Model Based Enterprise for Manufacturing

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Abstract
A Model-based Enterprise (MBE) is an organization that applies modeling and simulation technologies to integrate and manage its technical and business processes related to production and product lifecycle support. By using product and process models to define, execute, control, and manage all enterprise processes, and by applying science-based simulation and analysis tools to optimize processes at every step of the product life-cycle, it will be possible to substantially reduce the time and cost of product development and delivery. This paper presents an architecture for model-based enterprise focusing on manufacturing. Key infrastructure enablers for MBE and examples of MBE implementations are discussed.

Keywords
Model-based enterprise, manufacturing, product data

1 INTRODUCTION

A Model-based Enterprise (MBE) is an organization that applies modeling and simulation technologies to integrate and manage all of its technical and business processes related to production, support, and product retirement. By using product and process models to define, execute, control, and manage all enterprise processes, and by applying science-based simulation and analysis tools to optimize processes at every step of the product life-cycle, it will be possible to substantially reduce the time and cost of product innovation, development, production, and support [1]. The core MBE tenet is that data is created once and directly reused by all data consumers. A typical MBE architecture is shown in Figure 1.

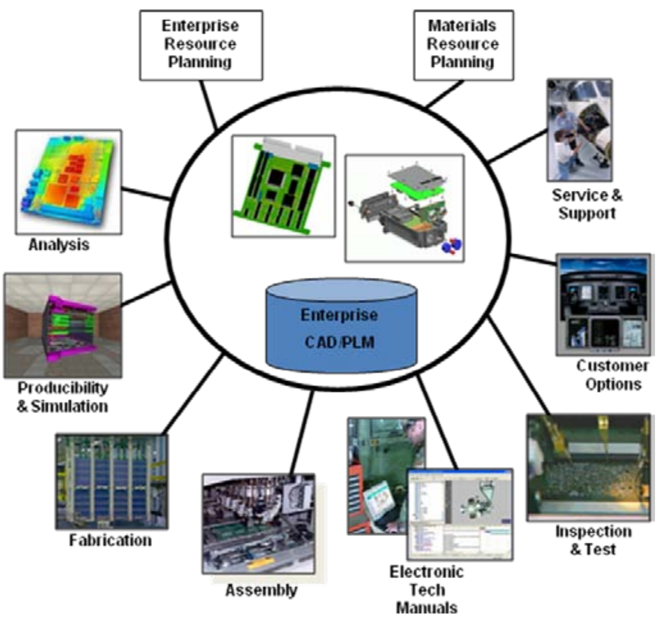

Figure 1 MBE Architecture

In order to clearly define a model-based enterprise, it is important to understand that there are many different types of models utilized in enterprise processes and that models are used to perform many different functions in the enterprise environment. The relationships between enterprise functions and how different models are used in enterprise processes is critical to the successful implementation of a model-based enterprise.

1.1 What is a Model?

A model is an approximation, representation, or idealization of selected aspects of the structure, behavior, operation, or other characteristics of a real-world process, concept, or system. It serves as an abstraction for its real world counterpart. A model is used to convey design information, simulate real world behavior, or specify a process. In the context of manufacturing, a model is a digital artifact created for use in one or more manufacturing software applications. A model will have different views in order to support different functions. Each view is a representation of the system from the perspective of that function [2]. The following definitions of models are relevant in the context of MBE.

- A model is a representation of a product. This is the most common usage of the term model in the context of a manufacturing enterprise. A product model is a digital representation of all attributes of a product that enable its manufacture, use, and support.
- A model is a representation of a process. In manufacturing and construction processes, a model is used to simulate a process. A process model is a mathematical description of a physical activity.
- A model is an integration enabler. An information model can enable data transfer among engineering and business systems. A product model, for example, can provide the design information that enables downstream processes.
- A model is a predictor of behavior. A behavior model, such as a weather forecasting model, can be used to predict system behavior given a model of the system and a set of input and boundary conditions. A behavior model enables the exploration of input options and quantification of expected results for each option.

1.2 Business Meets Engineering

Model-based business practices are critical to the model-based enterprise. The enterprise's business systems and processes must also be able to utilize model data. Business processes, such as Enterprise Resource Planning (ERP), should be able to extract needed information from product and process models. As an example, the materials planning component of the ERP system would draw from the product Manufacturing Bill Of Materials (MBOM) what materials and consumables need to be ordered, and when, to support production processes. Production engineering, resource allocation, finance, and other enterprise systems would interact with the product model based on their own models, rules, and data in order to optimize operations. In the ideal enterprise, all business processes are integrated, using models to share and act on requirements, knowledge, and resource information. Figure 2 shows functions and data object flow in a model-based enterprise.

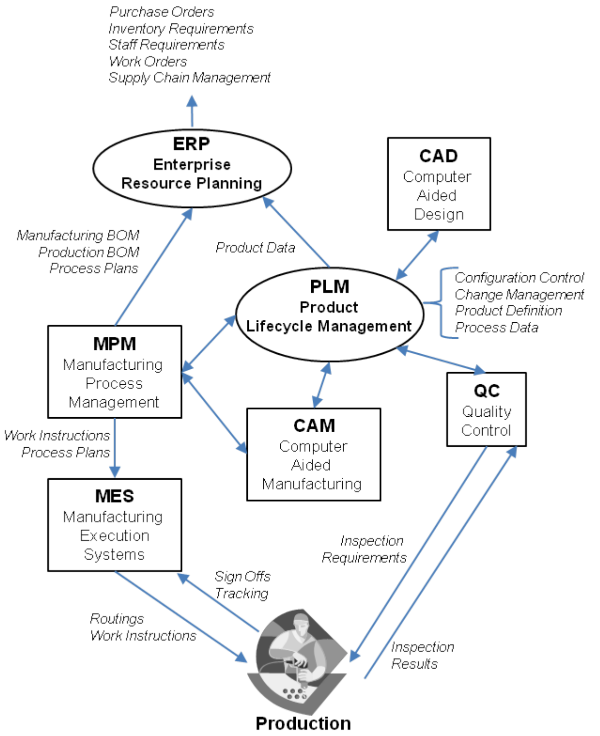

Figure 2. MBE Functions and Data Flow

1.3 PLM versus ERP

Enterprise Resource Planning (ERP) and Product Lifecycle Management (PLM) are the two fundamental enterprise application classes in a model-based enterprise. Each enterprise system must control its own data and not duplicate the functions of or interfere with other systems. PLM is the process by which manufacturing companies develop, describe, manage, and communicate information about their products from initial concept to end of life [3]. The ERP system is used to manage resources for production. While the ERP system utilizes product data and process plans contained in the PLM system, the architectures of ERP and PLM are fundamentally different.

The ERP architecture is transaction-based and organized around production resources. The PLM architecture is object-oriented and structured around product, product relationships, and configuration management functions. Successful (and seamless) integration of ERP and PLM is potentially the biggest barrier to model-based enterprise implementation.

2 WHY MBE?

2.1 Global Competition

US industry is facing significant challenges – competition from globalization, a decline in long-term technology investment, and an increase in the cost of doing business [4]. US manufacturing has declined as a percentage of gross domestic product (GDP) from 30% of the GDP to 12% [5]. Even with the current decline, manufacturing still represents one of the best sources of long term wealth generation for the US economy [6].

Innovation in product development and process technologies will help accelerate the generation of new, innovative products to the marketplace. The US manufacturing sector must take advantage of advanced manufacturing processes, such as model-based enterprise to drive productivity improvements, which will reduce production costs and increase competitiveness. Through improved processes, US manufacturers can transition to “high value” manufacturing and compete on a basis of productivity and excellence as opposed to low-cost labor sources.

Technology and the supporting infrastructure are the engines of economic growth. Enterprise technologies that support globally competitive manufacturing and model-based enterprise concepts can only provide point solutions without wider coordination. Industry leaders agree that realization of the model-based enterprise could potentially cut costs by 50% and reduce time to market by 45% [7]. Realizing these benefits will require substantial investment and coordination. The manufacturing infrastructure and technology tools (infratechnologies) in use today will not support US manufacturers in future global competition [8]. No single company or organization can supply the next-generation tools and especially the supporting technology infrastructure. This requires a commitment to and support from both the private sector and government.

2.2 Increasing System Complexity

Complex systems are everywhere. They are becoming the norm, not the exception. The continued evolution of complex, intelligent, global systems exceeds the ability of the humans who design them to comprehend and control all aspects of the systems being created. Problems with advanced cyber-physical systems such as regenerative automotive braking systems and advanced software control systems as on the Mars Pathfinder [9] are recent examples of unexpected behavior attributed to complex system interactions. Existing engineering processes are not able to handle the complexity of such systems. As models are becoming the driver, the role of modeling in systems engineering must mature to respond to this need.

Systems engineering processes and methods are generally practiced in an ad hoc manner and not integrated into the overall design and engineering processes. Systems engineering tools support various modeling techniques, such as functional analysis and object-oriented analysis, but only partially support model and data interchange. In short, systems engineers are facing the interoperability problems that have been successfully addressed through standards in the product modeling domain. The International Council on Systems Engineering *Systems Engineering Vision 2020* [10] identified both the lack of interoperability and the absence of convergent model-based systems engineering (MBSE) standards as significant impediments to the adoption of new model-based technologies.

3 INDUSTRY PRIORITIES

The US Department of Defense (DoD) and the National Institute of Standards and Technology (NIST) held a Model-based Enterprise and Technical Data Package (MBE/TDP) Workshop in December, 2009. The Workshop gathered over 75 subject matter experts from industry and government to make recommendations for changes to how DoD and its suppliers process technical data. These changes are needed to support a DoD transition to total lifecycle management based on digital models rather than 2D drawings. Most of the lifetime cost of a system is incurred during the maintenance, support, and refit portion of the system's lifecycle. In many cases, replacement components must be reverse engineered because the original data is not accessible or not usable. The cost of reverse engineering system components is potentially an order of magnitude more than the cost of producing components directly from the original model-based data.

The MBE/TDP Workshop report [11] identified the top critical issues affecting adoption of model-based technical data packages:

- Requirements and standards for completely annotated product models
- Standards to define requirements for 3D model product manufacturing information (PMI)
- Long term product data retention requirements
- Technical data quality validation processes

INCOSE's *Systems Engineering Vision 2020* [10] puts forward a path for moving from the document-centric approach that has been practiced by systems engineers in the past to a future where a model-based approach is fully integrated into the definition of systems engineering processes. The INCOSE MBSE Initiative developed a roadmap that identifies standards development as a critical area of effort for achieving the 2020 Vision.

The FIATECH Capital Projects Technology Roadmap [12] is a cooperative effort of associations, consortia, government agencies, and industry, working together to accelerate the deployment of emerging and new technologies that will revolutionize the capabilities of the capital projects industry. The vision of the future for the capital projects industry is of a highly automated project and facility management environment integrated across all phases of the facility lifecycle. Facility and equipment information is available on demand, wherever and whenever it is needed to all interested stakeholders. This integrated environment will enable all project partners and project functions to instantly and securely "plug together" their operations and systems. Interconnected, automated systems, processes, and equipment will drastically reduce the time and cost of planning, design, and construction. Priority information issues identified in the FIATECH roadmap are:

- Automated design processes
- Lifecycle data management & information integration
- Integrated, automated procurement and supply networks
- Real-time project and facility management, coordination and control

The Department of Commerce recently identified manufacturing as one of its high-priority goals [13]. NIST is working with industry to develop the standards and measurement infrastructure to support new manufacturing processes and technologies. Manufacturers have identified model-based enterprise as a critical component for cutting costs and improving competitiveness. Work needed to support an infrastructure for MBE will include developing, harmonizing, and validating standards; specifying and validating process models; and, prototyping new integration solutions. Standards development and interoperability are infrastructural investments that benefit all and for which no one enterprise can justify such significant investment.

4 MODEL-BASED PRODUCT DEVELOPMENT AND LIFECYCLE MANAGEMENT

Digital 3D models are replacing traditional paper drawings and blueprints because the digital models contain more information and can be reused by multiple applications. Digital information technology enables engineers and technicians in remote locations to access computer-aided design (CAD) models, diagrams, and engineering data critical for maintenance and repair of complex systems.

The same digital models can used directly to manufacture replacement parts faster and with fewer errors than with drawings. The use of CAD models instead of drawings can increase quality and substantially reduce the lead time for spare parts because suppliers do not have to manually re-enter product data into their manufacturing software applications, a time consuming and error prone process.

The 3D product data model is a collection of geometric objects, documents, and configuration information that forms a complete, integrated representation of the product. The central concept embodied in model-based definition is that the 3D product model is the most appropriate vehicle for delivery of all the detailed product information necessary for all aspects of the product delivery cycle. Any number of 3D views of the model can be composed, detailed, and annotated for specific downstream operations, such as manufacturing planning, production simulation, and materials procurement. Additional views of the model can be selectively annotated for other target operations, such as, quality assurance. A model with a sequence of prepared 3D views containing key dimensions, tolerances, annotations, and notes provides a supplier with a more complete communication of what must be produced. To the supplier, a 3D model is much preferred because it is possible to make additional (and completely accurate) measurements of the product that would have been impossible if only 2D drawings of the product were delivered.

4.1 Product Manufacturing Information

Product manufacturing information (PMI) conveys non-geometric attributes in computer-aided engineering and collaborative product development systems necessary for manufacturing product components or subsystems. PMI may include geometric dimensions and tolerances, 3D annotation, finish, and material specifications. Industry standards for defining PMI include American Society of Mechanical Engineers (ASME) Y14.41-2003 Digital Product Data Definition Practices and ISO 1101:2004 Geometrical Product Specifications. PMI annotation is usually created on the CAD model. This information can then be used by a number of down-stream processes. Some 3D modeling processes enable computer-aided manufacturing software to access PMI directly for numerical control (NC) machine tool programming. The PMI also may be used by tolerance analysis and coordinate-measuring machine (CMM) software.

4.2 Model-based Systems Engineering

Model-based systems engineering (MBSE) is the formalized application of modeling to support system requirements, design, analysis, and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases. Systems Engineering (SE) can be described the coordination of design decision-making across engineering disciplines throughout the product development, deployment, and disposal cycle. MBSE can also be viewed as a systematic way of “gluing things together;” it is about the interfaces.

Recent systems modeling standards are beginning to have a significant impact on the application and use of MBSE. The Object Management Group (OMG) Systems Modeling Language (SysML) is a general purpose graphical modeling language for specifying, designing, analyzing, and verifying complex systems that was adopted by the OMG in 2006 and is now widely implemented in MBSE support tools. SysML is part of a broader family of standards being developed by the Object Management Group that includes the XML Metadata Interchange (XMI). This standard provides a means to interchange modeling information between tools using the XML format. ISO 10303-233 Application Protocol Systems Engineering (AP233) is a data exchange standard designed to support the exchange of systems engineering data between the many and varied SE tools. Data from systems modeling tools is included in the scope of AP233; in fact, requirements for AP233 and SysML have been largely aligned. OMG and ISO have been working together and in cooperation with the INCOSE Model Driven Systems working group to align their specifications. Model and data interchange are essential to advancing the practice of MBSE to achieve the level of integration required among different modeling domains.

4.3 Model-based Product and Process Formalization

Product and process design has become increasingly complicated due to many additional factors that must be considered, and a wider range of collaborators involved. Designers are aware of many more stages of the product lifecycle, involving many new processes. They interact with a wide range of other designers, especially in sophisticated products and processes. This places a significant burden on designers to examine a larger set of alternative designs at varying levels of detail. They do not know about all the lifecycle stages at once, and usually no single design will optimize all criteria at all stages. They must develop many alternatives, from less to more detail, in consultation with many other engineers. Collaboration is often hampered by lack of uniform interpretation of product and process modeling languages and terminologies, leading to rework when discrepancies are discovered. Designers distributed geographically and organizationally in global economies worsen these problems [14].

5 DIGITAL MODEL CHALLENGES

3D models are used to drive product development and production processes. Engineering analysis, manufacturing process control, assembly instructions, technical manuals, and other downstream applications rely on the direct use of product models to streamline processes saving time and money.

The increased reliance on 3D product models, especially Computer Aided Engineering (CAE) models, has many advantages, but presents three significant problems when compared to 2D representations:

- Model quality – the quality of 3D model data is difficult to validate. Unseen errors can cause problems in manufacturing and other downstream applications that use the digital product data.
- Application interpretation – the view of the data may be changed by revisions to the software used to create the data (not so with drawings). This can present a problem even over the short term.
- Long-term data access – data may become irretrievable because the application used to create the data no longer exists or has changed so much that compatibility has been lost (in fact, many CAD systems have been merged or discontinued).

5.1 Model Quality

Many models contain hidden errors or have missing data. These data errors are not detected easily and can cause havoc in downstream applications. Bad models can result in inefficiency, cost overruns, and poor product quality.

Bad models can bring production processes to a halt. The corrupt model must be shipped back to the owner to be fixed; or in most cases, the downstream user is forced to reconstruct the model entirely. In addition to lost time and cost overruns, re-entering the model risks introducing errors or altering design intent. One industry study estimated that up to 70% of CAD models had errors or were not compliant with required standards. The same study showed that up to 22% of NC programming time was spent correcting model problems [15].

Model quality problems result from a variety of contributing factors that include operator errors, model development technique, CAD system errors, and data translation errors. Additionally, many designers do not fully understand the requirements of downstream applications. CAD designers have no efficient way to validate models against those requirements to identify potential problems.

Regardless of the reasons why they exist, the fact remains that if 3D model quality problems are not resolved, the models cannot be certified as the “master” reference. One solution is to implement model development standards and a model quality validation process. With such a process, designers can better identify and resolve these problems through a combination of improved modeling techniques and better error detection.

Model Quality Assurance

The increased reliance on 3D product models, especially CAD models, has many advantages, but presents several significant data validation challenges. The first and foremost is the sheer volume of data entities and relationships. Complex mechanical assemblies can consist of hundreds or thousands of intra-related data objects. A CAD file for a small part, such as a bracket, must be related to, for example, the bill of materials and the weight model for the entire assembly. MBE data validation must, by necessity, depart from the manual “checks” and lists used to validate drawings. Model data validation should be an automated or at least a semi-automated operation. Data requirements, standards, and deterministic metrics should be established by the certification authority. Model validity must be measurable.

Advanced data analysis and validation techniques make MBE data quality certification feasible. At least one automotive manufacturer requires its suppliers to certify their data prior to submission. This requires that sufficient metrics measurement tools can be specified. Several questions must be answered: What does it mean to have a certified model? What are the criteria? What are the figures of merit? What downstream applications are of most concern? What are their data requirements? Once a product model is certified, maintaining that certification over time is also an issue. There are currently no standard processes for validating that software application revisions maintain a consistent view of the approved (certified) data.

Validity is a measure of the attribute accuracy of the model. Each data attribute must have a defined domain and range. Validation is the process of determining if values are reasonable, complete, and logically consistent with respect to the intended use of the data. Validation will often consist of several steps, including logical checks, accuracy assessments, and error analysis. Model accuracy is usually measured against a known standard, whereas error analysis involves the evaluation of data with regard to measurement uncertainty, and includes source errors, user errors, and process errors.

5.2 Consistent Interpretation of Design Data

The increased reliance on digital product models presents a significant problem over time. Model data is stored digitally (as 1s and 0s). Model data stored in native format is intended to be read by the application that created it. Several years ago, the Navy noticed a problem when older CAD models were opened on newer versions of the CAD system used to create the model. Suddenly, the CAD models "did not look exactly like they did before," according to the head of the Aircraft Carrier Planning Yard Division at Norfolk Navy Shipyard. The changes were subtle, but significant enough to alert Navy engineers [16]. Similar problems with new software application revisions have been documented in other defense and commercial programs.

Engineering software applications are updated on average every 6 months with major new releases every 18 months to two years [17]. Newer versions of software applications are not always compatible with the previous ones. The revision of commercial software applications is not under the control of the user. There is no warning if the application changes the model when reading files created by a previous revision of the application. The user may have no idea that the data being viewed is different from the data view shown in a previous revision of the application. The key point is the DATA itself has not changed – the VIEW of the data has been changed (by the application). If the model is to be the master reference, then the applications must be certified to make sure the data being viewed is presented consistently with the way it was presented when the data was approved for use. This consistent view of the data must be persisted over time.

Until recently, digital archiving of engineering and manufacturing information meant converting hard copy drawings and microfiche to digital images and storing them in a database. Even modern 3D CAD models are archived by converting them to 2D drawings and saving the drawings as digital images. 2D digital image formats have advantages in terms of data viability over time when compared with native 3D CAD formats or even standards-based 3D formats; but, carry substantially less information than the original native 3D models.

5.3 Long Term Archiving of Model Data

Native models are easily accessible as long as the software applications that were used to create them are still available. When the Incline Cable Cars in Pittsburgh were refurbished by the Westinghouse Corporation in the 1990s, an old TRS80 computer was needed to run an analysis program used a decade earlier to perform repairs [18]. Not only must the data be archived, but the means to make sense of the data must be preserved as well. To assure access to native models for the long term, it may be necessary to archive the computer hardware, operating system, and application software used to create the model. In the case of data archived in a standard format, it is possible that only the data and meta-data definitions must be preserved.

The current version of an application is only the first technology in a series of technologies to be used to view the engineering data for the life of the product. Unless the original software application, operating system, and hardware are maintained for life of the system, the information content will have to be migrated through multiple generations of technologies over the life of the system. The content will have to be re-validated for consistency each time the data is moved to a new application or technology.

Pilot implementations of model-based enterprise have demonstrated reduced costs and faster product delivery, but have had difficulty dealing with digital-only records. Longer product lifecycles combined with digital-only records will require industry to create new and innovative methods to use and preserve MBE systems data.

The life cycles of many products and systems, especially building, transportation, and defense systems, are increasing as systems are refurbished and upgraded rather than replaced by new systems. The projected lifecycles of many systems (fifty years or more for aircraft, for example) are significantly longer than the expected lifetimes of the design and manufacturing software applications used to create the data.

Major activities that require access to data include maintaining systems in the field, creating design modifications, manufacturing replacement parts, refurbishing components, identifying functionally equivalent components, revising technical manuals, and recycling or disposing of worn out components safely. To achieve the goal of full lifecycle support, especially for long-lived systems, product data must be accessible even if the software used to create the data is no longer available.

Complex systems have huge amounts of associated data including design, analysis, testing, materials, manufacturing, technical manuals, etc. The data type and the probable future use of the data must be considered when selecting an archive format. Certain meta-data is critical to support indexing and search capabilities of the data repository. This is possibly the most important archiving function – if the data cannot be found, the format does not matter.

The number of formats available to represent engineering data is very large. The major classes are: proprietary native formats, standards-based neutral file format, and proprietary neutral file format. The selection of the product model data format is dependent on several variables. These include the type of data, the intended use of the data, the availability of translators, the projected duration of the program, and the maturity data definition specification. In general the longer the duration of the system, the more desirable formats are open, freely distributable standards.

If the data definition is stored with the data, it is reasonable to expect the data could be recovered even in the 50+ year time frame. To maintain constant access to the data, the data can be translated continuously as new applications are installed, but this is a very expensive and resource-intensive process. Many organizations choose to maintain the original application and computer platform. This method is effective, but the risk of equipment failure over time is high. Current data archiving methods include:

- Continuous migration of data in native format
- Original application and hardware preservation
- Standard formats, such as, ISO 10303, pdf, and standard image formats
- Widely supported proprietary formats

MBE data must be available for the entire product lifecycle. Data must be interpretable by applications that may be many generations separated from the applications that were used to create the data. To optimize data-archiving costs, data should be archived in accordance with how it will be used in the future.

6 MAKING MBE WORK

For a Model Based Enterprise to be successful, the model must (1) become the core database for collaboration among enterprise processes, (2) encompass a complete product definition, and (3) be completely application neutral.

The core MBE tenet is that information is created once and directly reused by all consumers. The model should be viewed as the *system of record* - the basis for configuration control. There are many examples of manufacturing enterprises that start with a 3D model, but capture design details on 2D drawings - creating a situation where the model may no longer represent the current configuration. This can be greatly exacerbated if the model is re-entered into a new system (re-mastered) by the manufacturing department or outside supplier. Configuration control is lost and changes made to the design for manufacturing are usually not fed back to the original design model.

Downstream process stakeholders should use the model to become involved in the product development cycle earlier. Manufacturing, costing, product support, and environmental impact functions are enabled by the model. Therefore, the model must contain more than just geometry. It must also contain manufacturing annotations, such as, GD&T, notes, and functional parameters that help communicate design intent. The model must represent a complete *technical data package*. It must contain or be associated with material data, process specifications, product support information, test and analysis data, and other documents.

The biggest barrier to utilizing model data effectively throughout the enterprise is moving model data between the various engineering and business applications that make up the enterprise. To the extent possible, model data should be maintained in a format that is independent of the current set of software applications used by the enterprise. The various functions of the enterprise are best served by being able to use best-available applications and not be locked into a particular vendor's set of applications because the model is in a proprietary (native) format. At a minimum, models should be archived and maintained in an open neutral format along with the native format.

7 SUMMARY

MBE has the potential to reduce the product development lifecycle and production costs dramatically. Multiple industry domains have identified model-centric integration of enterprise functions including engineering and business functions as high priority issues for improving production operations and reducing costs. Implementing MBE and a "digital-only" enterprise environment presents several significant challenges including model data quality, systems integration, and long term digital data preservation. Industry and government must work together to develop the standards infrastructure to support the evolution of the digital enterprise.

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