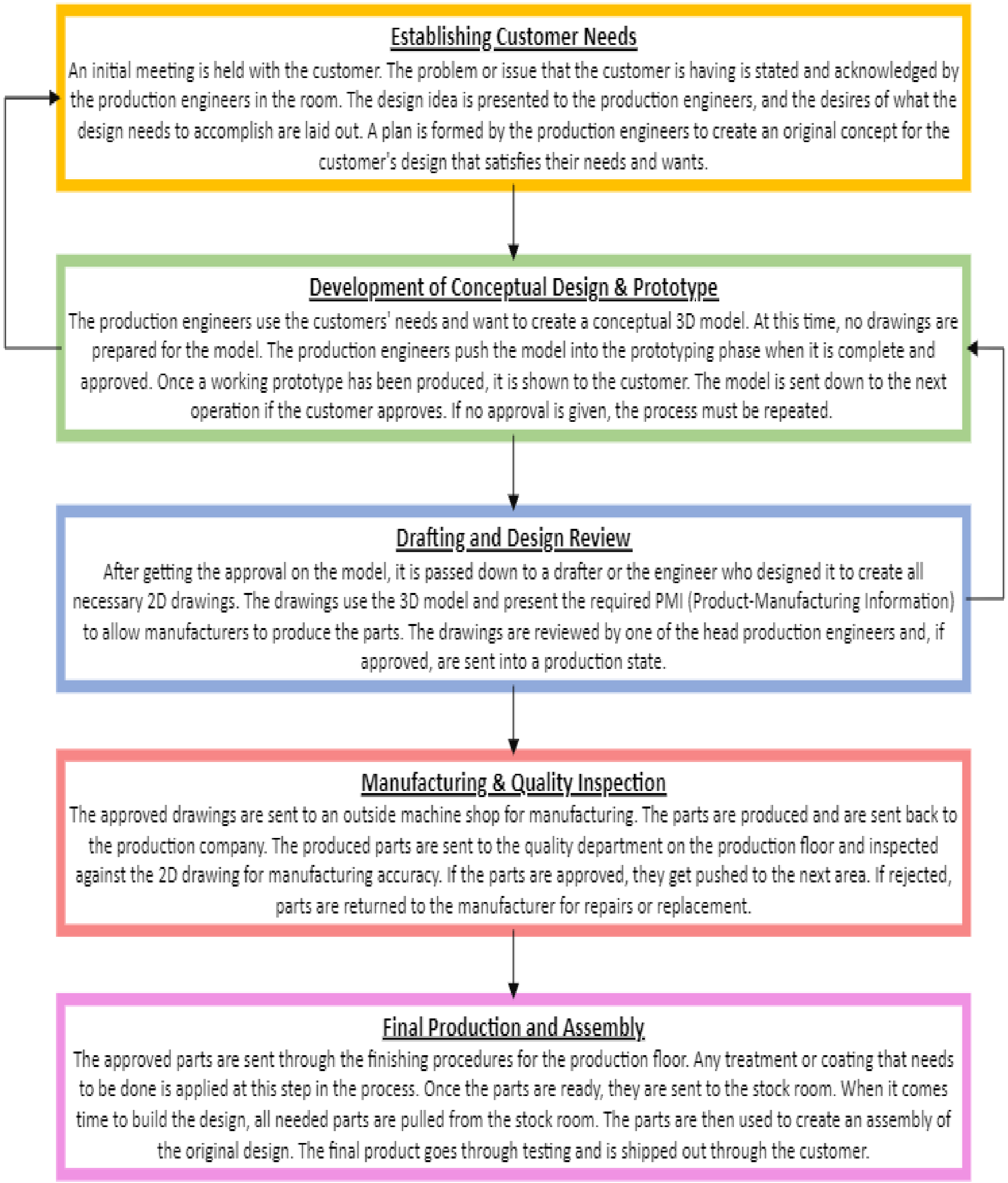


Figure 4.5 –Current production process for the local production company.

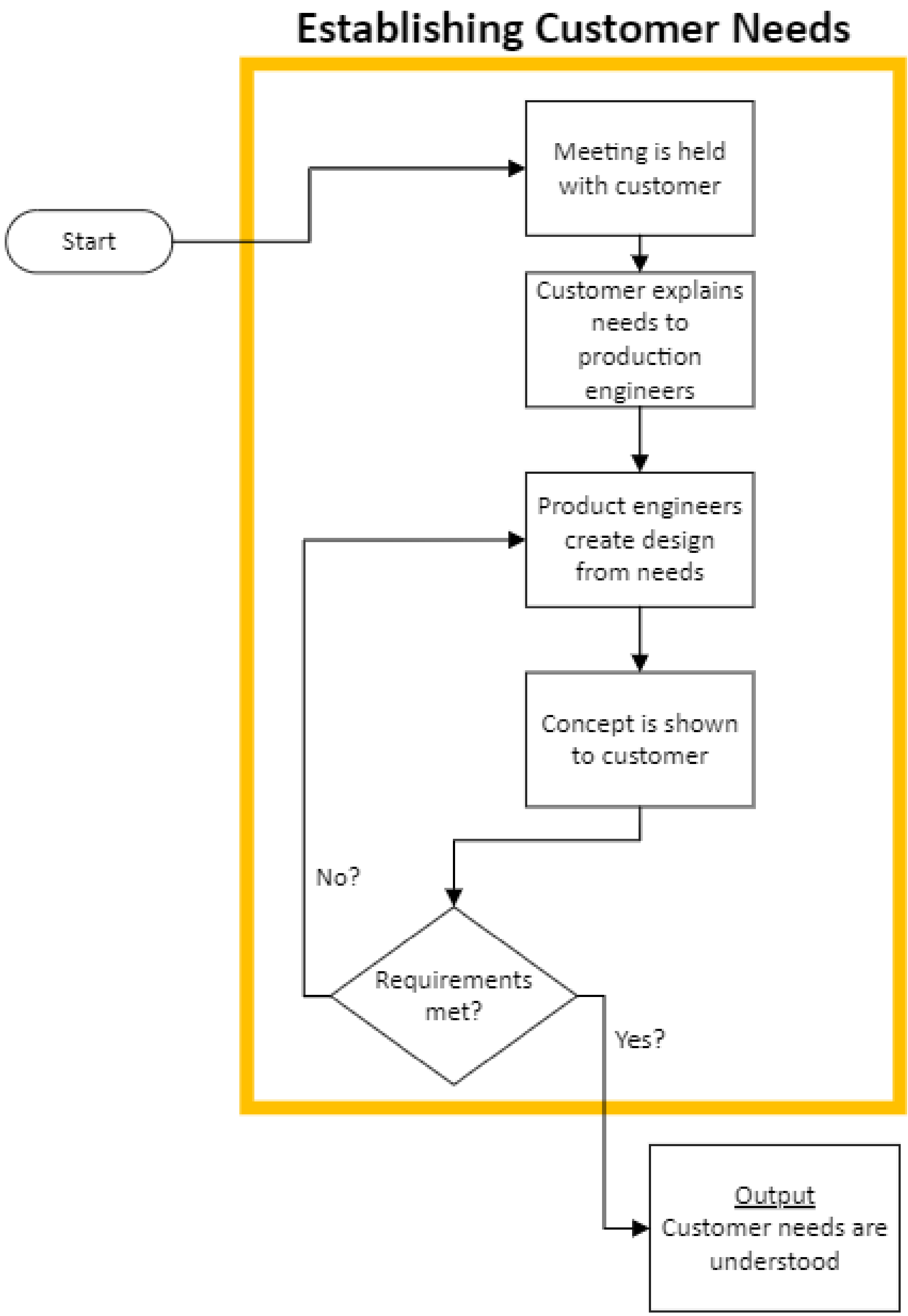


Figure 4.6 – Stage 1 of the current production process.

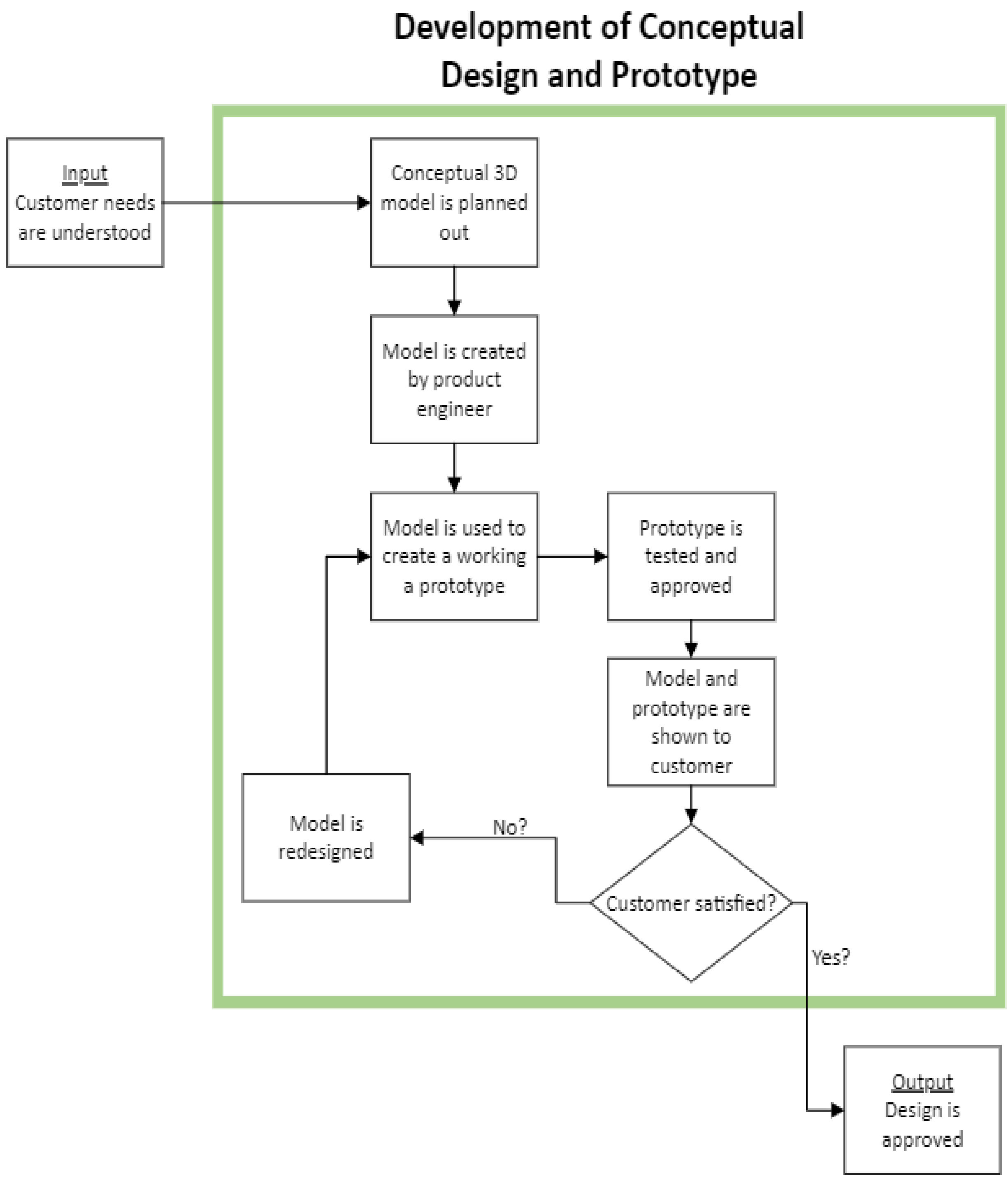


Figure 4.7 – Stage 2 of the current production process.

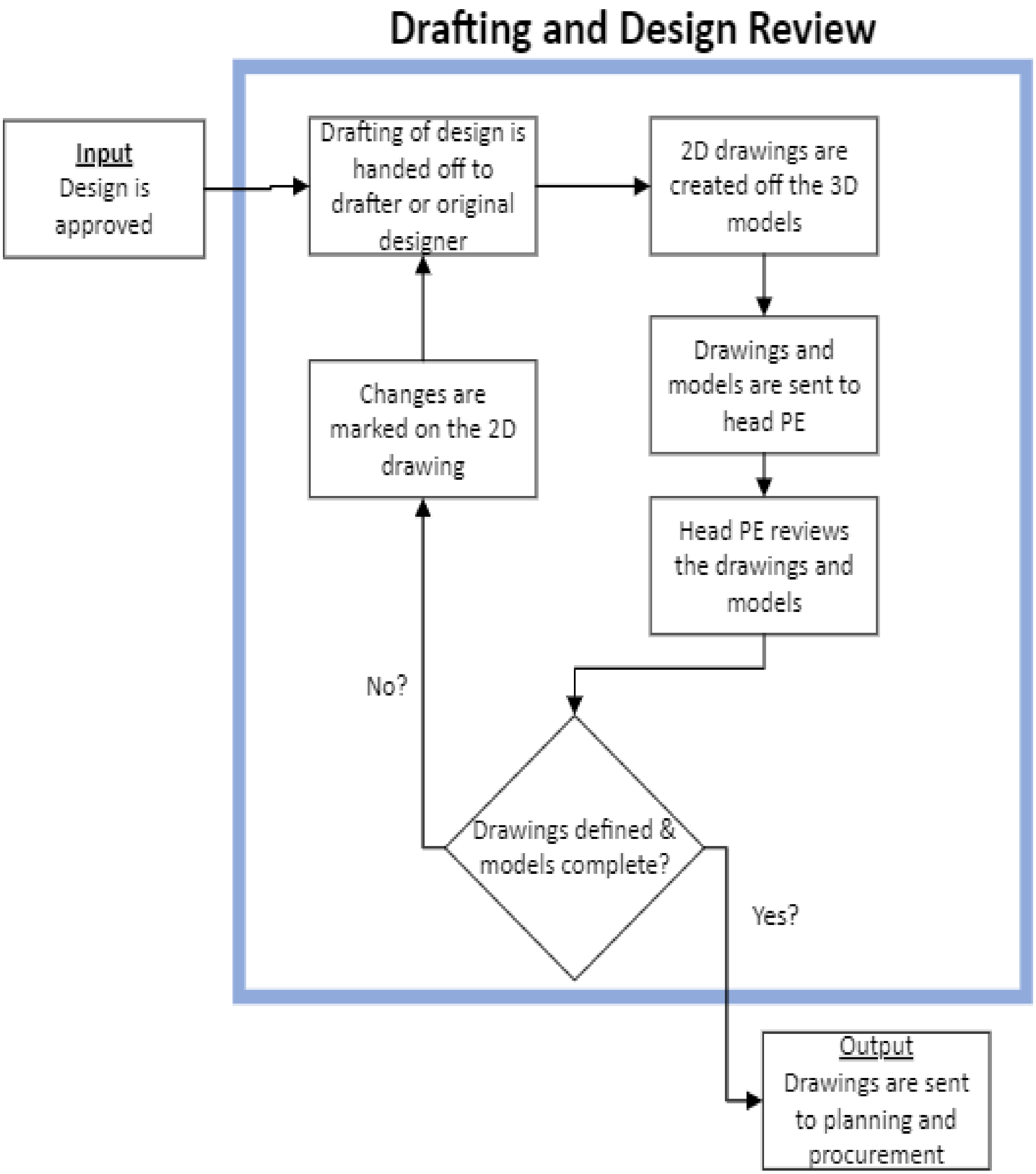


Figure 4.8 – Stage 3 of the current production process.

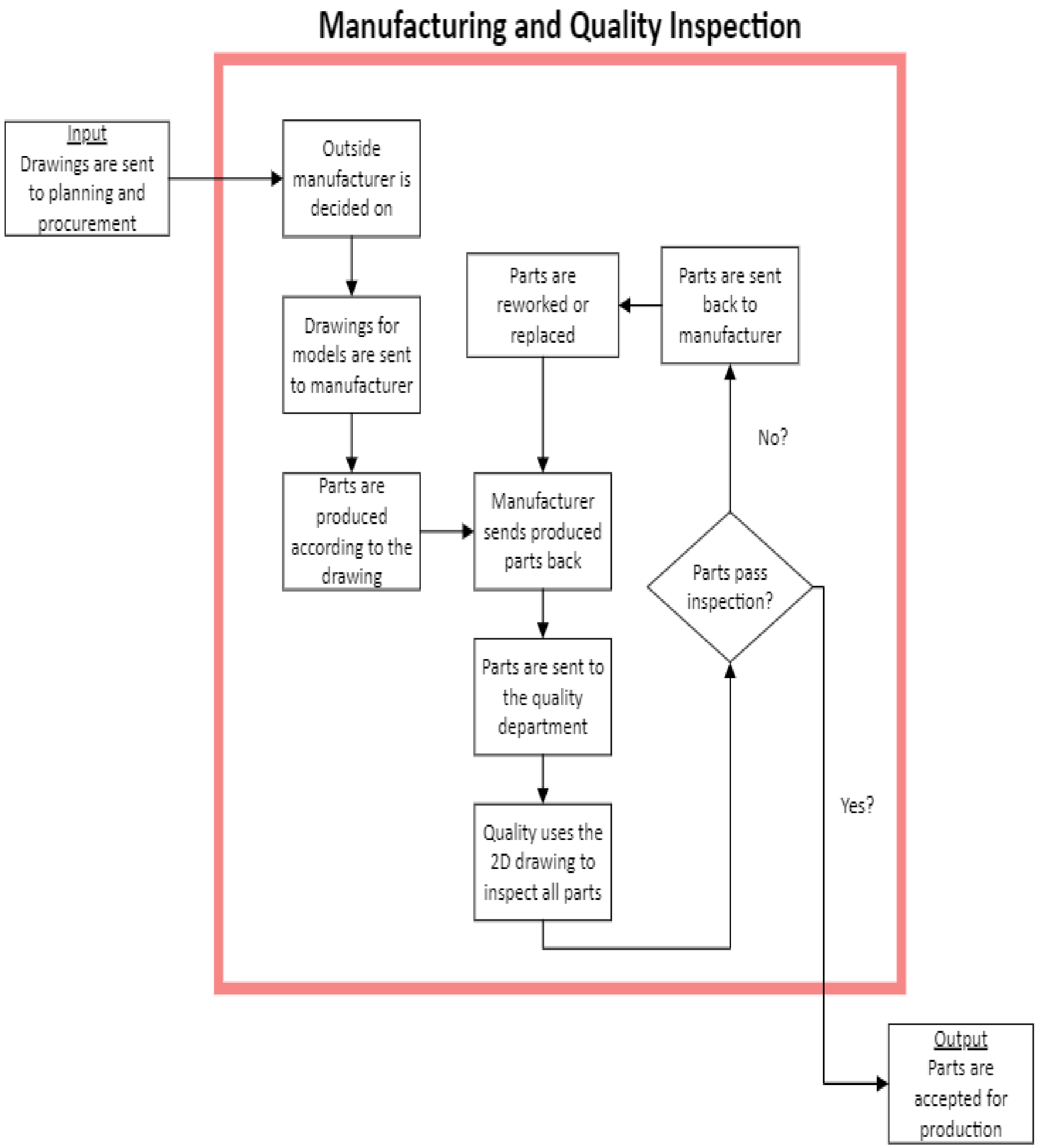


Figure 4.9 – Stage 4 of the current production process.

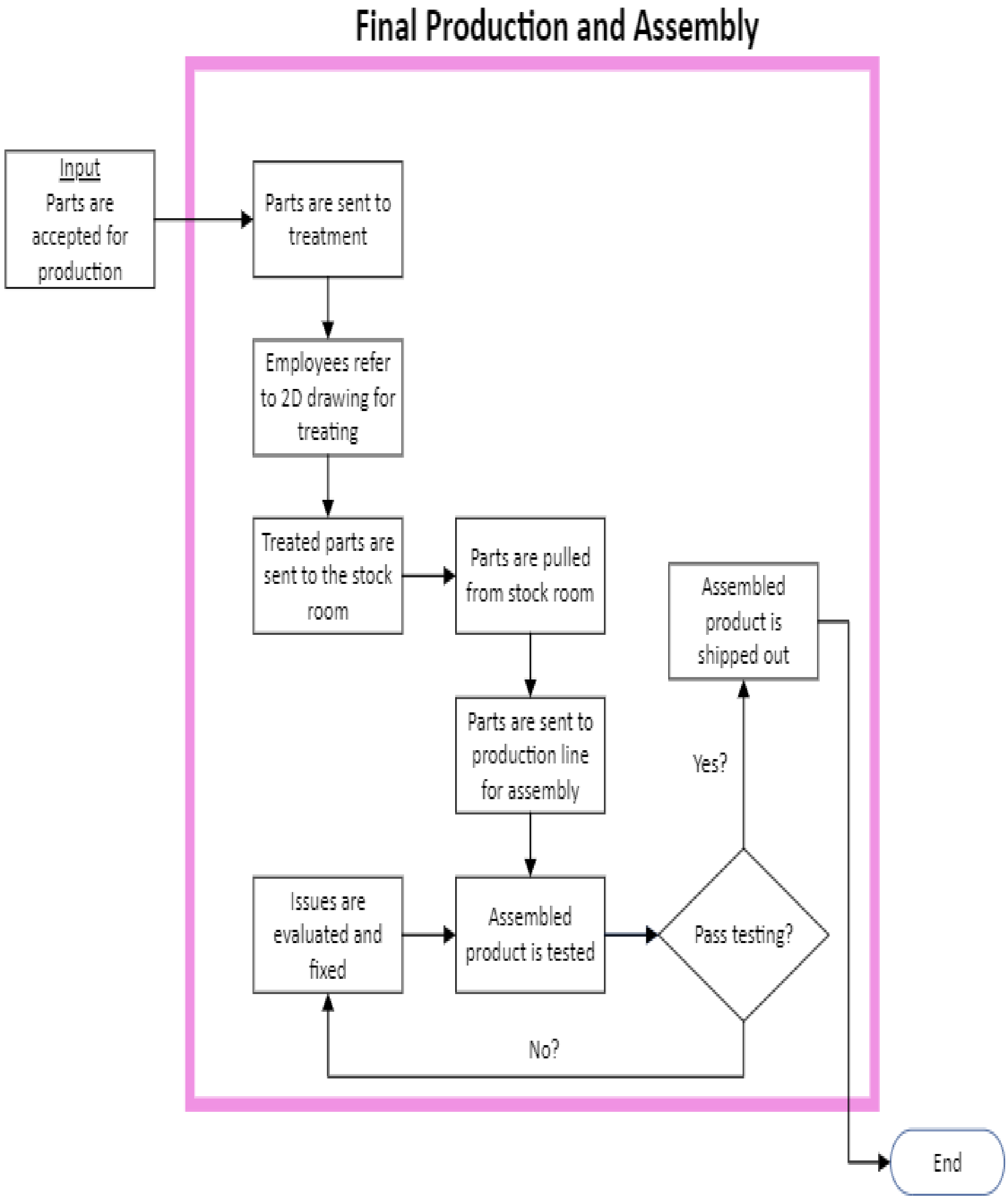


Figure 4.10 – Stage 5 of the current production process.

The process map presented above shows multiple areas of potential improvement. Many steps seen throughout the beginning stages, mainly stages 1 through 3, use the 2D drawing in various process steps. Many places can be targeted for MBD implementation by evaluating the earlier process steps. There are some areas within the process map where steps transition from model to drawing and back to the model for corrections. It can be inferred that more time is needed within this area due to updating two product information forms. The conceptual model is created before the drawing is prepared, meaning that extra time is spent on preparing documentation instead of refining or using what was currently created. Within the quality check of the fourth stage, the 2D drawing is the primary source used for checking manufactured parts. Looking at the data collected in the earlier sections of this chapter, trends show that time is saved in this area when using MBD over the 2D drawing.

4.7 Revised Production Process Map (MBD)

The process map presented in the following pages represents the process previously shown in section 4.6 but uses MBD as the primary source of information throughout the process steps. Some process steps are seen previously have been combined with other steps or have been removed entirely. The revised process map consists of 4 stages, different from the 5-stage process map previously shown. The process map follows the same path from initial product design to final assembly.

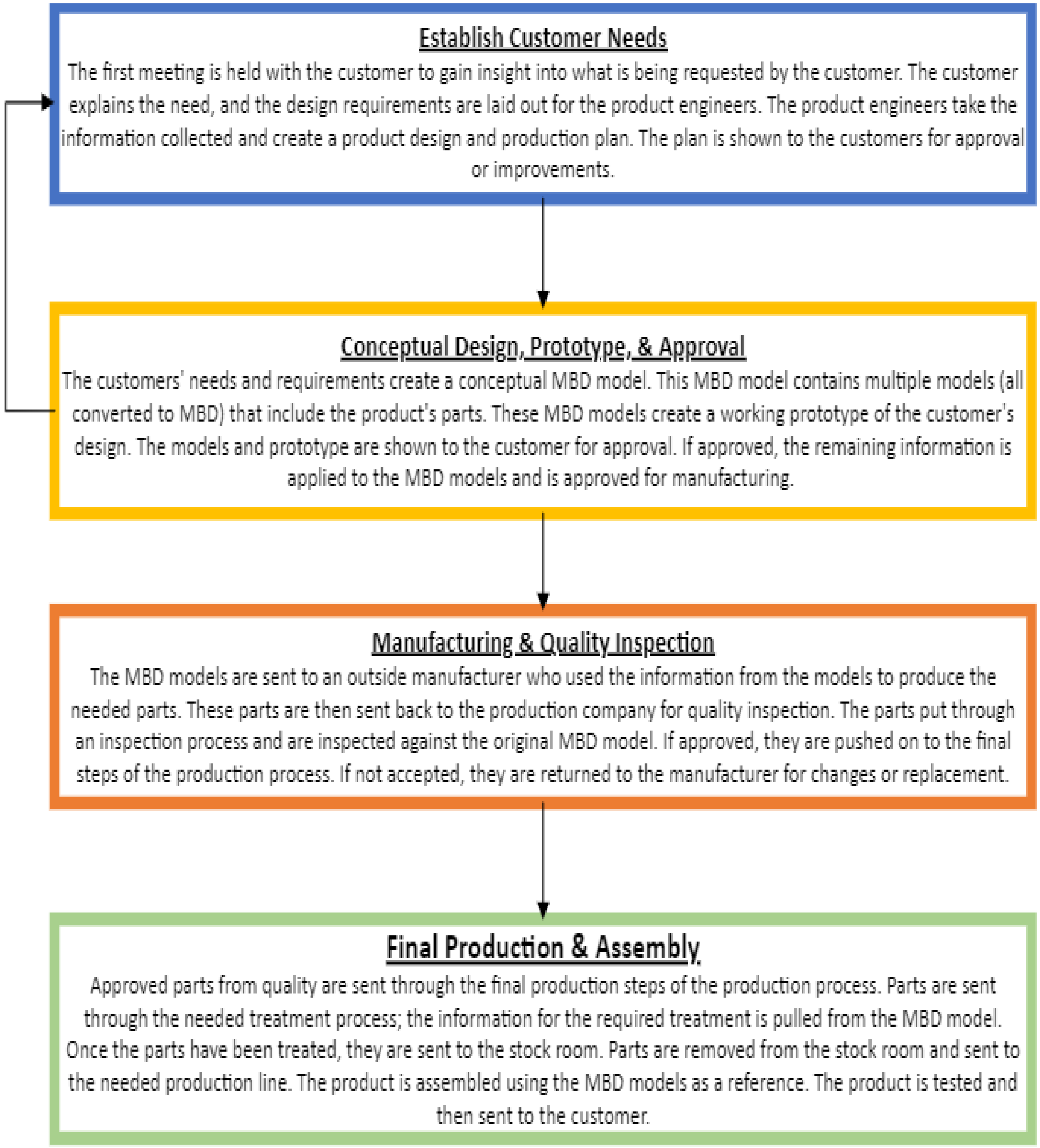


Figure 4.11 – Revised production process for the local production company.

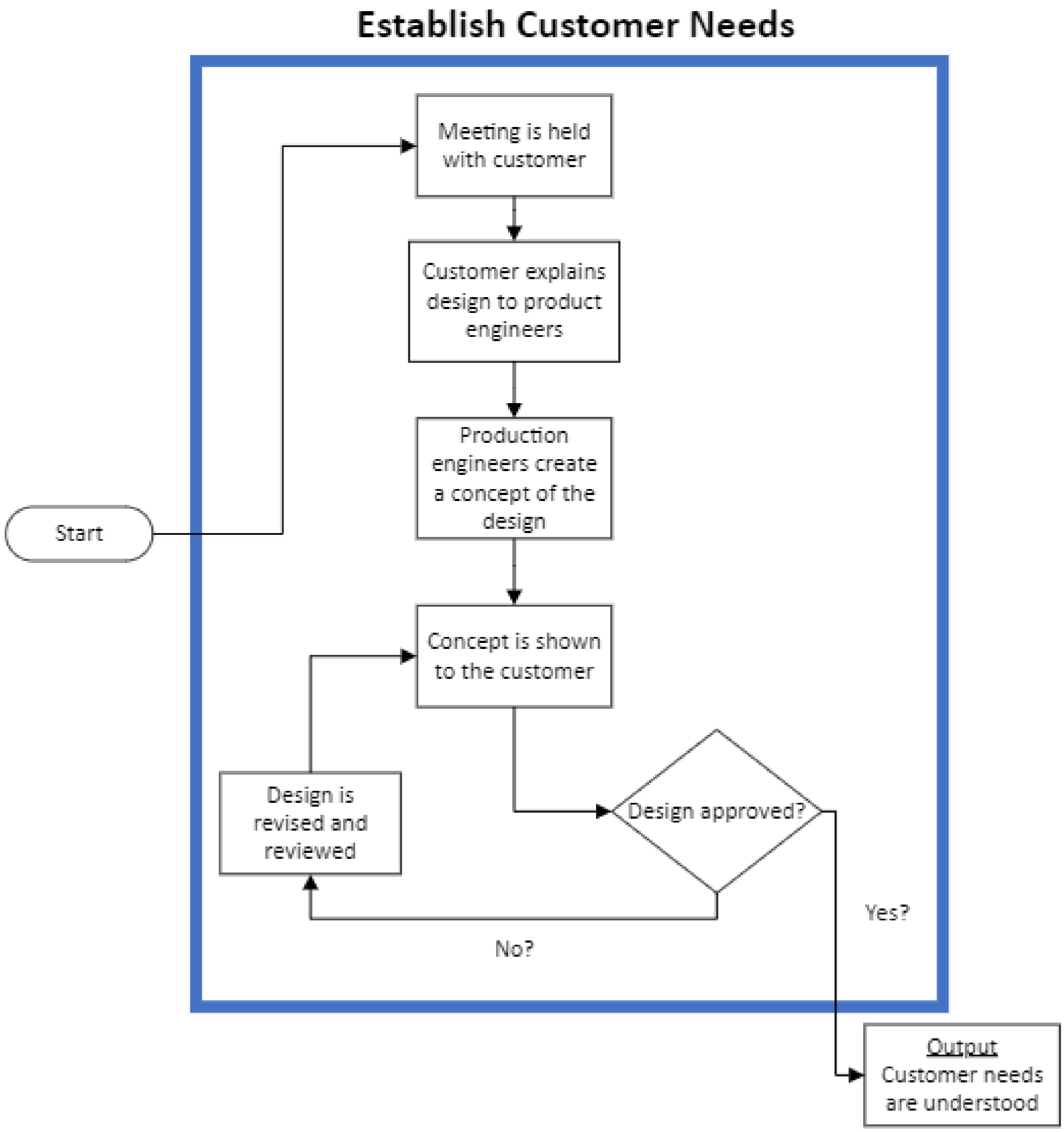


Figure 4.12 – Stage 1 of the revised production process.

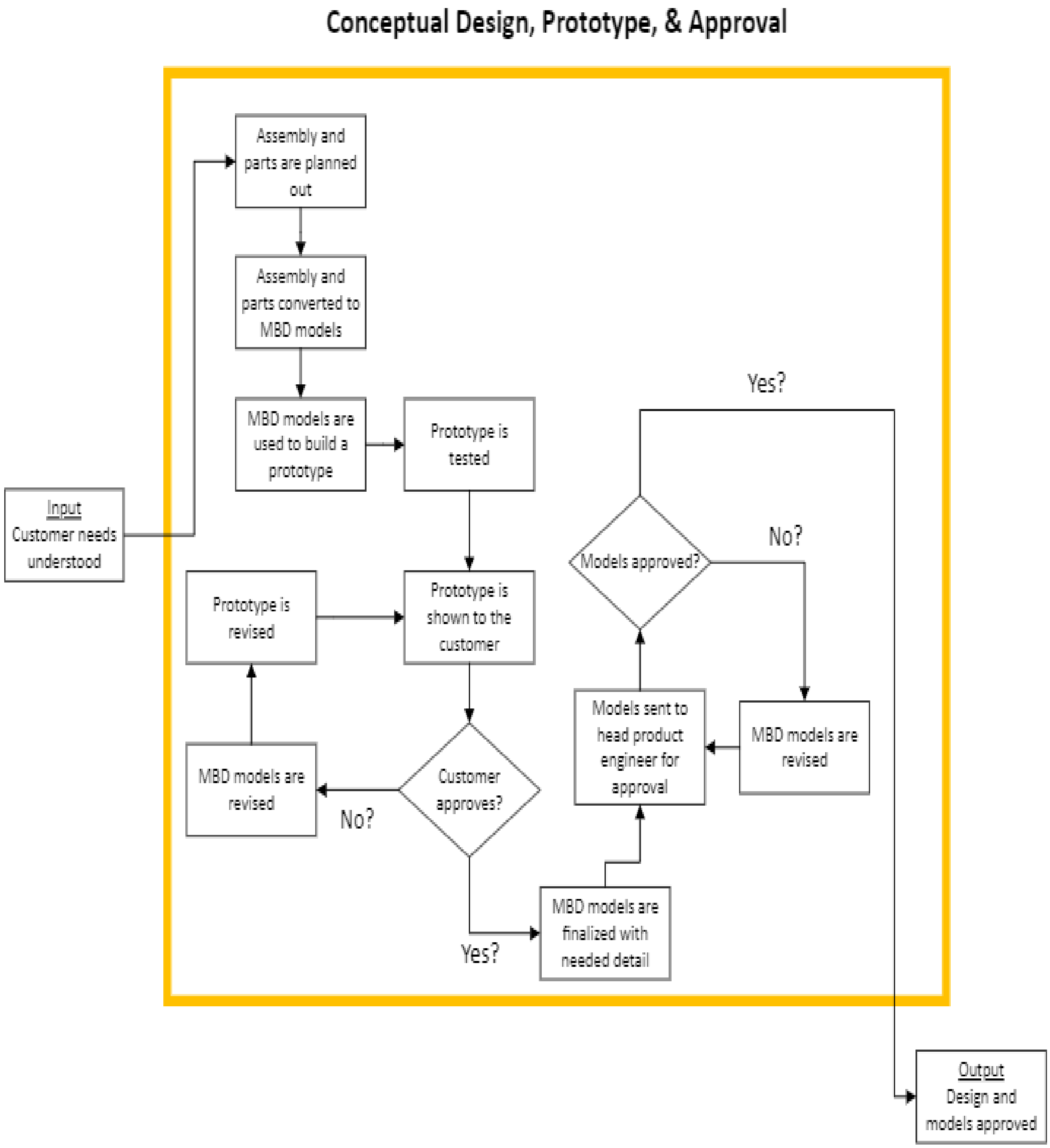


Figure 4.13 – Stage 2 of the revised production process.

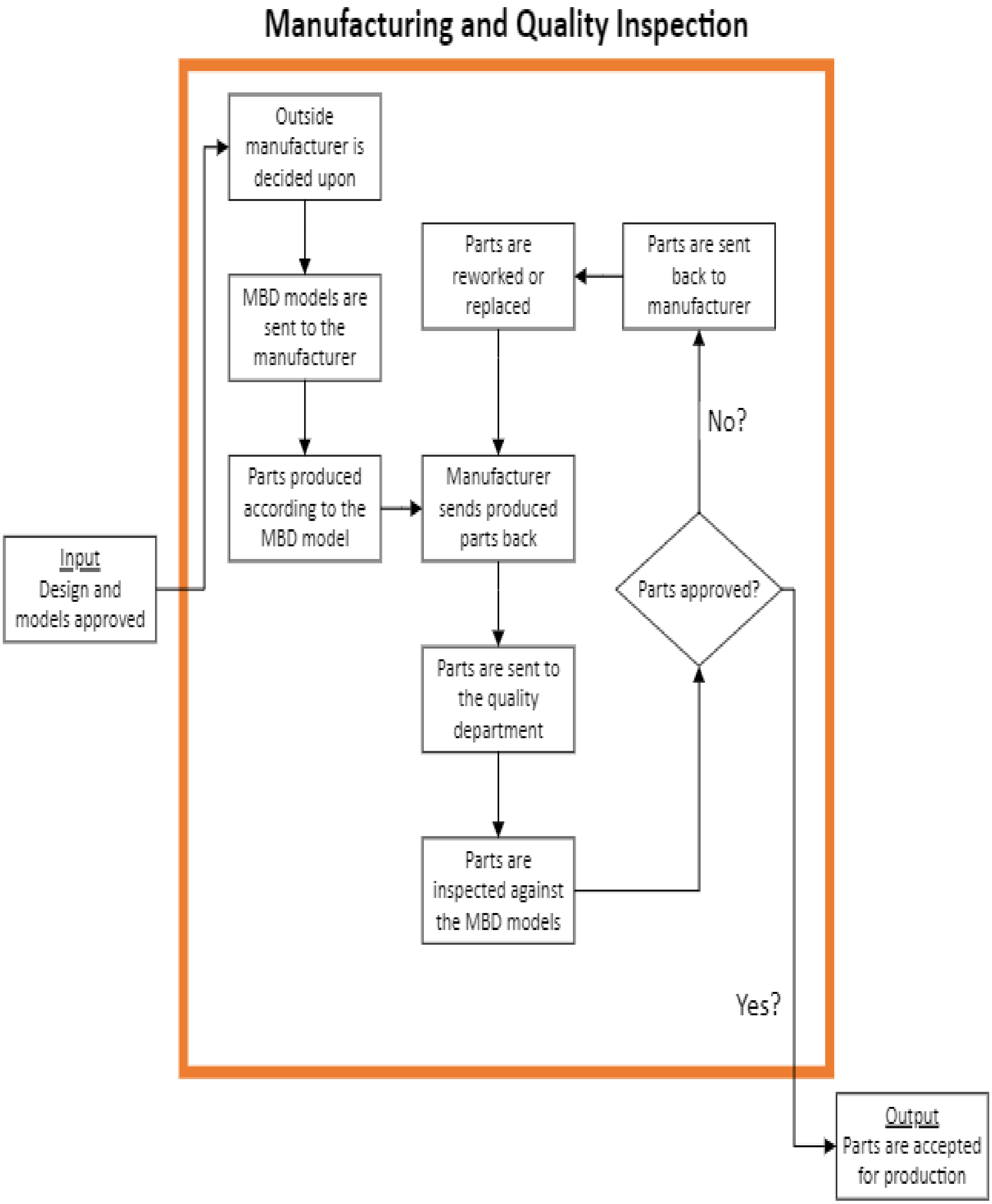


Figure 4.14 – Stage 3 of the revised production process.

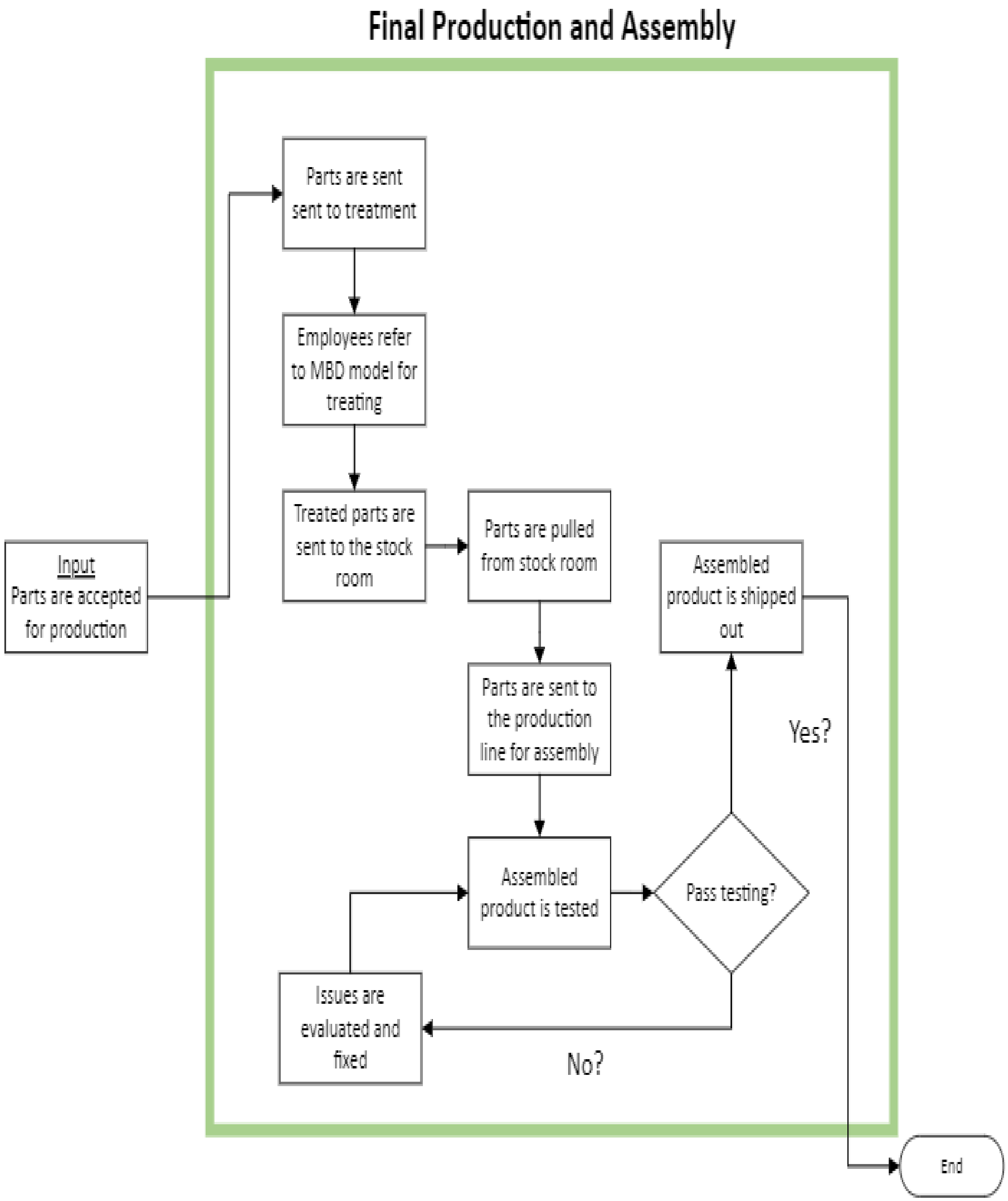


Figure 4.15 – Stage 4 of the revised production process.

Reviewing the revised process map, many changes can be seen. The beginning steps of the process map establish a single product definition method during the conceptual design and prototyping phases. Due to this, drafting steps need to be included within the revised process. Steps are added to help fully prepare the MBD models, but there needs to be a transition from model to drawing. The MBD model created at the beginning of the process shows potential time management and part production improvement throughout the remaining product steps. The second stage of the production process is a combined version of the original production process, where the approval of the prototype and models are completed and later sent to manufacturers. Final process steps do not see as much improvement due to only needing model information such as labeling and finishing procedures.

4.8 Post-Testing Survey Results

The following figures are a representation of all survey responses collected from the post-testing survey. The responses shown follow the same order of questions presented in chapter 3, section 3.2.4. The responses from the survey gauge the participants level of knowledge and experience while also showing their opinions on how MBD performs. One of the questions was confusing to the participants and caused answers to be inconsistent. Due to this, this question was removed and excluded from the results and discussion of this study.

	#1	#2	#3	#4
1.) Participant information Age: Sex (M/F): Education:	46 M HS DIPLOMA	49 M BS+ASSOCIATES	34 M BS	46 F BS+EXTRA COURSES
2.) Experience with modeling/drawing software (in years)	0	4.5	4	5
3.) More familiar with 2D/Digital 2D drawings or 3D models	2D Drawing	2D Drawing	2D Drawing	2D Drawing
4.) Indicate your knowledge of 2D drawings from 1 -10 (10 = excellent)	7	9	8	9
5.) Knowledge of 3D models from 1 -10 (10 = excellent)	3	9	6	5
6.) How often do drawings cause confusion during the inspection process?	Often	Not Often	Not Often	Not Often
7.) Have you heard of MBD before this experiment?	No	Yes	Yes	No
8.) Indicate your knowledge of GD&T on a scale of 1 - 10 (10 = excellent)	1	9	6	6
9.) What classes or training have you taken for 2D drawing/modeling practices?	On the job training.	CNC machining using fusion for drawing and dimensioning. Four levels of classes on print reading, part design, drawing, and writing code for CNC machines.	On the job training.	Several hours of training on reading and interpreting models.

Figure 4.16 – Collected post-testing survey results.

10.) Do you reference the model or drawing more during inspection?	2D Drawing	2D Drawing	2D Drawing	2D Drawing
11.) Have you used 3D PDFs before this experiment?	No	No	No	No
12.) Indicate how easy the information on the MBD model was to understand from 1 - 10 (10 being very easy).	8	10	9	6
13.) Which of the two methods did you prefer?	2D/Digital 2D Drawing	MBD	MBD	MBD
14.) Did the MBD model capture all part information properly?	Yes	Yes	Yes	Yes
15.) Was the 3D PDF easy to understand and did it contain all the required information?	Yes	Yes	Yes	Yes
16.) What aspects of the 3D PDF/MBD model did you like?	Easy to navigate and being able to rotate and analyze the model.	The ability to inspect parts and part features from different angles.	The ability to toggle and manipulate 3D views to inspect part features and grasp the geometry of the part.	Being able to move the model around to better inspect dimensions and having more options for viewing the model.
17.) What aspects of the 3D PDF/MBD model did you not like?	Unable to annotate dimensions correctly and missing some block information.	Nothing.	There was no easy way to add text boxes or check off on features that had been inspected.	Applying annotations to checked dimensiosn had to be done in a different area and in a specific way.
18.) If you could make any changes to the 3D PDF, what would they be?	Make it easier to annotate and apply more block information.	The way annotations are applied for checked dimensions.	The method for recording inspection results and applying them to the model.	The ability to apply annotations about inspected dimensions directly to the model.

Figure 4.17 – Collected post-testing survey results cont.

CHAPTER 5: DISCUSSION

The goal of this research was to determine if the use of MBD software and methods would be more beneficial for production than using traditional 2D drawings. Throughout this chapter, the data collected from testing and results will be further discussed in detail.

5.1 MBD Reduces Inspection Time

Average inspection completion times decreased for all four participants when using MBD over the traditional 2D drawing. Some were larger than others, and each participant could perform the inspection process more effectively using MBD. The table below shows the four participants and their decreased percentage between the two methods, yet none of these differences were statistically significant.

Participant #	% Time Decrease
1	5.77
2	7.10
3	3.34
4	5.97

Table 5.1: Percent time decrease for each participant.

The MBD model presented the information to the participants in a way they could understand and interpret. Bijnens and Cheshire (2018) found that more significant time savings and accuracy should be achieved through MBD implementation in any well-maintained production process. While time savings are apparent, they were not as large as those reported by Bijnens and Cheshire. Researchers found that for MBD to be adequately interpreted, a joint base needs to be established and tailored to the tools, products, methodologies, and way of working that people utilize in their line of work (Winkler, 2023). One factor that could have influenced the results was that the participants were unfamiliar with MBD, and only two of the participants had CAD software experience.

The different comparisons completed throughout the data analysis assisted in analyzing what factors play into the development of MBD application. When looking at the data presented for the comparison between experienced and less experienced participants, it can be stated that there was a statistically significant trend between MBD and experienced participants rather than what was seen in the correlation between MBD and less experienced participants. The participants who were more proficient with using MBD most likely used the knowledge and skills obtained in their daily operations to help understand the MBD models and the information presented through them. Some researchers found that when comparing experienced employees to inexperienced employees in a technological change process, the value of the experienced employees was higher than that of the inexperienced due to a more effortless transition to new methods (Meymandpour & Pawar, 2018). When evaluating the comparison of the two methods for different age ranges, no statistically significant data was found. Therefore, it cannot be claimed that the MBD method would perform better than 2D with younger or older inspectors. Other researchers completed a similar study to determine if the age of their employees affected the employee's performance, and out of the data collected, they saw that 61% of the data showed no significance in age difference (Viviani et al., 2021). The age of the participants doesn’t necessarily reveal their level of knowledge and skill within their work. Each of the participants could have varying backgrounds that could impact their performance. Assessing the comparison of different educational backgrounds between the participants revealed a similar outcome to what was seen in the age comparison. Due to the lack of statistically significant data, no claims can be made that MBD would perform better with lower- or higher-educated participants. Another study found that within their production process, their higher-educated employees performed more effectively in multiple work areas than lower-educated employees (Ng & Feldman, 2009). While each participant's educational background is known, the classes and things learned through their education aren't. This variable could change the outcome of which method performs better. Besides education, other training could have been completed in the past. The final comparison that evaluates the performance of the methods with trained and untrained participants in CAD/design experience shows slightly different results than what was seen in the age and education comparisons. A lower p-value was obtained for the trained participants, but not low enough to fall within the needed p-value range. However, there are signs of a statistically significant trend within the data. More research may be necessary to investigate further the impact of training with inspections using MBD. Other researchers believe that to benefit from CAD software, proper training programs must be applied (McDermott & Marucheck, 1995). Training programs that teach the concept of MBD before implementation could prepare inspectors better than direct application to the process. This could bring all inspectors to a similar understanding of how CAD software works and how MBD is used through them. Using this information and what was previously discussed, it can be stated that experienced quality inspectors are more efficient using MBD rather than 2D drawings, and the level of training a participant has could potentially impact their inspections using MBD.

5.2 A Majority of the Participants Prefer MBD

A majority of the study participants stated that they preferred the use of the MBD model over their traditional method of using the 2D drawing. It was found that most of the participants were fond of the MBD model for its ease of use, analytical abilities, and definition possibilities. It provided more unique ways of product definition, and primarily, only one or two discomforts were seen amongst the participants' survey responses. Research conducted with two large aerospace companies showed that a joint discomfort within their MBD implementation matched what was seen in this study; the joint discomfort is data management (Quintana et al., 2010). One thing that was not investigated within their research was the application of 3D PDFs into the production process. It was found in this study that the use of the 3D PDF was just as effective at portraying the product information as the MBD model was. Other researchers discovered that by using a 3D PDF to define a 3D model, a person can gain more information and a more robust perspective on what the model is and what makes up its features (Ruthensteiner & Heß, 2008). It can be predicted that an MBD model accompanied by a 3D PDF would be the most efficient form of sending product information from person to person or among company operations.

Observing the collected survey data, age, and experience do not appear to influence the acceptance of the MBD method. One factor that influences the acceptance of the method is the participant's education level. It was found that having a higher educational background makes learning and understanding the MBD method much easier than one with less educational background. The survey results also show that the participants with a high school diploma scored lower in their knowledge of 2D drawings and GD&T than the other 3 participants. One study found that when teaching GD&T at the college level as a singular course, students could better grasp the concept of GD&T and apply and analyze it quickly on drawings and models.

Participants with a high school diploma most likely do not have experience in such topics. Another study found that students who could use 3D modeling and simulation software could produce better results with their work than others who were not as skilled with the software (Xie et al., 2018). The participants in this study with higher educational backgrounds have a much greater chance of having taken these courses. They can understand the MBD models and 3D PDF information much better. Therefore, it appears that having an educational background where courses on 3D modeling and 2D drawings are taught is essential to understanding the concept of MBD fully.

5.3 MBD May Improve Process Efficiency & Reduce Cost

After reviewing the process maps shown in the results section of this paper, the revised process map creates a more efficient production process than what is shown in the current process map. The revised process map shows potential cost savings, time-to-market, and error reduction improvement. These three improvements can be seen primarily in the earlier to middle stages of the production process, and each improvement impacts the process differently.

All participants improved their average inspection times through MBD. This may allow the quality inspectors to save time inspecting each part, which could result in reduced labor costs needed to complete the work. Speaking with the quality department at the local production company, there is potential for significant reductions in cost. Taking the average reduction inspection time from the four participants, the costs saved per year can be calculated to see the benefits of switching to MBD. The quality department at the local production company provided their standard burden rate that is paid to their quality inspectors ($52.89 per hour).

Inspectors	3
Work (hrs/yr)	2000
Time Savings (%)	5.55
Labor Burden Rate ($/hr)	52.89
Hrs saved per year	333
Cost Savings ($/yr)	17612.37

Table 5.2: Cost savings per year

Using the MBD method in the production process can reduce errors throughout the process. By removing the need to include drafting within the production process, overall documentation is reduced. The production engineers within the revised production process only need to focus on creating a solid form of the MBD models. The MBD model used throughout the revised production process reduces the chance of misinterpreting information from department to department. The company kept a singular product definition style that encapsulated all the departments' needed information into one form. Researchers found that the best practice for a company to use MBD is to create a reusable, unified form that captures all company information (Alemanni et al., 2011). Accomplishing this results in the improvements mentioned in the above writing and the revised production process map.

Time-to-market can be impacted when combining time savings with reducing errors encountered throughout production. Production steps are being avoided and removed entirely, which reduces time in the production process. While some steps had to be added back into the revised production process to account for prepping the MBD models, this does not add as much time as drafting, checking the drawing, and making changes would have done. Using the model template shown in the methods section of this research helps push for faster model procurement. It contains the needed information for multiple departments and can be easily manipulated for further detail. This form of documentation helps push the product from the earlier stages of the production process to the final stages much faster.

5.4 Study Limitations

There were limitations to the study. Initially, there were plans to go to two or more companies to test the methods in different production processes. Due to time limitations and availability, only one company was tested. This made it harder to see how MBD works in different environments and how different processes are impacted by MBD. Testing with another company that undergoes different operations could help determine how easily MBD could be placed into an existing process that already uses working strategies. Another limitation that was encountered during this study was the number of participants that were examined. The local production company evaluated in this study stays busy, and many areas that showed testing potential were unavailable. The area that was free for testing only had four potential people at the time; fortunately, all were willing to participate in the study. Having a larger group of participants could have potentially improved the results found throughout the comparisons conducted in this study. Additionally, more people could help prove the statistical significance of the data found throughout the study. Another limitation found within this study was the sample size of parts. A larger sample size of parts could have improved the calculated results done for each of the comparisons. If a larger sample size also consisted of having more complex models and assemblies, the results could potentially show how well MBD can perform in more complex scenarios.

Only one software package was used throughout this study. Many other modeling companies are developing MBD packages that could provide better tools for creating these models. Other CAD software providers could be further investigated and tested to find similarities in the software, find what works best, and determine what needs to be improved. Testing with different software packages could have revealed other opportunities for creating MBD models with different tools or styles. If more time was available, other PDF editing software packages would have been explored to see if there are other ways of creating the 3D PDFs more effectively than using a limited free software. One that is fully-developed could have potentially made it easier to trasnfer information from model to PDF and might have allowed for more annotative capabilities than what was provided through the free software.

Another limitation was that the effectiveness of MBD was only tested in the quality inspection environemnt. Applying MBD to the production or design engineering process could yield additional benefits. MBD models could be applied to the prototyping and design phases of the production process and the impact evaluated.

CHAPTER 6: CONCLUSION

With the improvements seen throughout this study, the MBD method can reduce many inefficiencies encountered throughout the production process. The improved completion times of quality inspections with experienced inspectors and the removal of process steps can make significant changes to the production process. Factors such as substantial cost savings, reduction of data translation errors, and improved time to market can be impacted by these improvements. However, other factors need to be considered. Proper software packages are needed to create these models; this can cost significant amounts of money depending on the amount of licenses needed for the company. Classes and training will need to be held for employees across the company to help them understand the concept of the MBD method and how it is executed. Lastly, proper data management and security will need to be practiced to help protect and maintain the large amount of digital files created when using the method. Some larger companies have already begun taking these steps to implement MBD in their production processes.

One of the most crucial areas where these methods could be used would be college courses on 3D modeling and 2D drafting. Most of the world still uses traditional 2D drawings, so learning the techniques and preparation of these drawings at the college level creates a good sense of how parts and products should be appropriately defined. Additionally, introducing more advanced modeling courses that teach engineering students how to create and build models that utilize MBD techniques properly allows for a wide range of knowledge in product definition. This setup would better prepare students for what they could expect to see in the future when they graduate and begin working. A future goal of this research is to create lessons that introduce the Industry 4.0 concept while teaching proper Model-Based Definition techniques for 3D modeling. The data and information collected from this thesis study will assist in laying a foundation for how these concepts and methods should be taught. The evidence found within this study shows that the use of MBD within the production/design provess, under certain conditions, can provide better product definition than the traditional 2D drawings.

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