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A Comparative Study on the Use and Interpretation of Annotated 3D Models

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Abstract. As a key element in the Model-Based Enterprise (MBE), the Model-Based Definition (MBD) enables the use of annotated 3D models as sole carriers of product information, a practice intended to replace (or at least minimize) the need for traditional engineering drawings. Although both academia and industry have emphasized the benefits provided by MBD, little empirical research has been conducted on the use and human interpretation of annotated 3D models. In this paper, we present a study where annotated 3D models were compared to conventional engineering drawings in terms of efficiency (defined as the accuracy and time to find information) and cognitive workload. Our results show that there are no statistically significant differences between the two presentation formats. Annotated 3D models are a valid alternative to traditional drawings to effectively communicate product information, but their primary value may not be in terms of human interpretation, but in the automation mechanisms that can be enabled by the format.

Keywords: Annotated 3D model, Model-Based Definition (MBD), 3D annotations.

1 Introduction

Drawings are essential mechanisms to document and communicate technical information in engineering and manufacturing domains. They rely on visual abstraction [1] to carry, control, and maintain a product definition in a precise and clear manner without risks of misinterpretation or assumption [2, 3]. In industry, engineering drawings are used to convey critical design information (i.e., what to make and how to make it) and drive product manufacturing processes.

Many downstream operations and manual tasks depend on the interpretation of drawings to extract the necessary data and recreate the geometry of the product [4]. Traditionally, engineering drawings were created and consumed on paper, but electronic documents are gradually replacing paper as the main medium for information

delivery in many industrial environments [5]. The development of standards for digital product definition such as ASME Y14.41-2019 [6] and ISO 16792:2021 [7] has formalized the integration and organization of Product and Manufacturing Information (PMI) into three-dimensional (3D) models, which can now serve as the main source authorities and carriers of design information [3, 8–10]. Annotated models form the basis of the Model-based Definition (MBD) dataset, which provides a full representation of the product without any conventional two-dimensional (2D) drawings.

Annotated 3D models offer significant benefits over a static 2D definition of the product and provide a basis for many Computer-Aided Manufacturing (CAM) and Computer-Aided Engineering (CAE) processes throughout the lifecycle, and for the automation capabilities facilitated by them [11, 12]. In the context of Industry 4.0, utilizing MBD datasets to replace engineering drawings is a practical approach to realize the vision of the Model-based Enterprise (MBE). Indeed, many industries and companies have been slowly transitioning their practices to MBD approaches, minimizing the need to generate engineering drawings [10, 13]. The path toward a full transformation, however, has many obstacles, both technical and organizational [3, 9, 14].

Although MBD has been the subject of study from both academic and industry perspectives for the last two decades, few studies have examined the efficiency and cognitive workload demands for interpreting annotated 3D models versus 2D engineering drawings [3, 9, 11, 14–16]. Understanding how individuals interpret information in 2D engineering drawings and MBD formats can provide insights into new and improved information delivery mechanisms based on annotated 3D models.

In this paper, we present an empirical study where the performance and cognitive load of a group of participants were analyzed during a work session with annotated 3D models and compared to a similar session with traditional 2D drawings to determine the effectiveness of the two media. We define effectiveness in terms of the time to find information in the documents, the user's accuracy (i.e., number of errors), and the user's cognitive workload. The paper is structured as follows: first, we review the most relevant literature on engineering drawings and MBD. Next, we describe our hypotheses, research methodology, and experimental design. Finally, we present the results of our analysis and discuss conclusions and future work.

2 Background

Engineering drawings convey critical information about a product such as geometry, dimensions, tolerances, surface condition, material, assembly, etc. [3, 17] and communicate, in a formal and systematic manner, how to manufacture parts/products in an engineering environment [16]. Despite significant advances in the area of 3D CAD, 2D drawings are still widely used in engineering. In a recent survey [18], almost 60% of the respondents from industry admitted using drawings as the primary means of communication and an additional 15% responded that they still use drawings as a means to supplement 3D models.

Compared to 3D models, engineering drawings are often inadequate in many aspects [11]. For example, substantial cognitive processes, which usually involve a certain level

of spatial aptitude, are required to fully understand how a mechanical part/assembly represented in a drawing works [17, 19]. Ruemler in [20] states that “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.” The viewer of a conventional 2D engineering drawing must be able to mentally develop a 3D model of the part/assembly being depicted and break down the geometry to reconstruct it in a 3D setting. This recreation of information from 2D drawings, however, is time-consuming and error-prone as it relies heavily on the user [4].

MBD was developed as “the practice of using 3D datasets containing the exact solid representation, associated 3D geometry and 3D annotations of a product’s dimensions, tolerances, materials, finishes and other notes to specify a complete product definition” [21]. The vision of the Model-based definition, which originated in the 1980s and 90s, is rapidly being adopted in industrial settings [22].

The ASME Y14.41 standard [6] provides the first comprehensive standard for annotating 3D models. The standard does not change the methodology for constructing tolerances and dimensions, but provides standard rules for displaying, orienting, and querying the annotations when they are stored in a 3D model instead of a drawing [23]. In industry, many commercial CAD systems, such as CATIA, Siemens NX, and SolidWorks, provide 3D annotation tools to support the MBD paradigm. An MBD dataset contains the exact 3D model and 3D annotations of the product’s dimensions and tolerances (and may include parts/notes lists) to specify a complete product definition [3, 10]. MBD provides a single-source for defining the product and its geometry, and it has the potential to eliminate conflicts between CAD and engineering drawings [3, 18].

Many authors claim that MBD can lead to significant time savings and greater accuracy when compared to conventional drawings, not only because of how the data are handled within a CAD system but also because of the implications for Product Data Management (PDM) and Product Lifecycle Management (PLM) systems [3, 11, 15, 24, 25]. An example of an annotated 3D model is shown in Fig. 1.

Annotated CAD models are originally created in a CAD system, and must then be converted to an alternative neutral format, such as 3Di technical data, which is suitable for distribution and collaboration to allow downstream users with no access to the CAD application to access and review the information [3, 10]. According to the MIL-STD-31000B standard [21, p. 5], 3D Intelligent (3Di) technical data is “a 3-dimensional viewable representation of an item provided in a widely available software format (e.g. ISO 32000-1 Portable Document Format (PDF)). This representation details the complete technical description of the required design configuration to include but not limited to geometry, topology, relationships, tolerances, attributes, metadata and other features necessary to define a component or assembly.” In practice, 3D PDF is a popular file format that ensures the future compatibility of the information [26]. 3D PDFs are considered “interactive drawings”: the 3D content can be easily manipulated (e.g., zoom, pan, rotate), reviewed (navigation tools), and interrogated (e.g., measurements, sections) directly without the need of a professional CAD software [10, 26]. In our study, we use 3Di technical data (specifically, in 3D PDF format) to convey product definition as a replacement for conventional 2D engineering drawings.

1. Works (or has worked) for an engineering organization or a university or a Research & Development Center (with previous industry experience).
2. Has substantial knowledge and experience (at least two years) working with engineering drawings.

A set of engineering drawings and 3D PDFs were prepared for two different assembly models – pivot assembly and punch assembly – as well as a series of questions related to the documentation. The assembly models used in our study are shown in Fig. 2 and were selected and modeled by the research team based on the following criteria: (1) the assembly and all the components must have a reasonable level of complexity, i.e., it must be sufficiently challenging so finding the requested information is not obvious, but also not too difficult so the task can be completed within the allotted time, (2) the parts must have a reasonable number of dimensions and annotations, i.e., too many annotations may cause visual clutter on the screen and require users to be familiar with filtering mechanisms, and too few may cause users to find the information with no effort [27], and (3) for comparison purposes, the assemblies and parts must be equivalent in terms of complexity, number of parts, and number of annotations. For simplicity, Geometric Dimensioning & Tolerances (GD&T) were not included in the documents.

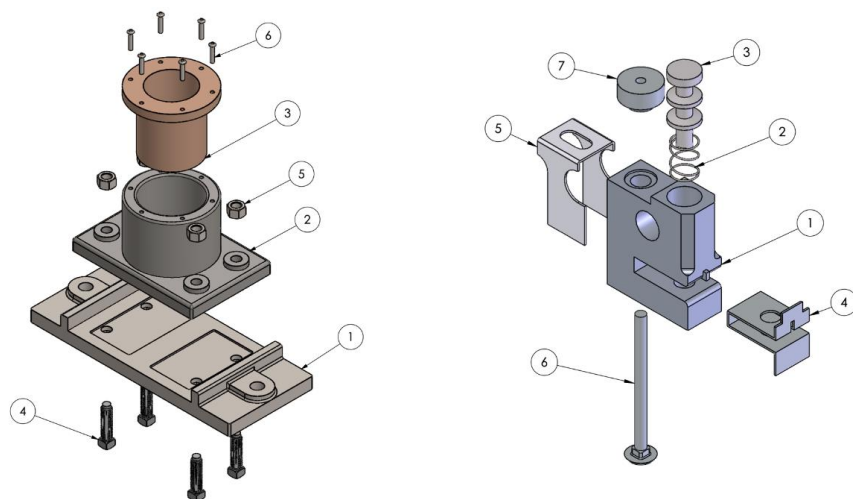


Fig. 2. Pivot assembly (left) and Punch assembly (right) models used in our study.

For the engineering drawings, both assembly models were represented using four drawings which contained an exploded isometric assembly drawing and three drawings with dimensioned orthographic views of the parts. For the 3D PDF document, the same assembly models and components with predefined views were generated. Side-by-side examples of the drawings and the 3D PDFs for two of the parts used in the study are shown in Fig. 3 and Fig. 4.

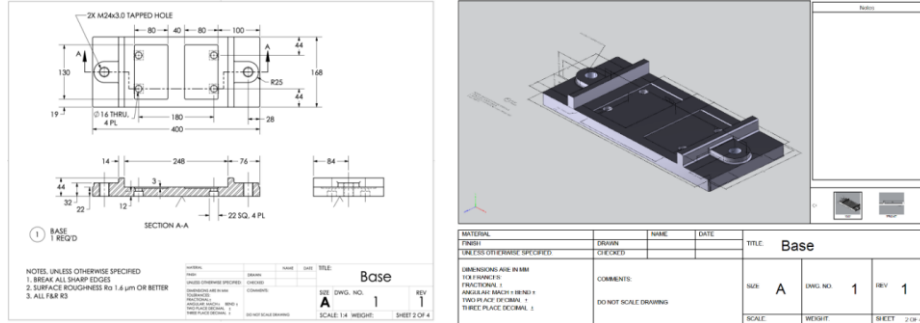


Fig. 3. Engineering drawing and 3D PDF of the Base component in the Pivot assembly model.

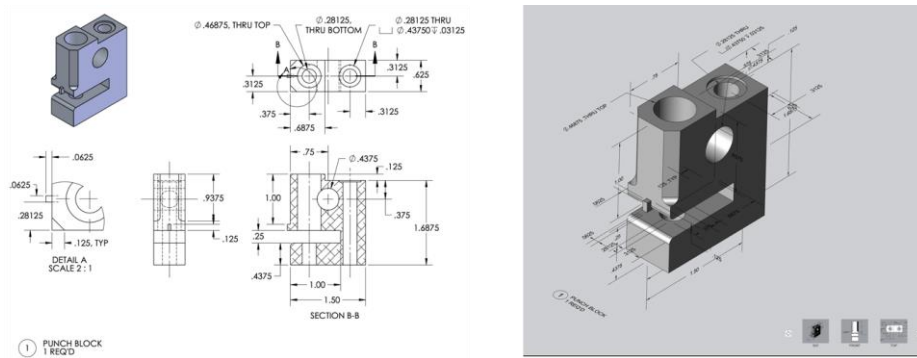


Fig. 4. Engineering drawing and 3D PDF of the Punch Block in the Punch assembly model.

Each assembly model was accompanied by a series of 14 multiple choice questions. The questions were deliberately not related to design rationale of the assembly or to any engineering design decisions, but about the information conveyed explicitly by the dimensions, notes, geometry, and other manufacturing knowledge.

3.2 Experimental Design

Our study was delivered over the internet [28] and the process was fully automated. All the required materials were distributed electronically. Before downloading the exercises, participants were instructed to install the latest version of the Adobe Acrobat Reader software to be able open and view 3D PDF files correctly. We assumed all participants in our study had basic computer skills.

We used a “within-subjects” design, a common type of experimental design in which each participant is exposed to more than one of the treatments being tested [29]. Each participant was asked to complete one set of exercise questions using the engineering drawings and the other set using the annotated 3D models. Participants were asked to complete the test as fast and as accurately as possible. Each participant completed two

tasks, which were timed and performed separately. A different assembly model (pivot assembly and punch assembly) was used for each task. Participants were randomly assigned the type and order of documentation for each exercise (engineering drawings and annotated models in 3D PDF format). The randomized test session arrangement was designed to ensure each participant was tested for both formats and both assemblies.

Our independent variable was the documentation format, with two levels: engineering drawing and 3D PDF. The dependent variables included completion time, accuracy (i.e., number of errors), and cognitive workload. Completion time is the time taken by a participant to answer all 14 questions for each assembly. Accuracy is the total number of errors made by a participant during each exercise.

Cognitive workload is a measure of the amount of mental resources required to complete a task compared to the total amount of mental resources available to that individual [30]. Cognitive workload was measured using the NASA Raw Task Load Index (NASA-rTLX) [31, 32]. The NASA-rTLX is a derivative of the NASA-TLX, one of the most widely used standardized subjective measures of workload [33]. It is a multi-dimensional tool that rates responses in accordance with six factors: (1) mental demand, (2) physical demand, (3) temporal demand, (4) effort, (5) performance, and (6) frustration. NASA TLX has been successfully used around the world to assess workload on operators working in various environments and with various human-interface systems, including aircraft cockpits, communication workstations, process control, and simulations. It is a common instrument to assess problem difficulty and how much thinking, calculating, and decision-making are involved in performing a task, such as the activity presented in our study. Immediately after finishing each exercise, participants were asked to complete the NASA-rTLX questionnaire for self-assessing the perceived mental workload for that particular task. Because our study did not include any physical tasks for the participants, the physical demand questions were removed from the questionnaire.

Unlike the traditional NASA-TLX, the NASA-rTLX does not weigh the subscales by their pairwise comparisons, resulting in a composite workload score from an average of the subscales [34]. Several studies found a strong correlation between NASA-TLX and NASA-rTLX, which favors the adoption of the simpler NASA-rTLX tool [34–36]. Moreover, in contrast to the original calculation, unweighted average produced better sensitivity and reliability than the weighted average [37]. Therefore, we utilized the NASA-rTLX tool to measure the cognitive workload of the participants in our study.

A description of the adapted NASA-rTLX factors and the measurement scale used in our study is shown in Table 1. Each factor is scored on a visual slider scale ranging from 0 to 100 in 5-point increments.

Finally, at the end of the second exercise, participants were asked to answer four additional questions to better understand their preferences and give them the opportunity to provide feedback and comments. A 7-point Likert scale ranging from (1 = strongly disagree) to (7 = strongly agree) was designed for the participants to rate each of the documentation formats.

Table 1. NASA-rTLX factors and descriptions (adapted from [33]).

NASA-rTLX factors	Description
Mental demand	How much mental and perceptual activity was required (e.g., thinking, deciding, calculating, remembering, looking, searching, etc.) to answer the questions? Was the task easy or demanding, simple or complex?
Temporal demand	How much time pressure did you feel due to the rate or pace at which the task occurred?
Performance	How successful do you think you were in answering the questions? How satisfied are you with your performance?
Effort	How hard did you have to work (mentally) to accomplish your level of performance?
Frustration	How discouraged, stressed, irritated, and annoyed versus gratified, relaxed, content, and complacent did you feel while answering the questions?

4 Results and Analysis

A total of 20 participants volunteered to be part of our study. Participants' backgrounds included Mechanical Engineers (25%), Project Managers (15%), CAD Design Engineers (5%), and other professionals (55%) with both industrial and academic experience (e.g., Application Engineers, CAD Design Landscape Architects, Engineering Professors, etc.). The demographic information of our sample is outlined in Table 2.

Table 2. Demographics of our study (N=20)

Years of experience	Mean	Std. Dev.
Engineering drawings	9.35	5.31
MBD	4.55	3.69

The responses from the participants were statistically analyzed through a paired sample t-test. The paired samples statistics and correlations are shown in Table 3.

Table 3. Paired samples statistics and correlations (N=20).

		Mean	Std. Dev.	Std. Error Mean	Correlation	Sig.
Time	Eng. drawings	951.85	366.017	81.843	.251	.286
	Annot. models	1160.29	405.266	90.620		
No. errors	Eng. drawings	3.35	1.926	.430	-.148	.533
	Annot. models	4.05	2.459	.550		

There was not a statistically significant difference in terms of time or accuracy (i.e., number of errors) for the drawings (M= 951.85, SD=366.017 for time, and M=3.35,

SD=1.926, for number of errors) and the annotated model (M=1160.29, SD=405.266, for time, and M=4.05, SD=2.459, for number of errors) conditions; $t(19)=-1.97$, $p=.064$, for the dependent variable time, and $t(19)=-.937$, $p=.361$, for the dependent variable number of errors. No statistically significant differences were found for engineering drawings despite the slightly lower means (both in terms of time and number of errors). NASA-rTLX scores were analyzed using a paired sample t-test. The statistics and correlations are shown in Table 4.

Table 4. Paired samples statistics for NASA-rTLX (N=20)

		Mean	Std. Dev.	Std. Error Mean	Correlation	Sig.
Mental demand	Eng. drawings	53.250	24.563	5.492	-.323	.164
	Annotated models	47.500	26.081	5.832		
Temporal demand	Eng. drawings	50.500	28.326	6.333	-.196	.407
	Annotated models	55.250	28.213	6.308		
Performance	Eng. drawings	82.750	16.421	3.672	-.050	.833
	Annotated models	82.250	14.278	3.192		
Effort	Eng. drawings	49.500	25.899	5.791	-.208	.380
	Annotated models	51.500	25.551	5.713		
Frustration	Eng. drawings	66.500	26.759	5.983	-.001	.995
	Annotated models	69.750	23.701	5.299		

There was not a significant difference in any of the factors for the drawings and the annotated model conditions; mental demand: $t(19)=.624$, $p=.540$; temporal demand: $t(19)=-.486$, $p=.633$; performance: $t(19)=.100$, $p=.921$; effort: $t(19)=-.224$, $p=.825$; and frustration: $t(19)=-.406$, $p=.689$.

Finally, the statistics for the evaluation questions at the end of the study are shown in Table 5. The frequencies shown in Fig. 5 illustrate the rating distributions for each question.

Table 5. Evaluation questions (adapted from [38]).

Question	Statements	Mean	Std. Dev.
1	I can easily and quickly find information in a conventional engineering drawing.	5.25	1.52
2	I can easily and quickly find information in an annotated 3D model.	4.70	1.89
3	Annotated 3D models are more prone to errors than conventional engineering drawings.	4.40	1.35
4	If I had a choice, I would prefer to use annotated 3D models over conventional engineering drawings.	4.75	1.74

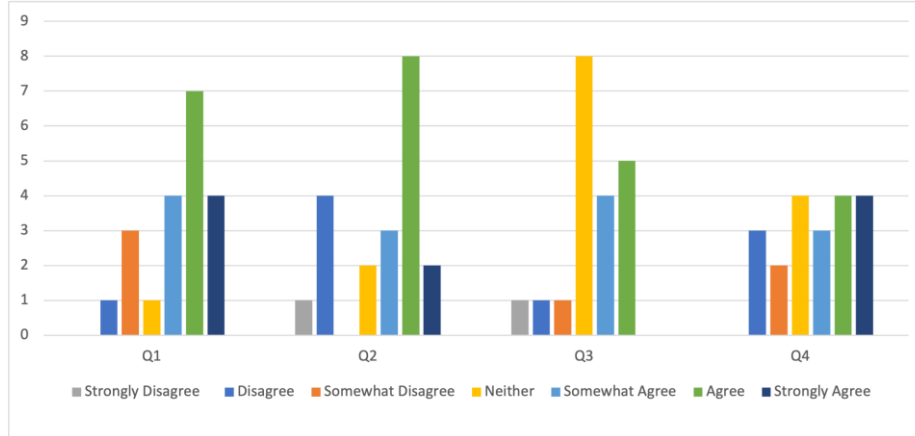


Fig. 5. Frequencies for the evaluation questions

5 Conclusions

The purpose of this study was to examine whether annotated 3D models are more efficient and provide a significant advantage over traditional engineering drawings in terms of finding and interpreting product information. In our study, efficiency is defined as a reduced number of errors, shorter completion time, and reduced cognitive workload demands. The study is presented exclusively from the point of view of human consumption of information. Other elements and benefits such as improved change management processes, reusability, machine-to-machine communication, and automation mechanisms have not been considered.

Our analysis showed no statistically significant evidence to support the proposed hypotheses H1, H2, and H3, which suggests that although annotated 3D models can be a valid alternative format to effectively communicate product information, the primary value of the annotated 3D model may not be the human interpretation aspect, but the automation mechanisms that can be enabled by the format (i.e., machine to machine communication).

The following observations and findings can be drawn from the study: First, our participants were admittedly more experienced with engineering drawings, which may explain some of the results and preferences reported in our study. We speculate our results might have been different for novice users with less experience interpreting engineering drawings but more familiar with 3D model manipulation. The lack of training in 3D PDF prior to completing the study might have also had an effect. Indeed, both documentation formats were rated similarly, with traditional engineering drawing scoring slightly higher. Nevertheless, many participants acknowledged the significance and value of annotated 3D models and expressed a willingness to use them in their future work.

Second, the fact that annotated 3D models are interactive means that the dynamics to navigate, explore, and find information are different. Six out of fifteen participants

who provided comments at the end of our study stated that they were not familiar with the interactive controls of the 3D PDF, which may have slowed them down during the task. In addition, differences in mouse settings with most commercial CAD software (i.e., rotating, panning, and zooming) can cause users to struggle when trying to find the correct mouse button combinations to manipulate the model.

Third, it is important to consider device compatibility when deciding the delivery platform for documentation in the form of annotated 3D models. For example, a desktop computer/laptop is the most suitable platform to read and manipulate annotated 3D models in 3D PDF. Even though the Adobe Acrobat Reader application is available in many tablets (e.g., iPad), only static PDF files are currently supported.

We acknowledge the limitations of our study, particularly the small sample size, the type of stimuli, and the assumption that the two assemblies used in the study are equivalent and have comparable levels of complexity. A larger sample size and more diverse and complex stimuli and tests are required to draw more generalized conclusions. Other elements such as age, gender, industry, and years of experience could have also influenced the study results.

To fully realize the benefits of the MBE approach, additional research and case studies are needed from both academia and industry. For example, similar studies can be conducted in other contexts such as assembly work instructions and component maintenance. Likewise, a comprehensive examination of how annotated 3D models may impact different workflows is also needed. For instance, in our study, completion time, number of errors, and cognitive workload were the only factors that were measured, but other factors such as the level of complexity of the overall design or the effect of the documentation format on change management processes in a real industrial scenario have not yet been fully investigated.

As an extension to our study, we are interested in examining more diverse industry sectors and additional documentation formats. We are also exploring the use of eye-tracking technology to capture and analyze the specific patterns of visual attention of the participants as they perform the requested tasks. Finally, to provide a full picture of the value of annotated 3D models, we need to consider the cognitive effort and time associated to the creation (not just the consumption) of the annotated model and determine how they compare to the creation of traditional engineering drawings. In this regard, a cost-benefit analysis on the creation and use of annotated 3D models as a means of product definition is needed.

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