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TOWARDS IDENTIFYING THE ELEMENTS OF A MINIMUM INFORMATION MODEL FOR USE IN A MODEL-BASED DEFINITION

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ABSTRACT

The Model-Based Enterprise (MBE) paradigm is being adopted by manufacturing companies in a variety of industries. Companies benefit from enhanced visualization, documentation, and communication capabilities when 3D annotated product definitions, or Model-Based Definitions (MBD) replace two-dimensional drawings throughout an enterprise. It is critical that product information, much of which is defined implicitly in drawings, is not lost in this transition. This presents a challenge to authors and translators of 3D models used through the product lifecycle. They must understand the semantics of the product information typically presented by a drawing then explicitly include this information, in a computer-interpretable form, in the MBD.

The research study described in this paper seeks to discover what is the minimum set of required information to carry out all the tasks in a given workflow of a model-based enterprise. A survey was conducted across various industry sectors to identify the foundational elements of this Minimum Information Model (MIM) in selected workflows. This study identified the information used within the specific workflows, the capabilities of 3D CAD models to carry this information, and the implications for doing so.

KEYWORDS.

Minimum Information Model (MIM)
Model-Based Definition (MBD)
Model-Based Enterprise (MBE)

INTRODUCTION

Model-based definition (MBD) is a digital <u>artifact</u> (representation) of an object or system. It is representative of the physical object or system and all of its attributes, and is used to communicate information within various MBx activities in a model-based enterprise. The model-based definition should be rich in information – shape, behavior, and context – and it travels the information architecture within an enterprise (including its extended supply chain and customers), providing input to the various authors and consumers who need it. However, in today's industrial environment the MBD is often thought of as a replacement for a 2D drawing. A model-based definition's effectiveness in communicating, visualizing and documenting information has led to widespread adoption. [1] Although MBD practices are of significant value, there are still concerns about the transition from drawings to models. One issue is that critical information stored in an MBD can be lost in machine to machine communication due to translation errors. Therefore, there is a need to understand the minimum amount of information required at each phase of a product's lifecycle to ensure critical information is not lost. A second issue is a lack of common understanding regarding the information to be included in an MBD that were historically included in a drawing. This research proposes the identification of the *minimum information model* (MIM). The minimum information model is the set of information which is required for the completion of tasks within specific phases of the product lifecycle.

MOTIVATION

The manufacturing environment historically used drawings in the engineering design and production process for communicating information, visualization, and documentation of design intent [1]. Put simply, drawings were the most effective method to communicate product definition because of the tools used in design; triangles and t-squares eventually gave way to 2D computer aided design (CAD) systems, however the primary output was still a paper-based artifact [2]. Even though CAD tools facilitated the design process, and enabled engineering drawings to be generated faster and more accurately, 2D CAD was still nothing more than an electronic drafting board [3]. As computer-aided design software matured, more complex shape definitions for increasingly complex products were able to be captured. However, the 3D model, while able to capture complex shape, typically did not effectively capture behavioral and contextual information as well. The variety of information historically found on a drawing is often missing from 3D CAD models due to the software's inability to completely capture behavioral and contextual information.

Since a three-dimensional model *can* contain significantly more information than a drawing, many companies are choosing to make annotated 3D models a key component for communication within their enterprise. However there is much debate about which information elements to include to support the extended enterprise outside of the engineering function. This has led to the concept of the *model-based entreprise* (MBE). A model-based enterprise is an <u>environment</u>. It is an organization that has transformed itself to leverage model-based information in its various activities and decision-making processes. In this environment, the model serves as a dynamic artifact that used by various authors and consumers of information for their respective tasks. The MBE embraces feedback from the various lifecycle stages to improve the model representation for the creation of subsequent products and product iterations. People working within the enterprise have an enlightened view of digital product information that can be leveraged in their daily work.

Just as people used drawings in their job functions throughout the product lifecycle, today people are beginning to use a model-based definition in their job functions inside engineering, manufacturing, supplier management and other areas of the organization. Model-based engineering, model-based manufacturing (MBm), model-based sustainment (MBs), and any other model-based [activity] (MBx) are categories of <u>activities</u> within the model-based enterprise. Any of these activities (and the people in them) use digital product data to represent shape, behavioral, and contextual information carried by the model-based definition to execute their functional role. Model-based activities are conducted by relying on the predictive and archival capabilities of the model, by replying on its high levels of fidelity to physical object or system.

A model-based entreprise presents a challenge to authors and consumers of 3D models used throughout the product lifecycle. Because not all authors and consumers need the same information to perform their job, the model must often be translated to a different form containing different amounts of information. This issue did not typically exist when using drawings because the medium of communication (paper) could seamlessly pass from one person to another. However due to proprietary data formats and incomplete implementation of data exchange standards in modern CAD tools, the types of information historically found in those drawings is often lost in translation. As such, the standards development community has differentiated between the *presentation* (graphical display) of information, and *representation* (contextual understanding) of information. This difference in the level of sophistication of information embedded in the CAD model is a fundamental tenet of a model-based definition. To successfully leverage the power of a model-based definition, it is important to understand the behavioral and contextual semantics of the product information typically presented by a drawing, and then explicitly include this information in a computer-interpretable form in the model-based definition. It is critical that product information, much of which is defined implicitly in drawings and not at risk of loss due to a change in the communications medium, be protected during the transition to MBD in practice.

Model-based definition standards, such as ASME Y14.41 and ISO 16792, attempt to prescribe rules for how to define specific model-based product definition information. Although these standards potentially provide a foundation for MBD that specifies *how* to express certain types of information in a model, they do not specify *which* information types should be included in a model for a given workflow. [4, 5] In this context, a workflow is a sequence of tasks which, when completed, accomplish a specified objective. The minimum information model specifies the set of required information that workflow participants utilize to complete their tasks. Accurately identifying this information will help a company transition to the use of MBD by providing a general framework for capturing necessary information.

The research described in this paper is the foundation for defining the minimum information model. This research was scoped to answer two questions: (1) from a predetermined list of information, what information does each specified workflow utilize? and (2) how do the humans involved in the specified workflows understand the capabilities of CAD tools to carry product information currently communicated to them?

As stated previously, the evolution of MBD towards the replacement of two-dimensional drawings has created a need to understand the minimum amount of information required in certain workflows so as not to inadvertently expose intellectual property or to unintentionally increase model complexity. The use of models; however, poses challenges to authors and consumers of information in the enterprise due to issues with software compatibility and information complexity. This research attempts to identify the MIM in order to ensure that the information required for specific common workflows promotes effective communication.

BACKGROUND

Information in Engineering Drawings

Historically, drawings were used to communicate information. In an engineering setting, they represented the most effective way to communicate how to produce something based on the design tools available at the time. Over time, drawings became more sophisticated in their information content and their representation of the object being documented. Modern technical drawings often contain more information related to the product definition than actual geometry views of the object [2]. While the orthographics views of the geometry explicitly define shape, the other non-geometric data contained on drawings is often defined implicitly, requiring contextual understanding on the part of the reader to make sense of the information. The level of contextual understanding needed is typically dependent upon the drawings reader's tasks in their given workflow [6]. This contextual information is not "called out" like a dimension or tolerance, rather it is interpreted by the reader of the drawing.

The implicit information is a critical component in engineering drawings; without it, production efforts would be hindered, inspection processes would often be incomplete, and assembly methods would tend to lack needed information to define the proper fit. As drawing creation evolved to meet the communication and validation needs within specific corporate production environments and their supply chains, the result was a variety of ways to apply the well-defined body of national and international drawing standards, with each application being unique to individual companies.

This individualized application of drawing standards within a specific company began to cause challenges within the various manufacturing sectors and their supply chains. Since any given company often has their own way of executing specific processes and interpreting specific sets of information, the resulting intepretations of information from drawings across industry sectors often meant a diferent interpretation of the same drawing from one company to another. Participants of different workflows would receive the same drawings, but each participant's interpretation of the information presented in the drawings will differ [7]. Even the definition of MBD standards for using 3D CAD models in place of 2D drawings [8, 9] has not stopped the occurrence of individualized interpretation.

As the evolution of product definition and documentation has prompted the transition from 2D, paper-based drawings to digit, 3D annotated models, the differences in contextual interpretation of those artifacts has remained. A related issue in this discussion of contextual interpretation of artifacts is spatial proximity. In the past, engineering employees often worked in the same location as the production personnel making the product, which allowed for quick, informal communication. This helped prevent the loss of implicit information and promoted behavioral and contextual understanding of the design and production of the product, because if a person was unable to understand an aspect of the drawing, they could easily find the answer. Now, global supply networks, and "design anywhere, make anywhere" business models have made it necessary that the semantic interpretations of digital artifacts (i.e., 3D model-based definitions) be explicitly defined [10,11].

While the transition to digital MBD representations has arguably made dissemination of product information easier, the disparate nature of information authoring tools has raised a vexing dilemma. Most companies do not store all of their product definition or production data in a common database, which makes aggregating that data difficult. While this was still true when people primarily used paper-based drawings, the challenge was slightly less in that the paper medium was the common denominator. Even when the transition was made to 2D CAD systems, the output that was shared was often paper-based. And since neither paper drawings nor 2D CAD drawings were associated parametrically to a 3D model, information could be readily changed without the overhead of affecting a 3D model or having to edit a 3D model to initiate a change in a 2D drawing. Moreover, materials data, work instructions, process specifications, and other information, which could easily be included on a 2D drawing and that might conceptually be stored in a model-based definition, are not easily aggregated today into a 3D model. The discontinuity among product data authoring systems must change in order for the MBD methodology to succeed in the long term as something more than a simple remaster of a drawing definition by including implicit information. While the method of product definition or interpretation is important, the method for information dissemination is just as critical [12].

Model-Based Definition

The digital, model-based definition is rapidly becoming the artifact of choice to document and communicate product definition information within many large companies, as well as their extended supply networks. The use of MBD allows companies to leverage the resources invested in the definition and creation of the product model, as well as the visualization and communication capacity that a 3D digital medium provides. In doing so, companies are beginning to eliminate the use of 2D drawings, or at least relegate the 2D drawing to being used as a reference document rather than the document of record [13]. Moreover, the efficiencies gained when a company transitions to being a model-based enterprise require the use of the model-based definition [14, 15]. Furthermore, industry has found success using MBD for workflows such as manufacturing, planning, product-services procurement, and marketing [4, 16].

Yet even in companies making the transition to the use of MBD in lieu of 2D drawings, the transition has not been without challenges. While the aerospace and automotive industries have led the 2D-to-3D transition [4], their extended supply networks have been slow to adopt the change in technology and methodology. Employee training costs, increased costs in software licenses, and the inherent complexity of 3D-based processes are often listed as reasons that small and medium manufacturers (i.e., automotive and aerospace suppliers) do not adopt or implement MBD technologies and processes. While the three-dimensional model as a geometry definition within the design and engineering functions has become ubiquitous across industry sectors, a redundancy has occurred as companies or certain functions within companies have not wanted to give up their use of 3D drawings [14, 17].

By using the three-dimensional model and adopting an model-based enterprise approach, a company potentially eliminates redundant product definitions. The advantage of the 3D CAD model is contains enough geometric information to consolidatedefinitions; however, by default, it will still lack the behavioral and contextual definitions withough a conscious effort on the part of the definition author to include them. So while the CAD model is likely to be used to define final product geometry, it may not necessarily be thought of as the master product definition today given the disparate locations of the data necessary to complete such a definition. However, the 3D CAD model is an opportunistic choice to embed and transfer product information [18] due to its communicative capacity and ubiquitous adoption when human consumers of product information are in the loop.

The consolidation of product definition data into a model-based definition provides numerous benefits across the lifecycle. For every user of 3D CAD models in design, engineering, or manufacturing, there are thirty potential users of data in marketing, product documentation, sales, support, customer service, and beyond [19]. Boeing demonstrated the power of successful MBD implementations. Boeing engaged in a Virtual Product Development technique where the product design, tooling, and manufacturing processes, prior to fabrication were verified virtually. This approach achieved a 62% reduction in product development time and 42% reduction in the cost of development [14, 20]. MBD has proven to be a more effective method of communication than engineering drawings. Due to this, 3D CAD Model usage will continue to grow. To maintain the benefits and maximize the utility of the 3D CAD Model, it can be used to consolidate product definition information.

Although models can carry the same explicit information defined in drawings, the next step in their development is the creation of a 3D CAD model that contains all information required for the specific individual who would use the model. The minimum information model would benefit multiple actors within the lifecycle by delivering the information neded in a specific workflow in a specific lifecycle stage. The use of MBD (and by extension, the minimum information model) within manufacturing companies is an appropriate approach due to the benefits offered by leeraging the 3D model [13].

Minimum Information Model

As stated previously, companies have begun the transition to model-based definition. Some of those companies already have successfully replaced the 2D drawing with the 3D CAD model, while others remain in the process of doing so. The capture of explicit drawing information was the first step of a longe process to the successful adoption of MBD. It is now necessary to develop understanding of the minimum information set necessary for employees within specific workflows of a product-producing company. The marriage of shape, behavioral, an contextual information within MBD processes has the potential to enhance productivity by capturing both the implicit and explicit information historically contained within 2D drawings. There is little documentation about how to develop MBD artifacts and methods past the level of definition of a drawing replacement. The current industry trajectory is to simply move the annotations from a 2D drawing into similar locations within the three-dimensional models as annotations visible to the user [13].

There is a growing body of literature and industrial interest in the identification of requirements for proper MBD implementation. One research team analyzed different levels of MBD implementation and analyzed their effectiveness. This research was process oriented and sought to identify what improvements need to be made for MBD implementation. Their research identified that the use of MBD as the master definition needed improvements in data standardization and process visualization [21]. The need to structure the process information in a useful and effective method has driven research to standardize the data representation. Information is contextual across the lifecycle and different departments and/or processes in the lifecycle may require different types of MBD datasets [22]. Researchers also have begun constructing design MBD (dMBD) and process MBD (pMBD) models and concluded that further identification of non-geometrical information still needs to be perfected [23].

Expanding MBD beyond drawing definition will also require improvements to CAD authoring software tools currently in use, as weill as improvements to the database and data model structures currently used by commercial CAD software and product data management software tools. While distributed product development systems, and innovations in communication technologies, are closing information gaps between engineering and the remainder of the lifecycle [24], enhanced data security, network architecture, and compression technologies will be needed to disseminate more well-developed MBD data files. Once these technologies reach adequate levels of performance, a complete understanding and definition of the model-based product information required will be needed.

This research study in the first stage of a two-part study, establishing the preliminary definition and context of the minimum information model, with the second stage expanding and validating that definition through the use of a future Delphi study. Once completed, the MIM would be the set of information that the workflow participants require for completing their tasks. This means that if an element of the MIM is missing, the workflows processes will be hindered. This research looks to build upon the MBD definition by providing guidelines for the information that will be created and passed to and from each workflow to streamline production. Therefore, one must understand the definition of an *element* in the context of the minimum information model.

The MIM is comprised of a set of elements. The elements exist in current workflows. The following statement must be true to classify information as a MIM element: the information is consulted in completing the tasks of the workflow the MIM represents. The MIM elements can be split into two subsets. These subsets are *primary information* and a*uxiliary information*. The primary information is the set of information that most work tasks in this workflow utilize. Dimensions are primary information for manufacturing. The auxiliary information is the set of information that is unique to specific workflow participants. To be an element of the auxiliary information set an element must be consulted by at least one participant of the workflow in completing the task. An example of an auxiliary information element is the atypical use of an analysis model by design, or manufacturing. A key aspect to consider for auxiliary information is that it has high variance. The MIM is the union of these two sets, and furthermore, an element of the primary information set cannot be a member of the auxiliary information set and vice versa. Understanding the components of the MIM set is critical to successful implementation of the MIM.

Both subsets of the MIM are valuable, but the primary information set affects a much larger population of the workflow, potentially all of it. The primary information must be communicated clearly and logically because improper communication may negatively affect the population.

The auxiliary information set has two aspects that confound identification of the information. The auxiliary information set contains low use information as well as industry, or company specific information. Handling of industry or company specific information will likely only be possible by further categorizing the MIM workflows. Second, it is possible that the auxiliary information set will be in a flux state, and therefore, difficult to maintain. It is possible that consistent evaluation of the information in use within the workflow can be done to maintain the auxiliary information, but how to best handle the Auxiliary information may not be clear, and may require a more interventionist approach, instead of presupposing the information required.

These two aspects of the auxiliary information set led to the pursuit of the primary information set elements in the minimum information model. For the remainder of this paper, when we discuss being considered part of the MIM, we are referring to being a member of the primary information set.

SURVEY DESIGN

We designed a survey in the pursuit to identify the elements of the minimum information model. This survey was distributed via a web service, Qualtrics, and was promoted via email blasts and social-media advertising. The questions in the survey targeted our two research questions: (1) what is the minimum amount of data that is necessary to communicate to the next consumer in the lifecycle and (2) what are the capabilities of CAD tools to carry the minimum information level?

Our goal was to ensure comprehensive responses from as many participants as possible. The will contain a standardized information base. For that to be possible, a large response group was required to confidently represent the population of participants' respective workflows. We recognize that the quality of the survey outcome is dependent on the quality of the survey questions posed and the responses received. Therefore, we worked with subject matter experts to validate the questions and provided multiple choice responses to minimize the uncertainty of the survey results and manage the overall quality of the survey.

The first portion of the survey collected demographic information. Questions one and two were geared towards the company with which the participant currently worked. The participants identified their own industry such as defense, automotive, medical, etc. Participants also indicated the size of their company. Company size was indicated in ranges of fifty employees, and capped at 500 or more.

Next, participants identified information about their company's geographic location and their own job area within the company. The locations were preliminarily divided into inside U.S. and outside U.S., and then further subdivided. If they were in the U.S., they were asked what region of the U.S. If they were outside the U.S., they were asked what continent. The participants then indicated their current job area within the company. A list of job areas was provided and participants had the option to enter their own job description if it was not represented by the job areas listed. This question identified positions such as design engineer, analyst, manufacturing engineer, or quality engineer.

Following demographics, two more questions about how engineering information was communicated were asked these two questions were: (1) how do you currently receive engineering related information? and (2) in which workflow do you most actively participate? The first question looked at industry's current level of model adoption. Participants indicated the method by which most engineering related information was communicated. The second question separated participants into one of the four workflows that were identified for the minimum information model. The four workflows were (1) concept-to-prototype, (2) prototype-to-detailed product definition, (3) detailed product definition-to-manufacturing, and (4) manufacturing-to-inspection. The participants also had the option to indicate they did not actively participate in these workflows. If participants indicated that they did not actively participate in one of the identified workflows, the survey concluded.

From here, the survey segmented into four distinct workflows, but with similar structure. The first question in each section was, "What type of information is created or used in the workflow?" Participants were presented with a series of check boxes that referenced specific information pertinent to their workflow and could select all that applied. An option to add free text was also provided.

Following this question, the participants indicated if drawings were used to communicate the information. If the participants indicated that drawings were not being used to communicate this information, then they would be queried on what other documents were used to communicate the information. Next, participants were asked, "In your company, could the items in Question 8 (What type of information is created or used in the workflow?) be communicated via a 3D model of the product instead of a drawing?" If their answer was no, then the participants were asked, "What prevents models from being used to communicate this information in this workflow?" However, if they selected yes, then the participants skipped that question. Each workflow was structured in this manner with the information indicated in the first question varying.

The final question was a qualitative question, which allowed participants to provide any comments on the topic of using model-based definition in place of drawings. This concluded the survey for identifying the minimum information model. In the following sections, the results are presented in detail.

RESULTS

The minimum information model survey had 89 respondents. Of these 89 responses, 76 completed the demographics portion. Eighty-five percent of the respondents were from the U.S. with 63 percent from the Midwest and approximately 10 percent respectively for the Northeast, Northwest, Southeast, and Southwest.

Of the 15 percent outside the U.S., 36 percent were from Asia and 64 percent were from Europe. These respondents indicated that they worked in a wide variety of industries, with relatively even distribution within each industry. The respondents answered a question to determine the size of the company for which they were currently working. The data reflects that this survey captures the opinions of both small and large companies with a slight skew towards larger companies, which could simply be due to larger companies having proportionally greater numbers of engineers.

Going forward with this survey, narrowing the MIM to an industry sector and company size would be better suited to address the specific needs of specific areas. There are potentially different variables in each field that affect the use of 3D CAD models and creating the MIM, capturing the differences between fields is an important aspect of the minimum information model. The survey collected information regarding the respondents' current job area, with this distribution highly skewed toward design engineer. Sixty-eight participants submitted an answer to this question, and 33 participants indicated they were design engineers. To improve the survey, it would be important to try and capture more positions at the companies outside the categories of *design engineer* and *management*.

Regardless of the highly skewed current job title, the distribution of their current workflows was excellent. Therfore, meaningful data was collected from each of the workflows and contributes to the use of the minimum information model. Maintaining a proper distribution of workflow participants should be kept in mind in follow on research efforts.

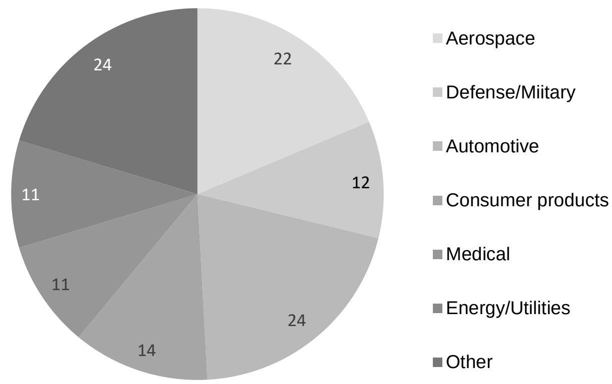

Figure 1 Distribution of Participants Industry

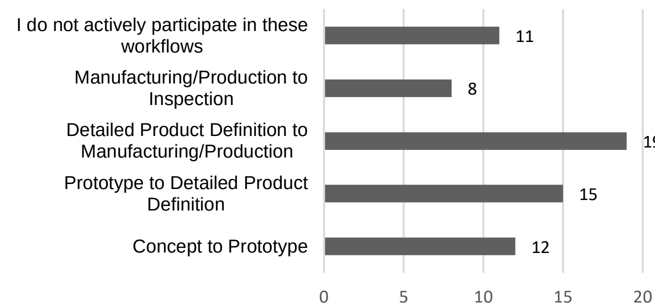

Figure 2 Participants workflow distribution

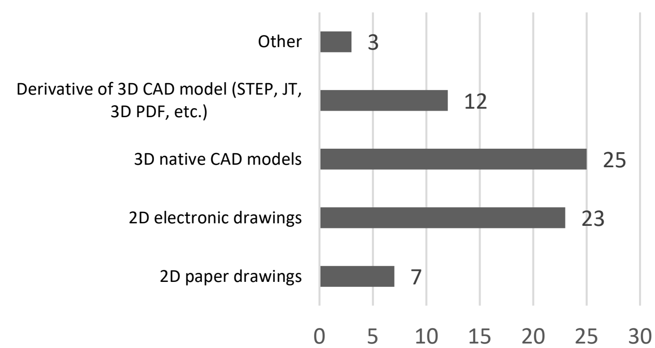

Figure 3 Response for how participants receive information

After respondents indicated the workflow in which they most actively participated, the survey placed the participants into groupings to determine the requirements and capabilities of each individual workflow with respect to model-based definition and minimum information model. The four workflows were *concept-to-prototype*, *prototype-to-detailed product definition*, *detailed product definition-to-manufacturing*, and *manufacturing-to-inspection*.

Each of these had very similar questions. In the cases where the questions were the same, they were aggregated. The remainder of this section summarizes the results of the aggregated data of identical questions.

The data displayed and discussed in this section reflects the responses of all participants in each of the workflows. Identical questions separated by workflow were aggregated. The aggregate data provided insight into industry's readiness to adopt model-based definition. These questions intended to identify industry's level of readiness to convert to a model-based enterprise. These questions targeted the methods in which data was consumed, created, and then transferred and whether 3D CAD models could perform these tasks in place of two-dimensional drawings. All participants in the survey could indicate the medium in which they receive product information for consumption. In Figure 3, 58 percent use a CAD model or a derivative of a CAD model and 36 percent use a 2D-electronic drawing. Only 11 percent still use 2D-paper drawings as the medium for data exchange. The distribution of 3D CAD models already compromises over 50 percent product information exchange. In addition, when including 2D-electronic drawings nearly 90 percent of the product information medium is considered.

It is apparent that the 3D CAD model is the primary source of data transfer for most employees at these companies and the use of the 3D CAD model as the master definition would be beneficial to industry. Even though the primary medium for data exchange is through CAD models or their tools, most information being consumed is through drawings. Ninety-six percent of respondents indicated that they only use drawings or drawings in addition to other auxiliary documents for use or creation within their respective workflows.

Utilizing a CAD or derivative model to carry information is the most common product definition format utilized in this survey. The replacement of drawings with three-dimensional models could provide numerous benefits, but the three-dimensional model first needs to replace two-dimensional drawings and capture all information they contain. Respondents were asked if models can deliver the data created or used within their respective workflows. Overwhelmingly, respondents indicated that the 3D CAD model can deliver this information.

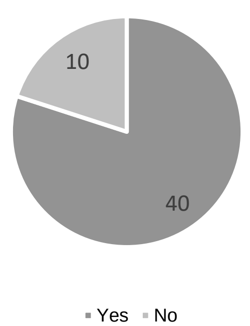

Figure 4 Could models be used in place of drawings in your workflow?

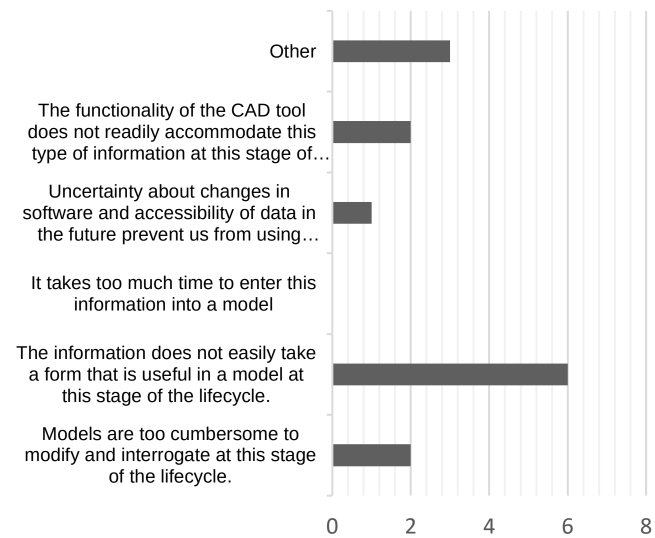

Figure 5 Issues adoption of MBD faces

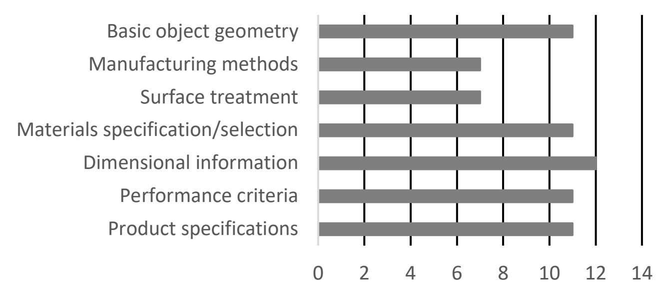

Figure 6 Participants responses for what information was created or used in the the product information for concept-to-prototype

The model is now at a point where it can replace the drawing, but to effectively make the transition, all information and issues must have discrete answers. Respondents who indicated that models could not replace drawings within their company were prompted to determine the inhibitors of 3D CAD model usage that ultimately inhibited the development of model-based definition.

In Figure 5, the main inhibitor of the use of 3D CAD models was that the information did not easily take a form that is useful in a model at this stage of the lifecycle. Each of the listed issues was indicated at least one time except for the issue that it took too much time to input this data into a three-dimensional model. There are concerns for the use of MBD, but most respondents believe model-based definition can carry the information that they are consuming or creating. In the follow paragraphs, each individual workflow is broken down. Regarding the information to be contained in the MIM, any information selected should be considered and further researched. This discussion only pertains to information that was selected by five or more participants. The purpose behind reporting only on information which had a selection of five or greater was to ensure that the information was necessary to that workflow. Individual respondent's processes will vary and may utilize different information, but there is a subset of information which is necessary to complete a workflow. The MIM is intended to identify this necessary information subset. The lists that were developed to help identify information used or created in each workflow were populated through discussion with companies. They are not intended to be a complete list of information to be standardized in the MIM, but they do formulate a foundation on which to start understanding and building the minimum information model. A low response rate does not signify exclusion from the MIM, but rather states that further research is required.

The concept-to-prototype workflow had twelve respondents (see Figure 2). concept-to-prototype respondents indicated the information that was created or used within this workflow (see Figure 6). Eleven concept-to-prototype respondents indicated that product specifications, performance criteria, materials specification or selection, and basic object geometry were created or used in this workflow. All respondents in this workflow selected dimensional information. Seven indicated that surface treatments and manufacturing methods were also created or used in the concept-to-prototype workflow. Respondents were then queried if this information was communicated via drawings. Eleven indicated yes, but with accompanying documents. One indicated no.

When drawings were not used to communicate information, then corporate standards, test documents and contracts were used to communicate the information being created or used. Participants were asked if they thought models could communicate this information. Seven indicated yes and four indicated no. The four whom indicated that models could not be used were polled to determine what inhibited the use of models. This group did not converge on one primary cause of the problem. Instead, the data shows that there are many concerns that could prevent the use of models to communicate this information. Three participants indicated that information did not take a useful form in the 3D CAD model and two participants indicated that models do not take a form that is conducive to work on the manufacturing floor in the other comments section of the survey. It was also stated in the other response that stakeholders do not have a method for 3D CAD model manipulation.

The prototype-to-detailed product definition had 14 respondents. Results for the material created or used within the workflow are listed in Figure 7. All fields within this section had at least one selection that the information was used or created.

Dimensional information (13) and materials specification or selection (12) were the most selected choices. Two other choices that also had 10 selections were refined object geometry and tolerance information. Revision or version history obtained nine. Performance characteristics, surface treatment and manufacturing methods has six, seven, and eight respectively. Refer to Figure 7 for all distributions. Most of this information was communicated via drawings with three indicating drawings only, nine indicating drawings and accompanying documents, and two selecting no. The two respondents who indicated that drawings were not used stated that corporate standards and specification drawings were used to communicate this information. Respondents indicated that the information created or used within their workflow was capable of being communicated by three-dimensional models. The respondents who indicated that models could not be used only indicated that internal processes prevented the use of 3D CAD models to replace drawings.

Nineteen respondents were part of the detailed product definition-to-manufacturing workflow. Results for what information is created or used in the detailed product definition-to-manufacturing workflow were highly varied with response ranging from four to 16. More than 10 participants in this workflow indicated detailed product geometry, final dimension information, tolerance information or geometric dimensioning and tolerancing (GD&T), materials specifications and finished surface characteristics. These respondents indicated that this information was communicated to them via drawings and other accompanying documents. Drawings were always involved in the communication of information between detailed product definition and manufacturing. Three respondents indicated that models could not be used to replace drawings in detailed product definition-to-manufacturing. Even with all respondents relying on drawings in this workflow, most respondents indicated that models can replace drawings.

Eight respondents indicated that they were part of the manufacturing-to-inspection workflow. The indication of information used or created is shown in Figure 9. Notable figures include, six respondents indicating that detailed product geometry, final dimensions, and manufacturing methods were used in this workflow. Seven indicated that finished surface characteristics were created or used.

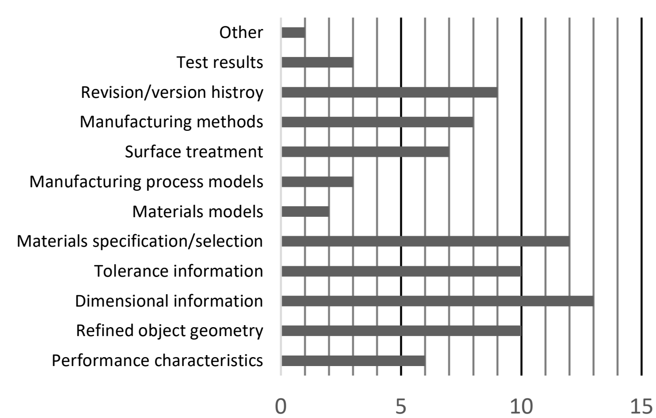

Figure 7 Participants responses for what information was created or used in the prototype-to-detailed product definition workflow

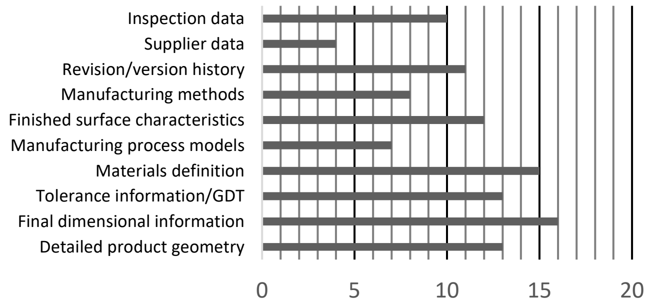

Figure 8 Participants responses for what information was created or used in the detailed product definition-to-manufacturing workflow

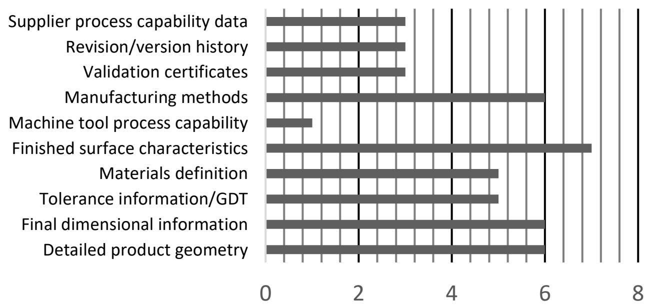

Figure 9 Participants responses for what information was created or used in the manufacturing-to-inspection workflow

The respondents indicated that drawings were always used to communicate information in this workflow and six indicated other accompanying documents were also required. Materials selection and tolerance information or GD&T were selected by five respondents. The options other than those discussed had fewer than five respondents. All subjects in this workflow indicated that the method for communication was either drawings or drawings and their accompanying documents. Overwhelmingly, this workflow indicated that models could replace drawings within the manufacturing-to-inspection workflow.

The only inhibitor indicated in this workflow is uncertainties concerning long term archival and retrieval (LOTAR). This workflow had one of the highest selections of the capabilities of CAD tools to communicate the information that was stored within drawings.

DISCUSSION

MBD has begun to infiltrate manufacturing companies in a variety of industries. Companies are using MBD to generate competitive advantage, enhanced time to market, and improved costs. Initial MBD was limited to the use of the model as a method of design, but the definition of the product was still captured with drawings. This leads to redundancy in the documentation of the product and possible confusion as to what is the master data.. A desire to replace the use of drawings with models was born from this problem. When addressing this conversion to MBD, it is crucial that no product information is lost. Creating a model-based enterprise requires an understanding of what information is needed in a model for an individual to complete all their required tasks. A survey of manufacturing companies was done to shed light on the information required within model-based definition. This level of information represents the minimum information model.

By minimum, it refers to the set of information needed to complete a task in a workflow. It is the amount of information for a specific domain to complete most tasks within that domain. A minimum information model cannot yet be fully defined from this survey, but critical information has been identified and insight into building the minimum information model. This survey also measured the capability of industry's readiness to use models as the master definition and the potential inhibitors of model use.

The minimum information model within the concept-to-prototype workflow has begun to take shape. The information (product specifications, performance criteria, dimensional information, materials specification or selection, surface treatment, manufacturing methods, and basic object geometry) that was indicated as used or created within the concept-to-prototype workflows were all indicated by more than five participants in the workflow. This data forms the foundation for the MIM within this workflow.

In addition to the information created or used in this workflow, participants indicated whether models could communicate this information. Only seven participants indicated that models could communicate this information. This was the lowest of all four workflows, and considering the sample size of 11, it was close to 50 percent. More research is required to address whether this workflow can use models as the master definition.

The majority response for why models could not be used was that the information does not easily take a form that is useful in a model at that stage. The inhibitors to using the three-dimensional model appear primarily related to the use of the CAD tool and not the abilities of the tool itself. The data suggests the inherent ease of use of drawings is not overcome by the effectiveness of the CAD tool, and that the use of the CAD tool to communicate this information would impede the communication of this information. In the other category, one of the respondents indicated that there is difficulty using the information on a manufacturing floor because it would require the setup of a terminal where floor workers could interrogate the model. This would also require the workers on the shop floor to train on use of the 3D CAD model. This workflow had the largest indication that CAD tools were incapable of replacing drawings, but the result may be tied to the comfort level of the respondents.

There was no indication that the model could not hold the information, instead only that it was difficult to use the information that was held by the model. This workflow needs to be analyzed further to ensure that using a model in place of drawings during the creation of a product is possible.

In summary, all options for information within this workflow appear to be contained within the minimum information model. Additional research is needed to understand how models could effectively allow information to be created and used.

For the prototype-to-detailed product definition workflow, 85 percent of respondents indicated that models could communicate the information used or created within their process. The choices selected by more than five respondents were refined object geometry, dimensional information, tolerance information, revision or version history, manufacturing methods, surface treatment, performance characteristics and materials specification or selection. Drawings communicated this information to 11 of 13 respondents.

Workflow participants had significant support for models can communicate the information used from drawings. Eleven out of 13 respondents indicated models could be used for this information. The respondents who indicated models could not be used stated that it was internal processes that prevented the use of models. One respondent did not indicate why. This suggests models can replace the information being used or created in this workflow, but the business process for the company will need to change to implement model-based definition. Adapting business processes to the use of models will be a challenging next step in MBD implementation.

detailed product definition-to-manufacturing workflow indicated that 3D CAD models could replace drawings for the communication of information use or created. This field had 18 respondents and they formed some consensus on the information required for this workflow. The information being used or created by more than 5 respondents were detailed product geometry, final dimensional information, tolerance information or GD&T, materials definition, manufacturing process models, manufacturing methods, revision or version history, inspection data and finished surface characteristics.

Regarding the workflows' readiness to adopt MBD, the workflow had an overwhelmingly positive response to the use of 3D CAD models. 83 percent indicated models can replace drawings for communication. On top of this figure, all participants in this workflow were using drawings to communicate the information. The respondents who indicated that models could not be used were primarily concerned that the CAD tool was not easily used for the communication of this information. One respondent indicated LOTAR as a barrier to replacing drawings.

Manufacturing-to-inspection had only eight respondents but they also provided a consensus on the type of information used or created within the workflow. More than 5 participants in this workflow indicated each of detailed product geometry, final dimensional information, finished surface characteristics, tolerance information or GD&T, materials definition, and manufacturing methods.

All but one workflow participant indicated that this information could be communicated via models. The one who did not believe models were capable, indicated that LOTAR held back the use of models, not the capability of the models. All respondents within this workflow also utilize drawings and some utilize models already. Although all workflow participants are using drawings, they all supported that models can deliver information at the same level as drawings.

Although the MIM is workflow specific, there is useful information to be considered across the workflows. This information's level of detail or completion varied, but the type of data was similar. This data was dimensional information, object geometry and material's definition. There are also interesting trends between the workflows. These three attributes may form the foundation for the "lifecycle" minimum information model. It was also indicated in a follow-up note that MBD requires each workflow to have its defined data levels to ensure that they are not overburdened with excess information. The minimum information model need within the MBE is already being felt.

Most respondents indicated models could be used to communicate the information within their workflows. It is likely the tools do not prevent the use of the 3D CAD model. There are some instances where a three-dimensional model may not be the correct method of communication. For example, one such case was indicated in the other category – on a shop floor it would be difficult to work with 3D CAD model instead of a drawing. There are many challenges with implementing three-dimensional model usage on a shop floor, such as the hardware to interrogate a 3D CAD model. However, the same hardware also provides many benefits such as the visualization tools, which come with a 3D CAD model medium. A related opinion was that it would be difficult for stakeholders who do not have a method to interrogate 3D CAD models. Both cases have a variety of solutions and are capable of efficient management.

Based on the results of this survey, industry is ready to adopt a MBD approach to data distribution. Most respondents indicated that models are currently capable of replacing drawings. Most responses indicating that models could not be used were related to use of the data when stored within a CAD tool. Specifically, the information does not easily take a form that is useful in a CAD tool. This implies that the data can be stored in a CAD tool and that it can deliver the information, but that a drawing is better at delivering this information. It is possible that this is more related to the CAD operator and less related to the capabilities of the CAD tool. The user of the information will affect the usefulness of the information.

This research has set the foundation for an important concept needed within MBD, the minimum information model. This research began moving towards the MIM definition, but did not identify the specifics of the MIM set within each workflow. Further research will need to be done to support this. This research did address the views of workflows participants on the model's ability to carry the information that they utilize regularly. The 3D CAD model is ready to begin replacing drawings in multiple workflows, and more research will need to be done to address the concerns raised by the research participants as to hindrances into implementing a more sophisticated model-based definition.

CONCLUSION

Moving towards an MBE presents many challenges and obstacles. One of these is having a complete understanding of the information flowing within the organization. This is difficult to capture, because of the nature of an organization, but there is significant value in it. The minimum information model is a formalized model meant to capture a specific subset of information communicated within an organization that will assist in communicating and presenting information within an organization. The following section presents on notable concepts developed from this research.

An interesting trend seems to be developing for data creation and use. When the previous workflow highly selected an information type, the following workflow would also select it highly. This indicates that the subsequent workflows would commonly use data created at the previous step in the lifecycle. An example of this is that tolerance information was highly selected in prototype and then dropped slightly in the subsequent workflows. There needs to be more data and a statistical analysis to confirm this. As of now, this is merely speculative. A follow-up survey could visualize the flow of information through the workflows and whether information loses or gains value to end-users as it passes through a lifecycle. Defining the minimum information flow through a company would assist in building the minimum information model. To build this information flow, an ontology of engineering information would need to be created. This would identify the equivalent information as it passes through the lifecycle. However, first one must identify the information used and created within each workflow.

Applying information science to discovery of requirements has long been needed. The key discovery is that it will remain difficult to use 3D models on the factory floor in the near future. Oftenly, the only computers at machine tools and additive manufacturing equipment on the factory floor are those used as operator interfaces and those will not be used to interrogate models. There are exceptions to this, but this is a concern for those who have not transitioned.

In addition to the shop floor difficulties, LOTAR provides a challenge to implementing MBD. A plan for LOTAR is imperative for MBD because LOTAR was indicated in two of the four workflows as an inhibitor of use of the 3D CAD model as the master definition. LOTAR is a concern when products can be used for extended periods (e.g., 70 or more years in aerospace) and software continues to upgrade. LOTAR was the only indicated inhibitor of 3D CAD models that addresses the CAD tool as not equally capable of delivering the same level of capabilities as a drawing. Developing a business plan for LOTAR before the implementation of a CAD tool must be done to begin model-based definition.

The data collected supports the use of MBD, and minimizing drawing creation to when required and as supplemental material to describe the product definition. The clear majority for data exchange within industry is either a 3D CAD model, a derivative, or a 2D-electronic drawing generated from a three-dimensional model. Industry is at a level where the 3D CAD model becoming the master model would streamline processes and reduce redundancy of product definition. To adequately make this change, industry will need to determine all information used or created in drawings.

Our survey represents a baseline level of information being consumed by the different workflows, but it may not reflect all information that is consumed within each of these workflows. For a company to make the jump from drawings to 3D CAD models, as the master definition, a company should survey its employees to determine the required information used or created within two-dimensional drawings.

Capture of implicit information is a critical first step to convert from the use of two-dimensional drawings. Loss of information during the transition would be detrimental to the production process. Many participants had positive feedback to using models in place of drawings in the other section of the survey, which indicates that it would be beneficial to upgrade to a MBD environment. Some concerns were listed as well, which were grounded in some real issues with the CAD tools, such as data fidelity and compatibility. One respondent indicated that each workflow needs its own defined data requirements to eliminate an information overload.

Industry's evolution from the use of two-dimensional drawings to MBD has begun to take shape. Specific information is emerging as the minimum required data the employee needs to complete his or her tasks. It is imperative that all workflow information is considered when building the minimum information model. Our survey represents a foundation for the requirements of the MIM and supports the hypothesis that 3D CAD models can replace drawings in a production environment. While the common MIM information elements identified by the survey seem clear, it is less certain the impact of the domain-specific influences on the ability of the user to consume the information. Targeting samples from user populations inside specific companies to build the MIM would be more beneficial than the broad scope of the current survey. Capturing all information within specific workflows is difficult when the respondents are not distributed across all positions in the workflows.

A follow-up survey should be undertaken to derive the information elements of the minimum information model. The follow-up survey should focus on narrowing the minimum information model requirements. Each workflow is to be given an abundance of options, possibly even options where the same information is being referenced, but with different terminology, to ensure that they are selecting only information they are using or creating. Inputting control information would also be beneficial to ensure that individuals are thoughtfully selecting data being used and not responding haphazardly. This will shed light onto what the MIM consists of for each workflow. In addition to creating control information, it would be beneficial to force respondents to indicate the information's level of value to them and the necessity of the information to create their data.

This survey would have alternative uses for identifying movement of data through the workflows. One such use would be defining the equivalent or derivatives of data types to identify how data is moving through workflows, as well as where it starts and stops. This visualization would help create a checklist for defining the medium to carry this information in each lifecycle. The following paragraph details research conducted along this thread.

A follow-on study exploring the minimum information model based on the research conducted in this paper is currently being pursued. A Delphi study was chosen as the most effective approach to detailing the minimum information model. A Delphi study format will allow the consultation of multiple established industry leaders and experts in different fields. This method has provided a connection of information that, while common in nature, differs depending on work sector or job role. The study was done to allow experts to collaborate on the idea of a minimum information model and to help us observe what specific information is required when passing information from one workflow to another

This research helps begin defining the MIM for use in model-based definition practice. More research is required to define the MIM within specific workflows, and follow on research will be necessary to complete the definition of the minimum information model. In addition, this research supports the notion that MBD adoption has begun and models are fully capable of replacing drawings in engineering processes.

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