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Identified research directions for using manufacturing knowledge earlier in the product lifecycle

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(*Original submission January 5, 2016. Revised May 16, 2016.*)

Design for Manufacturing (DFM), especially the use of manufacturing knowledge to support design decisions, has received attention in the academic domain. However, industry practice has not been studied enough to provide solutions that are mature for industry. The current state of the art for DFM is often rule-based functionality within Computer-Aided Design (CAD) systems that enforce specific design requirements. That rule-based functionality may or may not dynamically affect geometry definition. And, if rule-based functionality exists in the CAD system, it is typically a customization on a case-by-case basis. Manufacturing knowledge is a phrase with vast meanings, which may include knowledge on the effects of material properties decisions, machine and process capabilities, or understanding the unintended consequences of design decisions on manufacturing. One of the DFM questions to answer is how can manufacturing knowledge, depending on its definition, be used earlier in the product lifecycle to enable a more collaborative development environment? This paper will discuss the results of a workshop on manufacturing knowledge that highlights several research questions needing more study. This paper proposes recommendations for investigating the relationship of manufacturing knowledge with shape, behavior, and context characteristics of product to produce a better understanding of what knowledge is most important. In addition, the proposal includes recommendations for investigating the system-level barriers to reusing manufacturing knowledge and how model-based manufacturing may ease the burden of knowledge sharing. Lastly, the proposal addresses the direction of future research for holistic solutions of using manufacturing knowledge earlier in the product lifecycle.

Keywords: knowledge management; multi-criteria decision making; design for manufacturing; collaborative engineering; model-based manufacturing

1. Introduction

The engineering organization possesses the majority of cost influence on the product lifecycle while the majority of the actual product cost is distributed across supply chain (Dencovski et al. 2010). The Defense Acquisition University (Defense Acquisition University 2011) claims 60% to 80% of the product lifecycle cost is in the acquisition, operation, and support of the product. These claims highlight the importance for engineering to understand and provide the information needed across the product lifecycle. Engineering organizations (e.g., design offices) must have a certain level of manufacturing knowledge to support making effective design decisions and communicate the required information to the supply chain. Design for manufacturing (DFM) and especially the use of manufacturing knowledge to support design decisions has received attention in the research community (Hague, Mansour, and Saleh 2004; Cochrane et al. 2009; Garbie 2013; da Silva et al.

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2014), but a lack of attention amoung solution providers has limited the availability of industry-mature solutions.

Therefore, the question remains, how can manufacturing knowledge be used earlier in the product lifecycle to enable a more collaborative development environment to produce better designs? While previous research (Alizon, Shooter, and Simpson 2006; Guerra-Zubiaga and Young 2008; Young et al. 2005, 2007) identified possible solutions for using manufacturing knowledge for decision support, the solutions focused solely on technology issues (i.e., ontologies and models) and do not address the system-level issues (i.e., human factors and organization culture). Recent advances in technology may help overcome some of the system-level issues with the use of Model-Based Manufacturing (MBM), which is gaining adoption within industry.

MBM is part of the larger model-based enterprise (MBE) concept. MBE is an organization and/or an operation that uses model-based definitions (MBD) for the purpose of commissioning, operating, servicing, and decommissioning a product. The American Society of Mechanical Engineers (ASME) defines the MBD as an annotated model and its associated data elements that define the product in a manner that can be used effectively without a drawing graphic sheet (American Society of Mechanical Engineers 2016).

The MBM part of the MBE repurposes and reuses the MBD to manufacture the product. The results of a study comparing model-based processes to drawing-based process shows that MBM potentially reduces cycle-time and may provide significant advantages for industry (Hedberg Jr et al. 2016). The MBM process utilizes seamless, digital communication between the design and manufacturing functions of the product lifecycle. Increasing adoption of MBM, and the larger MBE concept, requires the availability of manufacturing knowledge earlier in the lifecycle so the MBD contains data needed for manufacturing and the rest of the product lifecycle.

This paper will first provide a brief background into the cultivation and reuse of knowledge throughout the product lifecycle. Then, in Section 3, this paper will discuss the results of a workshop on MBM that helped identify open research questions. Section 4 proposes research directions for investigating the relationship of manufacturing knowledge to shape, behavior, and context characteristics of MBD to produce a better understanding of what knowledge is most useful and why that knowledge is useful to enable MBM. Lastly, Section 5 addresses the potential future for MBM, which would include holistic solutions that could dynamically use manufacturing knowledge earlier in the product lifecycle.

2. Background

The engineering drawing has stood the test of time. The first use of illustrations and drawings for technical purposes dates back to the Egyptians in 2500 BC. Pythagoras, Ptolemy, da Vinci, Descartes, and scores of inventors, continued various technical uses of drawings over the years (Booker 1963). Today, the engineering drawing, in the form of two-dimensional (2D) illustrations, is a tool used without question. In most cases, it is the legal document for communicating engineering requirements. However, the transportation-manufacturing industries (i.e., aerospace, automotive, shipbuilding) are starting to challenge the relevance of the drawing. In fact, these industries are proposing an increased use of three-dimensional (3D) models as the medium to communicate engineering requirements (Camba et al. 2014; Whittenburg 2012).

These 3D models contain all of the information included in the drawings, but that information is communicated in digital form. Shannon introduced the idea of information-based entropy in 1948 as a way to model digital information loss (Shannon 1948). In fact, Shannon's (1948) theory may be considered as the optimal rate of compression applied to a signal without losing any of the information being carried by the signal (Rezakhanlou and Villani 2008). In engineering, Rezakhanlou and Villani's (2008) description relates to the compression of the original product information to the interpretation of the design intent from a 2D drawing. That is to say, the amount

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of information that must be communicated has surpassed the loss-less compression capabilities of the 2D drawing.

Over the past several decades, the number of components in a product has increased. Product definitions are reaching new levels of complexity that are difficult to capture and interpret correctly using only traditional 2D definition drawings. Therefore, designs are beginning to reach an absolute limit of complexity. However, Shannon's (1948) theory only helps with half of the problem by helping ensure no data is lost. But Shannon (1948) doesn't provide a solution for dealing with the additional interpretation challenges introduced with the increased complexity. Industry is investigating how to use 3D models as the predominant mode of defining the product-design definition to help overcome the challenges from increased complexity. The hope is a 3D model will allow more interpretable information to be stored without the level of compression needed to store the same information in a 2D drawing. This would enable both increased accuracy and precision in the interpretation of product data.

The industrial shift from 2D drawings to 3D models also enables adding both behavior and context of the product to product definition, which are primarily shape definitions today. The first step in extending the product model is to include product and manufacturing information, known colloquially as PMI in industry. 3D model annotations are the main enhancements that PMI brings to the 3D model. Alducin-Quintero et al. (2012) conducted a study with Spanish and Mexican CAD students. The study showed using PMI helps reduce the time to perform engineering changes in existing models by between 13% to 26% (Alducin-Quintero et al. 2012). However, the goal of including PMI is not to benefit only the design / engineering organizations. The real benefit of including PMI in 3D models is the ability to reuse, repurpose, and trace the 3D models throughout the entire product lifecycle.

Camba et al's (2014) study showed statistically significant improvement in work performance. The study included 60 participants who used an annotation manager linked to the product definition contained in a 3D model. This suggests that the use of an enhanced product definition is a valuable approach to improving design-intent communication. 20 years ago, industry latched on to the concept of DFM to help clarify the communication through knowledge management and commercially available DFM tools (e.g., DFMPro (Geometric 2015), Calibre DFM (Mentor Graphics 2015), DFA / DFM (Boothroyd Dewhurst Inc 2016)) aided in the adoption of DFM.

The current state of the art for DFM utilizes rules within computer-aided design (CAD) systems that enforce specific design requirements. Those rules may or may not dynamically affect geometry creation. If the functionality to implement DFM rules exists in a CAD system, the implementations are customizations typically on a case-by-case basis. Intelligent-modeling environments that dynamically change the options a CAD user has at his disposal are starting to gain use in industry, but the environment is still rules based. In addition, engineering organizations may use external software advisers (i.e., third-party CAD plug-ins) for designing to specific production processes (e.g., molding, casting, machining). However, the external tools are used mostly as bolt-on exercises at the end of the design process. Not integrating these tools into the design process forces back-and-forth action between the CAD environment and the advising environment. Overall, the current options available to industry return to the CAD model for the manifestation of the design requirements.

To help the model evolution, Chang, Rai, and Terpenny (2010) provides a method for using ontologies to capture knowledge within the manufacturing domain. Ontologies, in general, support structuring information to simplify the processing of that information. But knowledge capture in ontologies, from an information science context, is ineffective for real-time manufacturing processing because much of the supply chain still relies on humans to process information. Humans gain little value from the creation of ontologies without a supporting computing system to support the information processing. While, MBM is gaining adoption within industry, the majority of the data included in models is still defined for human consumption. A computer-accessible representation of the product is paramount to the success of leveraging manufacturing knowledge in the product

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definition.

CAD systems contain some ability to apply manufacturing knowledge to shape data, such as, defining a "hole" with a hole function in a 3D model instead of executing a Boolean remove of a cylinder from a solid. While both options provide the same shape aspect, using the hole feature relays to manufacturing that the shape aspect is to behave like a hole. Relaying that behavioral information enables manufacturing to use software applications to directly reuse 3D models without a human needing to re-enter information. Neutral 3D formats, like STEP AP 242 defined in ISO 10303-242:2014 (International Standards Organization 2014), also define machining form features, which would allow contextual manufacturing information from a proprietary CAD format to support data exchange. However, the question remains, why isn't manufacturing knowledge being used more pervasively earlier in the product lifecycle?

Technical and systemic challenges of reusing data directly from engineering in the supply chain need to be understood to ensure design organizations meet manufacturing-data requirements. Resolving the challenge would enable further adoption of model-based practices. But more research is needed to answer the questions for leveraging manufacturing knowledge.

3. MBM Workshop – identifying research needs

We participated in a workshop at a PDES, Inc.[1] meeting. The workshop included attendees from industry, academia, and U.S. government organizations. The industry participants included domain experts from both the design and manufacturing domains. However, several industry participants have operations roles within their respective companies and they are charged with setting policy for collaborative engineering activities. These industry participants were of particular interest because they have the practical expertise to speak to the barriers of integrating design and manufacturing knowledge.

The objective of the workshop was to elicit ideas for increasing the use of MBE methods, processes, and tools to significantly enhance the use of manufacturing knowledge earlier in the lifecycle. The participants were asked to address three questions:

- How can manufacturing input be included as part of early system trade studies?
- How do manufacturing requirements, constraints, and decisions affect upstream processes (e.g., system trades, functional and physical allocation, and design)?
- How do manufacturing requirements, constraints, and decisions affect downstream processes (e.g., sustainment, support, and maintenance, repair, & overhaul (MRO))?

The workshop participants discussed using manufacturing knowledge earlier in the product lifecycle. The discussion on DFM processes explored how early in the product lifecycle manufacturing knowledge can be used to support design decisions. The workshop participants also pursued how the design process might integrate effective consideration of both production-process capability and characterizing machining and manufacturing processes.

During the workshop, participants reviewed state-of-the-art and emerging capabilities currently under development. The workshop participants identified existing solutions and tools that partially address technology needs of industry, but they also identified additional technical and social barriers that impede earlier lifecycle use of manufacturing knowledge. The workshop participants agreed on the following observations:

(1) Rules-based manufacturing analysis focuses typically on shape, but industry must also consider in what context is the product to be used and how is the product expected to behave (i.e., function).

[1] http://www.pdesinc.org

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(2) Information for design intent (why versus how) should be captured and transferred across the lifecycle.
(3) Models across the digital thread need to provide both machine interpretable (e.g., shape, PMI) and human interpretable (e.g., text, visualization) information.
(4) Current solutions use file-based interoperability, while industry needs could be served better through relationship-based interoperability.
(5) Industry creates custom tools when tools do not meet needs or tools do not exist.
(6) Significant time and resources are required to ensure technology environment configurations are in-sync and interoperable across multiple entities (organizations).
(7) Standards are based on domain-specific concepts, are not always interoperable, and may compete with each other.
(8) The need exists for information standards that derive requirements to facilitate upstream and downstream flow in the product lifecycle – data-format standards are not enough to accomplish the information flow.
(9) Industry needs are served best from a dynamically updated enterprise knowledge-base.
(10) There is a desire to leverage virtual-model capabilities, including both manufacturability and assembly of the product, to assess DFx (e.g., producibility, assembly, testability, maintainability) earlier in the product lifecycle.

4. Proposed Research Directions

On the surface, barriers identified during the workshop appear simply as technology barriers. However, closer examination reveals a social aspect to each barrier. Therefore, each barrier is considered a socio-technical[2] barrier.

For example, barrier (7) has both technological and social challenges that must be resolved to ensure a successful solution. A technological challenge is ensuring the data models defined by standards are interoperable with both vendor-specific and vendor-neutral data models to support the exchange of data. However, a conflicting social challenge is that functions of the product lifecycle (e.g., Design, Manufacturing, Quality, Sustainment) are 'siloed' and the functions often have limited support for cross-functional interoperability. The following subsections propose three research directions to address the socio-technical barriers observed during the workshop.

4.1 *Dynamic Knowledge-bases*

Socio-technical aspects raise the question, how do we overcome barriers when the solutions to technological and social challenges are conflicting? Moreover, how do we overcome social (e.g., organizational, functional, human factors) barriers, which could be harder to solve than the technological barriers? Observing the workshop output suggests further research is needed to find solutions to these questions before industry can be more effective and efficient in using manufacturing knowledge earlier in the lifecycle. Generating knowledge-bases dynamically in near-real time would address barriers: (3), (4), (6), (8), (9), (10). This, of course, is easier said than done.

Generating knowledge-bases dynamically requires linking data from several sources across the product lifecycle. Then, data-driven techniques (e.g., machine learning) could be applied to automate the knowledge building to generate updates in batches based on new data and information generated since the previous knowledge-base update. Today, knowledge-bases are typically large binders of paper with plain language requirements for various (e.g., design, manufacturing, quality) process. The requirements take into account previous experience of the authors, but information may be missed or excluded if the authors do not know about other information available from the

[2]Socio-technical refers to the interaction between human behaviors and infrastructure.

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product lifecycle. In addition, a page in these binders of paper can take at best months and at worst years to update because of the complexity of achieving expert consensus. Some requirements may be convertible into rules that could drive a DFM tool. Using data-driven techniques would accelerate the update and generation process of the knowledge-bases and could even dynamically generate DFM rules.

Research is currently underway at the National Institute of Standards and Technology (NIST) into how data could be linked together to support dynamic knowledge management (Hedberg Jr 2016). This research is using the engineering-change-request (ECR) process as a use case. The goal is to dynamically generate knowledge on a product by linking engineering, manufacturing, and quality systems and then identify opportunities for design changes that would enable more efficient and effective manufacturing of the product.

4.2 *Minimum Information Requirements*

Another observation is that context and behavior of a product are not captured in models that determine manufacturing processes. Yet, it is paramount to consider a variety of manufacturing approaches during early lifecycle studies to trade-off context and behavior. Each phase and function in the product lifecycle adresses a specific viewpoint for observing data and information (Regli et al. 2016). Knowing this, answering the question of what is the minimum information required by the product lifecycle to complete one lifecycle loop would begin to address barriers: (1), (2), (3), (7). In addition, context and behavior information could be better integrated with shape information.

The fuel nozzle in the new GE LEAP engine (GE Aviation 2013) is a good example of examining behavior and context for a part design relative to the manufacturing process. GE Aviation chose additive-manufacturing processes over traditional-manufacturing processes to produce an improved part that is able to achieve desired engine-fuel efficiency through optimized size and weight constraints. This shift in processes supported achieving the total-cost-of-ownership target for the program. But, how did this new manufacturing process become part of the trade studies? Industry would benefit from knowing how understanding context and behavior of the part was included in the product-definition data and incorporated into the overall trade studies. Combining shape, context, and behavior information in the product definition enables effective decision making in a MBE.

Therefore, what is needed in MBE for a model to contain context (the viewpoint) and behavior (the why) and how can the information be shared effectively (the interoperability) across the product lifecycle? In the example above, how could the knowledge of additive-manufacturing process be shared via MBE with the behavior and context models of the early trade studies and impact the definition of the design model? That is, how do we know what the minimum information required for the manufacturing workflow and who should be authoring that information. In this discussion, *behavior* refers to the materials characteristics, influence of physics, effects of external mating parts, and the more traditional structural, thermal, and fluid dynamics domains that are often involved in the analysis stages of a product. However, parts and products are not made and used in a vacuum – there are interacting and mating parts in a larger product structure, and most products operate in a given context of fairly well-understood parameters. *Context* information in the MBD includes elements such as the part's interaction with a machine tool, spatial interaction within the larger assembly model, or in-situ data captured during product operation and analyzed afterwards. Context provides perspective to the data for a specific viewpoint. Behavioral and contextual information are crucial in influencing the outcome of the shape definition, and the shape definition is useful in communicating behavioral, and contextual information for the human in the lifecycle.

Work has begun in addressing minimum information requirements (Hedberg Jr et al. 2016; Trainer et al. 2016; Reumler et al. 2016). Hedberg Jr et al. (2016) compared model-based processes

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against drawing-based processes. The study showed a significant reduction in both manufacturing and quality cycle-time. The study conducted by Hedberg Jr et al. (2016) could assist with the social issues of converting product-lifecycle processes from drawing-based to model-based. However, the project identified several technical issues with data interoperability. Trainer et al. (2016) identified technical gaps in using model-based processes. Trainer et al. (2016) was able to complete design, fabrication, and inspection using standards-based neutral formats. The study also provided recommendations for closing technical gaps and began a discussion on minimum information requirements. Lastly, Reumler et al. (2016) have started down the path of gathering industry stakeholder needs for the information contained within a MBD. Purdue University is using the results from Reumler et al. (2016) to develop a Delphi study to further understanding of industry's "complete" information needs based on the several contextual viewpoints that exist. The overlap in those information-needs viewpoints would be considered the minimum information of the product lifecycle.

4.3 *Interoperability Support*

MBE could be a significant enabler to DFM and the re-purposing and reuse of information. But manufacturers and industry, as a whole, must feel confident in their ability to deploy MBE practices successfully. Increasing pressure by industry executives to reduce cycle-time leaves manufacturing practitioners with little room for failure. The "digital thread" (Hedberg Jr et al. 2016) helps create support and industry "buy-in" for MBE. The digital thread is a concept that describes the data flows between engineering, manufacturing, business processes, and across supply chains (Barnard Feeney, Frechette, and Srinivasan 2015). From a manufacturing viewpoint, the digital thread is a way for different machines in a manufacturing process to all follow the same set of digital instructions; deviations are caught automatically, which ensures end product is the same as the original design The digital thread would support solutions for overcoming the socio-technical barriers to using manufacturing knowledge for design support. However, data formats and information models are not interoperable across the entire product lifecycle. More scientific pilot projects with releasable data are needed to further gain industry confidence in MBE and address barriers (4), (5), (6), (7), (8).

There are several open research questions such pilots should answer. One is, how is information captured effectively and made available for designers to evaluate DFx opportunities (e.g., manufacturability, producibility, sustainability, and other "ilities") earlier in the design cycle? We expect this to be a difficult question to answer because capturing the information happens in various non-standardized ways throughout industry. Enterprises have developed proprietary data capture processes, which they treat as trade secrets and competitive advantage. In addition, answering the question requires understanding how purely technological and socio-technical concerns interact.

Another research question is how does an organization discover knowledge and then put it into a model-based environment in a useful way? This relates to the need for the dynamic knowledge-bases discussed in Section 4.1. Moreover, can the digital thread enable manufacturing to become part of the system trade studies (discussed in Section 4.2) – instead of being an optimization exercise after the system trades have been decided? Answering this question would reveal the value in moving beyond interoperable models (e.g., file-based threads) and into transformable model-based parameters (e.g., information-based threads).

The MBE strategy must ensure model-based-data interoperability between design activities (e.g., product and assembly design) and manufacturing activities (e.g., fabrication, assembly, and quality assurance). STEP AP 242 defined by ISO 10303-242:2014 (International Standards Organization 2014), MTConnect (MTConnect Institute 2014), and Quality Information Framework (QIF) (Dimensional Metrology Standards Consortium 2014) are three emerging standards that show promise for enabling interoperability throughout the product lifecycle. Helu and Hedberg Jr (2015) pro-

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poses a cyber-physical systems test bed for integrating the various product-lifecycle systems that exist today. This test bed aims to link design, manufacturing, and quality data together for the purposes of decision support, requirements management, and control methods.

STEP AP 242 represents the "as-designed" configuration of products defined in the cyber-space. MTConnect and QIF represent the "as-fabricated" and "as-measured," combined into the "as-manufactured," configuration of products realized in the physical world. Effectively observing the relationship of the configurations would enable the ability to generate robust designs for the complete lifecycle, not just one domain process (e.g., manufacturing, quality, maintenance). These robust designs would be less sensitive to the dynamic nature of product lifecycle because data from across the product lifecycle would be linked, knowledge would be generated, and then decisions and requirements could be effectively managed. Further, control methodologies could be applied to the whole product lifecycle because knowledge would be gathered to understand how decisions propagate through the product lifecycle, thus providing diagnosis and prognosis opportunities for managing the product lifecycle.

5. The Future of Manufacturing in a Model-Based Enterprise

Industry needs guidance in using MBM. Industry has been fabricating parts using 3D models for last few decades thanks, in part, to the rise of computer-based numerically controlled machines. However, the goal of MBE, which encompasses MBM, is to tightly integrate design, manufacturing, and the entire product lifecycle all around a single product model – the MBD.

Information technology advances (e.g., data analytics, service-oriented architectures, and networking) have triggered a digital revolution (Wu et al. 2015) that when coupled with operational technology (e.g., hardware and software for sensing, monitoring, and control of product and processes) holds promise of reducing costs, improving productivity, and increasing output quality. Modern manufacturing enterprises are both more globally distributed and digital, resulting in increasingly complex manufacturing system networks (Wu et al. 2013; Xu 2012). Manufacturers are under mounting pressure to perform digital manufacturing more efficiently and effectively within these distributed manufacturing systems. To do so, industry is changing from paper to models for communicating product definitions.

The transitioning to MBE is industry's solution to the mounting pressures. MBE has introduced new requirements on data usage in manufacturing systems. MBE calls for each phase and function of the product lifecycle to adopt model-based-data standards to effectively integrate data for efficient reuse and exchange between product-lifecycle phases. The need for automated methods to collect, transmit, analyze, and act on the most appropriate data is gaining attention in the literature Energetics Inc. (2015); Gao et al. (2015); Helu and Hedberg Jr (2015); Li, Gao, and Wang (2006).

Also, as model-based definitions become more refined in their representation of the physical world, machine tools must increase their capability to consume the more intelligent model. The manner in which this is accomplished remains to be seen, but a standards-based approach may present the best option for success. Short of embedding geometry-modeling kernels into machine controllers, modern machine tools need to be able to consume a MBD authored in different environments. True topological and behavioral feature recognition, material characterization, real-time metrology capability, and contextual process monitoring are required to support multiple environments.

Coupled with a more complete product definition and more intelligent machine tools is the need to create a digital link between the product definition, production, and *in-situ* use of the product. Current 3D-modeling technology provides an ability to define the basic, ideal shape of the as-designed object. First-article inspection and modern scanning technology provide the ability to capture the as-manufactured part. Comparing those two digital definitions is simply the next logical step in the evolution of metrology. As continuity is solidified between the as-designed and as-

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manufactured states of the digital representations, industry then needs to look towards capturing digital representation of the "as-used" state of the object. Once all three levels of detail have been gathered, comparisons can be made, and higher degrees of fidelity can be achieved, between the digital representation defined in the cyber-space and the physical object.

However, what is often missing is the shape depiction of the object once it has been in use. Given the portability of current scanning and points-processing technologies, products could be scanned, and a 3D representation captured, of the as-used condition during normal maintenance or overhaul procedures. And while none of the three aforementioned scenarios is novel or groundbreaking in itself, it is the act of collecting this information consistently over time and linking it together that would significantly impact manufacturing in a model-based enterprise. As those digital representations are gathered, variations in key dimensions can be analyzed and tracked, providing a distribution of data available for use as the basis in predictive modeling to inform future design scenarios.

6. Conclusions

Overall, the workshop discussed in this paper highlighted both technology and social barriers to using manufacturing knowledge earlier in the product lifecycle. In fact, the barriers at the intersection of technology and human behavior could present the most challenging aspects to overcome. We've shown the ability to use manufacturing knowledge earlier in the lifecycle has garnered attention from academia and industry. But the results of the workshop show more work is needed to bring efficient and effective solutions into practice. While the technological challenges are being studied, the social barriers to using manufacturing knowledge earlier must receive equal attention. Pursuing answers to the open research questions presented earlier would enable industry's realization of a model-based enterprise.

It appears an emerging goal for many industry and academic constituents is the creation (or completion) of a more holistic, model-based, product definition. There is discussion in standards communities (e.g., ASME Y14 (American Society of Mechanical Engineers 2012), ISO TC 10 (International Standards Organization 2015)) currently regarding what it means to produce a model-based product definition; but in most cases this tends to imply the use of 3D-CAD models with complete PMI annotations in lieu of 2D-technical drawings in specific workflows. And while simply acting as a substitute for drawings is one application of MBD, this substitution approach leaves much to be desired. Rich information could be supplied by a model to support spatial relationships, human-visualization, and machine intelligence. OEMs and suppliers need new, more salient ways to communicate in a synchronous, parallel fashion. Moreover, they need to be able to perform that communication with a product definition artifact and a process that does not leave anyone out based on the nuances of their job role

Historically, technical drawings were information-rich artifacts that carried more than just views of the object and dimensional information. However, to understand the information on the drawings presented as a combination of text and symbols, the information needed to be used or interpreted within its proper context. Engineering specifications, material notes, assembly instructions and much more had no meaning to the casual observer without the benefit of context. Yet, technical drawings providing the most value would have this level of information (and possibly more) by default. The challenge industry faces today is CAD models lack information richness when compared relatively to historical drawings. Most companies do not bother to embed the high levels of information in CAD models beyond shape definition. Behavioral and contextual product information should become routine additions to all model-based product definitions.

Finally, in MBM, and the larger MBE, the design community would use information to better select tolerances and dimensional information in future product iterations. The procurement or supplier-management community would use information to better select and evaluate supply-

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chain production capacity and capability. In addition, production personnel will learn to engage with others in the product lifecycle via a different communications mechanism – an annotated-3D model rather than a paper-red-lined-2D drawing. The role of the human operators would change, as they move from what were predominantly consumers of design information to more a balanced role of consumers and authors (e.g., producers/consumers) of information. A question that remains is how would job roles (e.g., design, manufacturing, quality) across the product lifecycle change as information becomes more integrated and connected? Would job roles also become more integrated? These are two questions that could be answered in future studies. Nonetheless, the dynamic communications process we described would enable more timely communication, more accurate decision-making, and (hopefully) increased product quality and longevity.

Acknowledgement

We wish to thank PDES, Inc. and its membership for the support and time dedicated to the workshop. We also wish to thank Allison Barnard Feeney, Albert Jones, Vijay Srinivasan, and the peer-reviewers for their review and comments.

Disclosure

The work presented in this paper is an official contribution of the National Institute of Standards and Technology (NIST) and not subject to copyright in the United States. Certain commercial systems may be identified in this paper. Such identification does not imply recommendation or endorsement by NIST. Nor does it imply that the products identified are necessarily the best available for the purpose.

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