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PROMOTING MODEL-BASED DEFINITION TO ESTABLISH A COMPLETE PRODUCT DEFINITION

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ABSTRACT

The manufacturing industry is evolving and starting to use 3D models as the central knowledge artifact for product data and product definition, or what is known as Model-based Definition (MBD). The Model-based Enterprise (MBE) uses MBD as a way to transition away from using traditional paper-based drawings and documentation. As MBD grows in popularity, it is imperative to understand what information is needed in the transition from drawings to models so that models represent all the relevant information needed for processes to continue efficiently. Finding this information can help define what data is common amongst different models in different stages of the lifecycle, which could help establish a Common Information Model. The Common Information Model is a source that contains common information from domain specific elements amongst different aspects of the lifecycle. To help establish this Common Information Model, information about how models are used in industry within different workflows needs to be understood. To retrieve this information, a survey mechanism was administered to industry professionals from various sectors. Based on the results of the survey a Common Information Model could not be established. However, the results gave great insight that will help in further investigation of the Common Information Model.

INTRODUCTION

Model-based definition (MBD) is a strategy for moving from two-dimensional (2D) paper-based drawings to three-dimensional (3D) computer-aided design (CAD) models where the model will contain all the information so that one day drawings may no longer be needed. However, in today's modeling environment, drawings are still used [1]. With advances such as better time-to-market, efficiency, and improved product quality, MBD has gained substantial popularity within the aerospace and defense industry [2]. However, a good majority of companies are not yet convinced on the idea of moving to an environment with no drawings [1].

While MBD has been gaining popularity, several questions remain regarding the full definition of MBD. Standards such as ASME Y14.41 [3] and ISO 16792 [4] exist to document how a model should be defined with annotations. These standards also help in understanding how to interpret the data within the model. However, the standards do not document the required amount of information that the model must contain [5]. It is important to understand what information needs to be communicated when considering moving from drawings to 3D-CAD models so the engineers can continue to do their jobs efficiently.

In today's industry, it is common that several disciplines and enterprises collaborate and share resources to complete various tasks. Elements that describe this type of scenario include entities and connections between the entities. The entities include applications, persons, and enterprises, whereas the connections between these entities include data exchange and collaborations. Product models are crucial in achieving this interoperability within the network of entities [6]. It is important to organize the information that is relevant to the user inspecting or working with the model so that they do not have to sift through layers of unnecessary data [7,8]. Designers from different disciplines usually work on the same models, which can distract them when they interact with design details that are unnecessary to them. Finding a common ground between different design disciplines can provide several benefits including protecting sensitive information, enabling collaborative supply chains, and facilitating multi-disciplinary design [9].

This paper is focused on finding the information that is common among different aspects of the product's lifecycle. Design, manufacturing, and quality is the main focus of this paper. Maintenance, sustainment, and decommission will be addressed in future work. Ultimately, all phases of the product's lifecycle will be reviewed – leading to a Common Information Model. Establishing an understanding for what all information needs to be in a 3D-CAD model so it represents and communicates the same level of information as a 2D drawing is key in formalizing the Common Information Model and the main reason why this paper focuses on the early phases of the product's lifecycle.

LITERATURE REVIEW

A review of relevant academic literature has been composed to further investigate MBD and the information that needs to go into a 3D model to relay all the necessary information a drawing traditionally carries as well as how ontologies can be integrated to help product data. A review of frameworks and workflows has also been conducted.

Model-based Definition

MBD is the strategy of moving away from drawings and other means of product definition and moving to 3D-CAD models. This would establish the 3D-CAD model the only source for defining the product and its geometry. Adamski [10, p. 40] talks about the evolution of how MBD came to be:

> "In the past, 2D-drawing sheets with geometric dimensions and tolerances were used to define a part. Next, 3D models with 2D drawings, projection, geometrical dimensions, tolerances were used … So, model based definition includes one system file, model 3D geometry, GD&T [geometric dimensioning and tolerancing] data with notes and comments such as base coordinate system, dimensions, tolerances, flag notes and technical comments concerning material, surface smoothness, weight and general notes. Model-based definition is a process that allows the design team to input all their information into the 3D model, thus eliminating the need to create a drawing."

Traditional drawings have been used in industry to communicate design because they are easy to understand. The engineering drawing's main purpose is to carry and maintain product definition in a way that no assumptions or misinterpretations can be made. However, CAD software's development over the past decades has helped with the production of engineering drawings. Product development within CAD systems has become the standard and engineering drawings are no longer used as the primary product-definition source [1].

MBD is not widely utilized yet within industry [10,11]; however, it is gaining popularity in engineering and manufacturing environments due to a wealth of benefits [2]. The benefits of MBD include reduction in manually reproduced data, reduced errors in design, better communication, quicker response times, fewer files to maintain, and reductions in cost [10,11].

Domain Ontologies

Anderson and Vasilakis [12, p. 11] define an ontology as "a rigorous conceptual model of a specific domain." These conceptual models have several contexts including "advanced information retrieval, knowledge sharing, web agents, natural language processing, and simulation and modeling." Ontologies can either be domain specific or general. Domain specific ontologies model information used in a specific setting, while a general ontology serves several domain-specific ontologies [12].

Anderson and Vasilakis [12, p. 14] take their definition of an ontology further by stating:

> "An ontology embodies some sort of world view with respect to the given domain. The world view is often conceived as a set of terms (e.g. entities, attributes, and processes), their definitions and inter-relationships; terms denote important concepts (classes of objects) in the domain. This is referred to as conceptualization. Recording such a conceptualization with an ontology is referred to as ontology development."

The benefits to ontologies are they share a common understanding of information in knowledge domains, and they can improve interoperability within applications that use domain knowledge. Ontologies make assumptions explicit so applying changes is easier as assumptions evolve, and they enable re-use of domain knowledge, which means the ontology can be used by multiple applications [12]. Ontologies help bridge the gap of data interoperability between different software systems and assist the communication between software systems during a product's lifecycle. Ontologies can be used with standard file formats to allow various data types to be contained with a product, which can help convey design intent. Using ontologies with standard file formats is also good for long term archival [13].

Frameworks

A framework is created to help support a product throughout all phases of the product's lifecycle. The framework is to help information flow and be obtained through the different phases of the lifecycle. Frameworks for PLM have been deployed to help integrate business and technical information systems. They also allow partners to collaborate effectively when creating products. According to Srinivasan [14, p. 464] these frameworks:

> "Allow engineering and business objects and processes to be built or composed as modular pieces of software in the form of services that can communicate with each

> other and be used across different parts of a business. These modular software pieces can be reused and reconfigured in new ways as business conditions change, thereby saving time and money for companies."

When used in a PLM system, a framework is "intended to capture product, design rationale, assembly, and tolerance information from the earliest conceptual design stage…to the full lifecycle" [15, p. 1399]. According to Sudarsan et al. [15, p. 1402], the National Institute of Standards and Technology (NIST) information modeling framework has the following attributes:

> "It is based on formal semantics, and will be supported by an appropriate ontology to permit automated reasoning; it is generic; it deals with conceptual entities such as artifacts and features, and not specific artifacts such as motors, pumps or gears; it is to serve as a repository of rich variety of information about products, including aspects of product description that are not currently incorporated; it is intended to foster the development of novel applications and processes that were not feasible in less information-rich environments; it incorporates the explicit representation of design rationale, considered to be as important as the product description itself; and there are provisions for converting and/or interfacing the generic representation schemes with a production-level interoperability framework."

The NIST information modeling framework's implementation will provide a repository of all product data and information from every stage of the design process. The framework will serve all product description data to the PLM system using a single information exchange protocol, and "support direct interoperability among CAD, CAE, CAM and other interrelated systems where high bandwidth, seamless information interchange is needed," [15, p. 1399].

The NIST information modeling framework contains four components. These components are the Core Product Model (CPM), the Open Assembly Model (OAM), the Design-analysis Integration Model (DAIM), and the Product Family Evolution Model (PFEM). The CPM establishes a base-level, generic product model. It is capable of capturing the entire context commonly shared in development. According to Sudarsan et al. [15, p. 1404-1407], the OAM establishes "a standard representation for exchange protocol for assembly and system-level tolerance information." The DAIM is "a conceptual data architecture that provides the technical basis for tighter design-analysis integration than is possible with today's tools and information models." Lastly, the PFEM "represents the evolution of product families and the rationale of the changes involved."

Workflows

Understanding how information flows throughout a company and through different processes is crucial knowledge. Workflows are an important technology. There are a vast amount of tools that support workflow design. Having a good workflow can help share data efficiently. Good workflows can also help workers find where data was created and understand how the "original source of data was used [16, p. 537]."

A primitive science of workflow designs contains workflow orchestration, workflows, and workflow instances. According to Deelman et al. [16, p. 528], "workflow orchestration refers to the activity of defining the sequence of tasks needed to manage a business or computational science or engineering process." A workflow is a template for the workflow orchestration and a workflow instance refers to the specific workflow of a problem, which includes the definition of input data. In a science and engineering environment, these terms have a broader meaning and can be spread out into four areas. These four broad areas are composition, mapping, execution, and provenance. Composition, representation, and data model refer to the composition of the workflow using means such as text, graphics, etc. Mapping is defined as "mapping from the workflow to underlying resources [16, p. 529]." Execution is the "enactment of the mapped workflow on the underlying resources [16, p. 529]." Metadata and provenance refers to "the recording of metadata and provenance information during the various stages of the workflow lifecycle [16, p. 529]."

Common Information Model

A Common Information Model represents details that are relevant in different versions of models including design, manufacturing, and quality models. Within these models used in different workflows are domain specific elements. The Common Information Model will contain the information that is common amongst these different domain specific elements. To reach a Common Information Model, several sets of information will need to be understood. In an MBD environment, the model is the main knowledge artifact for product definition – what information a MBD needs to provide must be known. Also, in certain circumstances, different disciplines in industry will use the same model, but require different perspectives or contexts of the model. Breaking the data up across different platforms can be a challenge, but beneficial to the users. Bouikni et al. [7, p. 71] state "generating an appropriate view makes it possible to provide a favorable environment to the actors, where information is targeted in quantity and in contents to be adapted to the requirements of the task." To understand what information is common among different versions of models such as design, manufacturing, and quality, the information that goes into an MBD environment must be understood.

What Needs to Go In. Before attempting to establish a Common Information Model, it is important to understand what information needs to be in the 3D-CAD model to be able to communicate the same amount of information as a 2D drawing. Quintana et al. [1, p. 506] point out "significant time and effort is required to properly assess the drawings' replacement," meaning it will not be easy to determine what information needs to be contained within the 3D-CAD model.

GD&T Information. For models to convey all the information contained in drawings, they will need to contain a wide variety of data. MBD should consist of one central knowledge artifact containing 3D geometry with GD&T and functional tolerances and annotations (FT&A). GD&T and FT&A refer to the products dimensions, tolerances, and any other annotations that the model must contain to be correctly interpreted [10].

Relevant Information. Product Lifecycle Management (PLM) is imperative and its core aspects should be consistent for the designer to keep that designer focused on the information that is relevant for a particular phase. According to Bronsvoort and Noort [8, p. 929]:

> "A major goal of integral product development, which is an important aspect of product lifecycle management, is to allow the designer of any development phase to focus on the information that is relevant for that phase, without being diverted by information that is relevant for other phases only. On the other hand, the information for all phases should be integrated, so that no inconsistency can arise."

Basic Characteristics. Companies within industry have certain standards while working with CAD/CAM systems. These standards include layers arrangement, new projects naming and numbering rules, rules for creating drawings, rules for creating 3D-CAD models, rules of creating models of parts machined on computer numerical control (CNC) machines, notes, comments, tolerances, etc. MBD files must contain basic characteristics of the product. These characteristics that must be contained within the model are notes, base-coordinate systems, dimensions, tolerances, flag notes, technical comments regarding material, surface smoothness, weight and other general notes [10].

Information Assurance. Information assurance is critical within each step of a models process through PLM, and there are several information assurance issues in the context of collaborative design. Information assurance creates new problems that need to be addressed accordingly so there can be development of collaborative CAD systems. These issues include protecting sensitive information; enabling collaborative supply chains; facilitating multi-disciplinary design, role-based viewing, and security framework for collaborative CAD and role-based-view generation [9].

Security. Each process of PLM security is extremely important for any company. Certain technologies exist managing digital rights. Organizations such as NIST's Information Technology Laboratory and the World Intellectual Property Organization (WIPO) are creating standards within this area [9].

Standardization. Standardizing product meta-data is crucial for company collaboration and efficiency in production. Product meta-data includes information such as part number, bill-of-material, product-assembly structure, author, approver, supplies, version, and change history. Having this information standardized throughout engineering systems reaches out to other information systems. These systems include Enterprise Resource Planning (ERP), Manufacturing Execution Systems (MES), Customer Relationship Management (CRM), and Enterprise Asset Management (EAM), which leads to an increasing demand for standardization. Srinivasan [14, p. 465] clarifies on this increase:

> "One of the most striking developments in the past few years is the wide-spread acceptance of product meta-data as business objects and the enterprise-wide engineering processes as business processes. This metamorphism, as it were, is profound because it has propelled PLM as an information system of concern from essentially engineering organizations to a much wider business enterprise. This, in turn, has provided the impetus to standardize business objects, and languages for business process modeling and execution."

Singular Data File. A critical part within each process of a Common Information Model is keeping it a singular data file for downstream consumers, in which case can be easily distributed within other areas of other departments such as design, manufacturing and inspection. Briggs et al. [14, p. 11] state:

> "All the data required to define the product are currently captured and available to downstream consumers, such as manufacturing, although these data are actually captured and distributed in a single electronic source. One widely understood benefit of MBD is a significant reduction in manually reproduced data."

Transformation of Information. Aside from what information needs to go into the Common Information Model, another issue that must be addressed is if the model needs to be used in a different software package or if the model will ever need to be translated using a neutral file format. If this is the case, it is important to know what information needs to come out of the model after being translated as opposed to what information actually does come out in the resulting file. It is also important to know and understand what information gets lost in this translation.

METHODOLOGY

To help investigate the Common Information Model, a survey was conducted with industry professionals. This survey was sent out to a large number of industry professionals from multiple companies and locations around the world. This diverse group of industry members helped give a good look into how models are used throughout different industries. The survey helped understand how models are used in different industries and where industry members are when it comes to using models in the place of drawings.

The survey was comprised of a demographics section, which gave background information on from where the results are coming. Questions about how information is received, as well as in what format were asked, and also where models are used in processes. If the respondents to the survey did not use models, the survey ended. If the respondents did use models in their processes, more questions were asked to get a better understanding of how and where. An understanding of where the respondents' level of capability was with using 3D-CAD models in their processes is crucial information for this study. After this, we asked what types of inspections the respondents do in-house, as well as what tools they use. Along with this, respondents were asked what types of manufacturing processes they use. The respondents were asked to give impacts of different issues typically faced within a manufacturing environment. The last set of questions for respondents was on why they have not moved to an MBD environment and the risks involved.

The survey information was collected and observed using charts and graphs. The following section is a summary of the survey results. Conclusions about the survey have been made, as well as recommendations, and will be given after the survey summary.

SURVEY RESULTS

To get an understanding of how models are used within companies, the Promoting Model-based Definition survey was given to industry professionals and returned 37 responses. To give an understanding of the sample being used, some questions were asked regarding the size of their company and where they were located. The largest amount of respondents (38%) worked at a company with more than 500 employees. Most of the responders (86%) are located within the United States, with the majority (75%) being located in the Midwest. The primary role of the respondents within their companies varied greatly as seen in Figure 1. These answers were fairly diverse and ranged from sales, engineering/design, manufacturing/production, quality/inspection, management, as well as others, with the majority coming from engineering/design and management. The respondents who answered "other" possessed roles such as CEO, system analyst, owner, training, and consulting. This range of roles can help provide a diverse look into the questions within the survey.

The respondents were asked how they receive customer order information and were given the following options: drawings only, primarily drawings (with supplemental models), primary 3D-CAD models (with supplemental drawings), and 3D-CAD models only. There were 27 responses for this, and Figure 2 is a breakdown of the responses. Primary drawings with supplemental models was the highest at 44 percent. 3D-CAD models only received just over a quarter of the responses at 26 percent. And drawings only and primary 3D-CAD models with supplemental drawings received 15 percent of the responses each. This shows that drawings are still play a crucial role in the transfer of data with 74 percent of the responses using a drawing somehow. While 85 percent of the responses use 3D-CAD models in some fashion for carrying data, only 41 percent of the responses use the 3D-CAD model as the only or primary source of information.

FIGURE 1 - PRIMARY ROLES OF THE RESPONDENTS WITHIN THEIR COMPANY

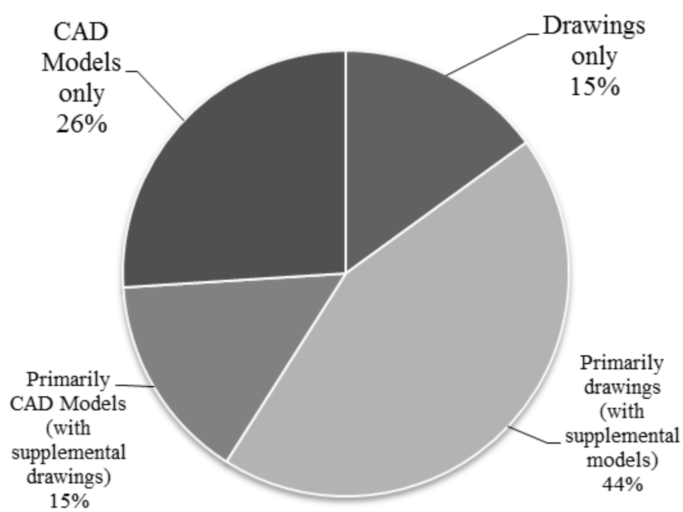

FIGURE 2 - BREAKDOWN OF HOW THE RESPONDENTS RECEIVE CUSTOMER INFORMATION

The next question asked to the respondents was whether or not they would be able to produce a part according to specification if given only a 3D-CAD model and no drawing, which received 25 responses. Figure 3 gives a breakdown of the responses, with only 4 percent of the respondents giving a definite "no". A solid 36 percent responded they could produce the part with no other conditions. The other 60 percent responded they could produce the part to specification; however they would need to interrogate the model manually for dimensional information, with 40 percent of the overall respondents needing to consult with the customer to gather manufacturing and inspection detail.

The respondents had a diverse use for models in their processes. The respondents were to select all the processes for which they use models. There were 26 responses, and most of the options presented to the respondents were selected with high quantities, almost evenly, with CMM/Inspection programs receiving the most selections. Only one respondent selected that they do not use models in their production inspection or processes. Figure 4 gives the distribution of the answers. The two votes for “other” were finite element analysis and design.

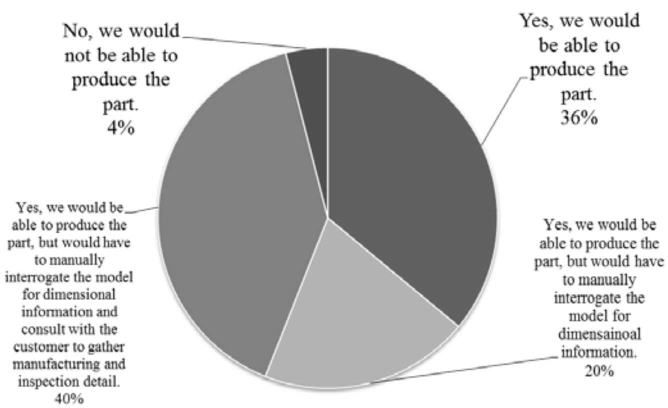

FIGURE 3 - BREAKDOWN OF WHETHER RESPONDENTS WOULD BE ABLE TO PRODUCE A PART TO SPEC GIVEN ONLY A CAD MODEL AND NO DRAWING

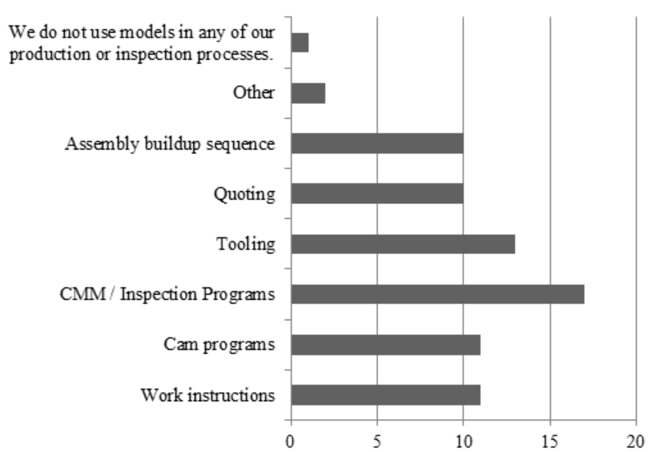

FIGURE 4 - WHERE THE MODELS ARE USED IN PROCESSES

After seeing where the respondents were using models, the respondents were asked in what formats they receive information for making parts and to select all formats that apply. There were 18 responses. Figure 5 shows the responses, with native 3D-CAD model (14) and STEP (11) receiving the most responses.

Knowing how the respondents received information, they were asked what format of information to make parts best suits for their process/needs. Figure 6 gives the distribution of these answers, which came from 18 of the respondents. The options given were native 3D-CAD model, 3D PDF (Portable Document Format), JT (Jupiter Tessellation), STEP (Standard for the Exchange of Product model data), IGES (Initial Graphics Exchange Specification), 2D PDF, DXF (Data Exchange Format), and other. Native 3D-CAD model received the highest selection at 56 percent. The next highest was STEP with 22 percent. 3D PDF, IGES, 2D PDF, and DXF all received 6 percent and there were no selections for JT.

The next question in the survey was regarding what types of inspections were done in house. Again, there were 18 responses. The options were first article inspection (FAI), receiving, in-process, and final. All options received several selections, with FAI, in-process, and receiving getting the most, as seen in Figure 7.

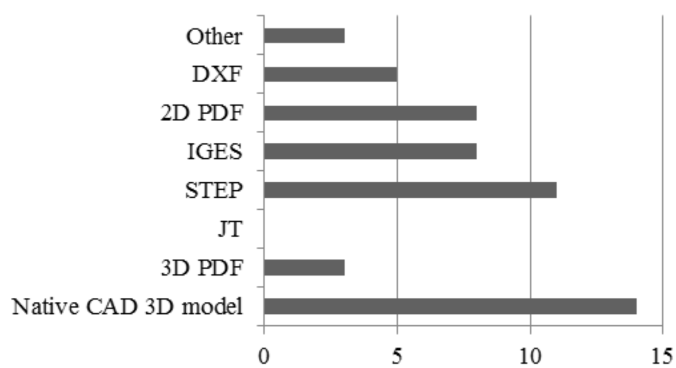

FIGURE 5 - WHAT FORMAT INFORMATION IS RECEIVED IN

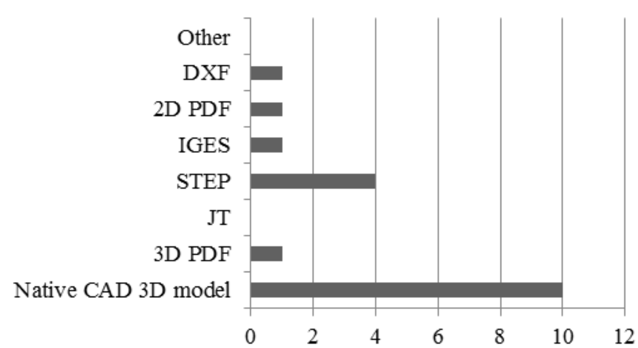

FIGURE 6 - FORMATS OF INFORMATION TO MAKE PARTS BEST SUIT THE PROCESS/NEEDS

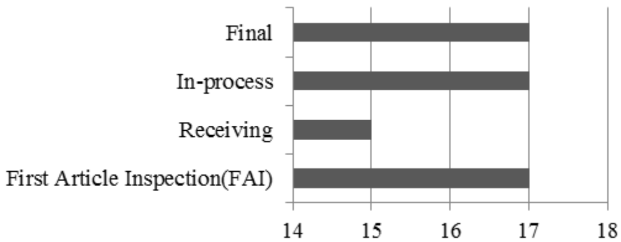

FIGURE 7 - WHAT TYPES OF INSPECTIONS ARE DONE IN-HOUSE

Knowing what types of inspections the respondents do in-house, they were asked what inspection equipment they currently use. All 18 responded, however none of the respondents selected that their inspections were outsourced. The highest selected options, in order, were visual, non-CMM gauges, and CMMs with 3D-CAD models only. The lowest two options receiving votes were CMMs with drawings only and scanning, as seen in Figure 8.

The next question in the survey asked the respondent to rate the level of impact of issues on their business from 1-4, 1 being not an issue and 4 being a serious issue. In between were minor issue (2) and moderate issue (3). Figure 9 shows the mean frequency of the impact of the issues. Below are the issues given to the respondent (1-19) to rate. In Figure 9, these issues are represented by the number associated with them. There were 18 responses to this question.

1. Performing inspection is a bottleneck
2. Performing off line programming for inspection is time consuming
3. Receiving multiple files and/or media formats for as single product
4. 3D-CAD models and associated drawings don't agree
5. 3D-CAD model derivations/translations are problematic
6. Verifying CMM programs is time consuming.
7. 3D-CAD model is not available from customer.
8. Communication with customer is difficult and/or not timely.
9. New designs have producibility issues.
10. Time/volume of report requirements is overwhelming.
11. There are limited design feedback opportunities from supplier to OEM.
12. There is too much variation in production scheduling from OEMs.
13. Data such as 3D-CAD models, drawings, and specifications from customer are not always up to date.
14. Unable to change manufacturing processes due to certification regulations or customer policies.
15. Certification process is sometimes difficult.
16. Obtaining capital is challenging.
17. Ability to hire and retain qualified/skilled workers is problematic.
18. It is expensive to implement Model-based Manufacturing.
19. Help from local, state, and the federal government is either nonexistent or hard to identify.

According to the chart in Figure 9, the issues that impacted companies the greatest (mean above 2.7) were the ability to hire and retain qualified/skilled workers (3.17), performing inspection is a bottleneck (2.89), 3D-CAD models and associated drawings don't agree (2.89), and new designs have producibility issues (2.72). Several issues still had a mean over 2.6 including obtaining capital is a challenge (2.67), it is expensive to implement Model-based Manufacturing (2.67), verifying CMM programs is time-consuming (2.61), data such as 3D-CAD models, drawings, and specifications from customer are not always up to date (2.61). The issues with the lowest impact based on mean were 3D-CAD model derivations/translations are problematic (2.33) and unable to change manufacturing processes due to certification regulations or customer policies (2.33).

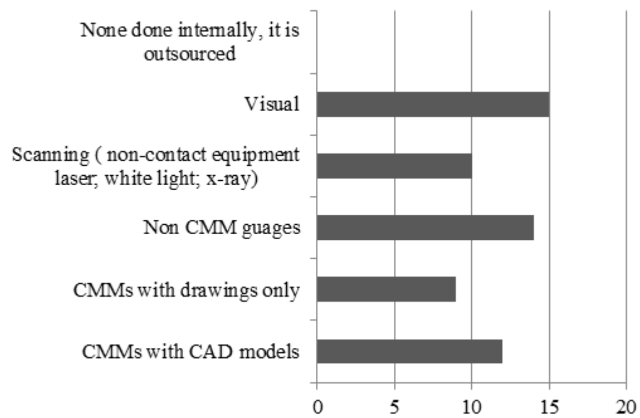

FIGURE 8 - INSPECTION EQUIPMENT USED IN-HOUSE

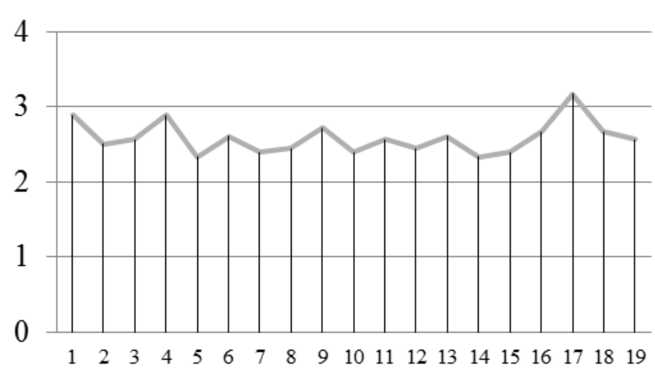

FIGURE 9 - MEAN FREQUENCY OF IMPACT OF ISSUES

Respondents were then asked their current level of capability with using 3D-CAD models as input to their CAM and CMM processes and given three options. The answers they had to choose from were:

- Highly proficient; only minor difficulties
- Somewhat proficient; internal deficiencies still exist
- Currently using drawings and manual input, but have no desire to move to model-based manufacturing

Only one of the respondents claimed they used drawings and had no desire to move to model-based manufacturing. Eleven of the 18 respondents selected somewhat proficient, and six selected highly proficient.

The survey then asked the respondents to select all their manufacturing processes, with only 17 respondents opting to answer. Figure 10 gives a distribution of the selections. Traditional material removal such as cutting, turning, milling, and drilling received every vote, with assembly being the second highest selection.

To wrap up the survey, the respondents were asked what they perceived was the biggest risk for adoption of the Model-based Manufacturing approach as manufacturing and inspection technologies increasingly rely on 3D-digital data. Eighteen respondents were given seven options including other, and capital investment is too large was biggest risk at 28 percent. Figure 11 gives a breakdown of the responses. The responses for other were interoperability.

This breakdown helps give insight into why some companies are not interested yet in moving to MBD. Legacy designs (22%) is almost always an issue because drawings have been used as the main source of information and moving all that data to models can be time consuming and costly. Of the respondents, 22% said there was a lack of business pull, which appears to be that companies do not necessarily see the potential benefits of MBD just yet.

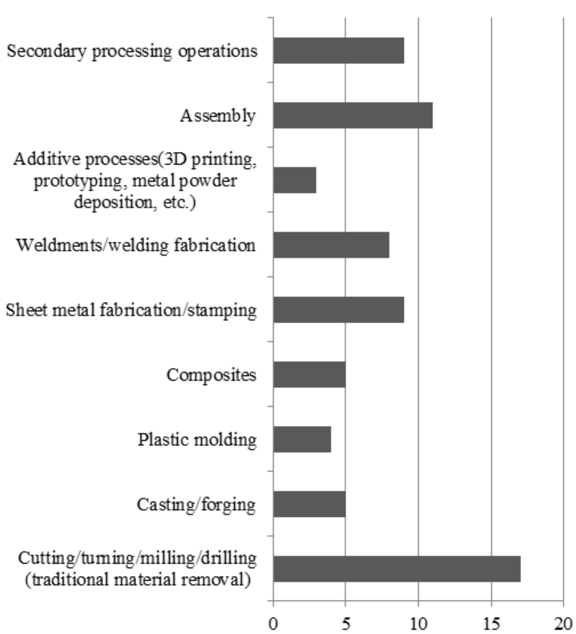

FIGURE 10 - MANUFACTURING PROCESSES USED

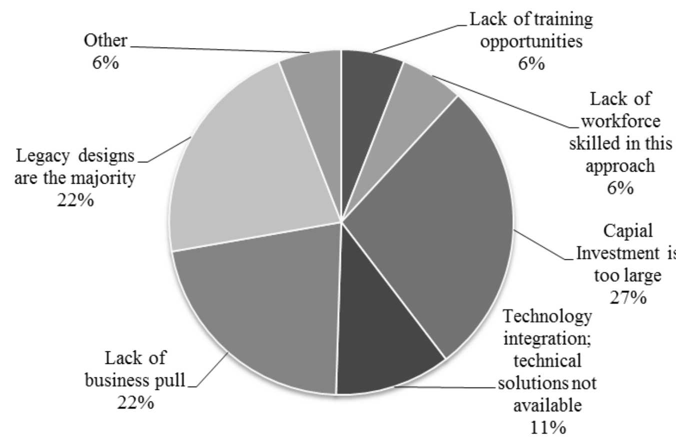

FIGURE 11 - BREAKDOWN OF THE BIGGEST RISKS OF THE ADOPTION OF THE MODEL-BASED MANUFACTURING APPROACH

DISCUSSION AND CONCLUSION

The survey helped give insight to current standing in industry. A fairly wide range of affiliations were represented as well as job positions. A Common Information Model cannot yet be fully defined from these surveys, but critical information has been identified. This information will be used to develop plans for replacement of drawings with 3D-CAD models. These surveys developed the capability of industry's readiness to use models as the master definition and the potential inhibitors of their use.

This paper has supported the need to establish a Common Information Model. A Common Information Model contains the information that is the same from domain specific elements among different aspects of the product's lifecycle. A review of literature was conducted and a survey was analyzed to help give a greater understanding of what information needs to be addressed in the Common Information Model, and where industry stands in terms of implementing MBD. The following are the key results upon which we drew our conclusions:

- A majority of the survey respondents are potentially accepting of the idea of MBD
- Most of the survey respondents already use 3D-CAD models as a source of product data
- Most of the survey respondents still utilize 2D drawings (along with their 3D-CAD models)
- The survey respondents have skepticism and concern about eliminating 2D drawings
- The survey respondents identified several risks when moving from drawings to 3D-CAD models

From our observations of the survey results, we conclude (1) the Common Information Model would need to be workflow specific and (2) more information is needed to establish a Common Information Model for the early phases of the product's lifecycle.

The conclusions from the survey seem to contradict each other; however, they are consistent with what was concluded from the literature review. Industry may be accepting of the idea of MBD, and most already utilize 3D-CAD models for product data, although most still use 2D drawings along with their 3D-CAD models. From these results, it can be concluded industry only accepts the idea of MBD as long as 2D drawings are still used because skepticism remains in completely getting rid of 2D drawings.

While research, such as Hedberg et al. [17], shows MBD can be a major benefit to companies, the survey shows that many industry members have legitimate concerns for only using 3D-CAD models. For example, there are times when using 2D drawings would be easier or make more sense to a company, such as on a shop floor where the company does not have the infrastructure to support 3D-CAD technology. Many respondents felt there was too big of a risk in moving solely to 3D-CAD models from 2D drawings.

While the survey provides evidence that industry is potentially accepting of the idea of MBD and may support the fact that 3D-CAD models can be used as the main source of product data in a production environment, it cannot yet be concluded what information needs to go in to the Common Information Model. The survey helped lay a foundation of knowledge, but more research needs to be done to help understand what specific information goes into the models in the different aspects of the lifecycle.

As of right now, it is difficult to conclude what information is common amongst different models. Based on the results of the surveys, a proposed Common Information Model would need to be workflow specific because of the varying degrees of information in the different workflows. A general Common Information Model would lack enough information to be beneficial to a company's processes.

To establish a Common Information Model, more specific information regarding the workflows is needed. Also, a clearer definition of "common" and "domain specific" will have to be established. A proposed solution would be to have a follow up survey that lists the different elements from this survey and has the respondents "rank" each of them from 1-10, 1 being common and 10 being domain specific. This could help shed light on how the members of industry see the different elements from the lifecycle, which would help further establish the Common Information Model.

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REFERENCES

[1] Quintana, V., Rivest, L., Pellerin, R., Venne, F., & Kheddouci, F., 2010, "Will Model-based Definition Replace Engineering Drawings throughout the Product Lifecycle? A Global Perspective from Aerospace Industry," Computers in Industry, **61**(5), pp. 497-508.

[2] Huang, R., Zhang, S., Bai, X., & Xu, C., 2014, "Multi-level Structuralized model-based definition model based on machining features for manufacturing reuse of mechanical parts," The International Journal of Advanced Manufacturing Technology, **75**(5-8), pp. 1035-1048.

[3] ASME Y14.41-2012, 2012, *Digital Product Definition Data Practices*, The American Society of Mechanical Engineers, New York.

[4] ISO 16792, 2006, *Technical Product Documentation–Digital Product Definition Data Practices*, International Organization for Standardization, Geneva, Switzerland.

[5] Camba, J. D., & Contero, M., 2015, "Assessing the Impact of Geometric Design Intent Annotations on Parametric Model Alteration Activities," Computers in Industry, **71**, pp. 35-45.

[6] Fiorentini, X., Rachuri, S., Suh, H., Lee, J., & Sriram, R. D., 2010, "An Analysis of Description Logic Augmented With Domain Rules for the Development of Product Models," Journal of Computing and Information Science in Engineering, **10**(2), Paper No. 021008.

[7] Bouikni, N., Rivest, L., & Desrochers, A., 2008, "A Multiple Views Management System for Concurrent Engineering and PLM," Concurrent Engineering, **16**(1), pp. 61-72.

[8] Bronsvoort, W. F., & Noort, A., 2004, "Multiple-view Feature Modelling for Integral Product Development," Computer-Aided Design, **36**(10), pp. 929-946.

[9] Cera, C. D., Kim, T., Han, J., & Regli, W. C., 2004, "Role-based Viewing Envelopes for Information Protection in

Collaborative Modeling," Computer-Aided Design, **36**(9), pp. 873-886.

[10] Adamski, W., 2010, "Adjustment and Implementation of CAD/CAM Systems Being Used in Polish Aviation Industry," Journal of Machine Engineering, **10**(3), pp. 37-47.

[11] Briggs, C., Brown, G., Siebenaler, D., Faoro, J., & Rowe, S., 2010, "Model Based Definition," AIAA Paper No. 3138.

[12] Andersen, O. A., & Vasilakis, G., 2007, "Building an Ontology of CAD Model Information," *Geometric Modelling, Numerical Simulation, and Optimization*, Springer Berlin Heidelberg, New York, pp. 11-40, Chap. 1.

[13] McKenzie-Veal, D., Hartman, N. W., & Springer, J., 2010, "Implementing Ontology-based Information Sharing in Product Lifecycle Management," 65th Midyear Meeting Proceedings.

[14] Srinivasan, V., 2011, "An Integration Framework for Product Lifecycle Management," Computer-Aided Design, **43**(5), pp. 464-478.

[15] Sudarsan, R., Fenves, S. J., Sriram, R. D., & Wang, F., 2005, "A Product Information Modeling Framework for Product Lifecycle Management," Computer-Aided Design, **37**(13), pp. 1399-1411.

[16] Deelman, E., Gannon, D., Shields, M., & Taylor, I., 2009, "Workflows and e-Science: An Overview of Workflow System Features and Capabilities," Future Generation Computer Systems, **25**(5), pp. 528-540.

[17] Hedberg Jr, T. D., Lubell, J., Fischer, L., Maggiano, L., & Barnard Feeney, A., 2016, "Testing the Digital Thread in Support of Model-Based Manufacturing and Inspection," Journal of Computing and Information Science in Engineering, **16**(2), pp. 1-10. doi:10.1115/1.4032697