MECHANICAL MODEL CENTRIC DESIGN AT LOCKHEED MARTIN

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Abstract

Worldwide, the Aerospace Industry is reassessing the processes that generate, and the data that constitutes, mechanical product definition. Lockheed Martin Corporation (LMC) is no exception. This reassessment is being driven by a variety of factors in our business environment. Principal among these factors are efforts within our customer base toward more "network-centric" concepts of operations characterized by initiatives such as Simulation-Based Acquisition and Networked Systems-of-Systems Simulation. In LMC, this effort is known as Model Centric Design (MCD). This paper discusses the implementation of Model Centric Design within Mechanical Engineering from a corporate perspective. Current activities and pilots are highlighted. Business benefits and barriers are stressed.

1 Introduction

This paper will address the process development and implementation of MCD within Mechanical Engineering, from a LMC corporate perspective, stressing lessons learned as LMC reassesses its product definition process. As background, the role of EPI Program in LMC in the reassessment of the process will be described. The majority of the focus will be on lessons learned by individual businesses and programs – highlighting results of current activities and pilots. In addition, the presentation will spotlight implementation benefits and barriers at a local and corporate level.

2 Lockheed Martin Corporation

Lockheed Martin Corporation (LMC) is an advanced technology company, formed in March 1995, by the merger of Lockheed Corporation and Martin Marietta Corporation.

Headquartered in Bethesda, Maryland, LMC employs about 130,000 people worldwide principally engaged in the research, design, development, manufacture and integration of advanced technology systems, products, and services.

LMC is the largest provider of systems integration services, information technology (IT), and training to the U.S. Government. Nearly 80% of LMC’s our business is with the U.S. Department of Defense and other U.S. federal government agencies. The remaining portion of LMC's business is comprised of international government and some commercial sales of LMC’s products, services, and platforms. In 2003, the corporation reported sales of $31.8 billion, an order backlog of more than $75 billion, and free cash flow of $1.8 billion.

Lockheed Martin's operating units are organized into five broad business areas:

- Aeronautics develops aircraft, and performs aeronautical research.
- Electronic Systems provides maritime systems and sensors, missiles and fire control, training solutions, and systems/platform integration for Command and Control, Communications, Computers

and Intelligence (C4I) for a variety of customers.

- Integrated Systems and Solutions develops horizontally-integrated network-centric operations to address the growing needs of LMC's customers.
- Space Systems includes businesses engaged in space launch, commercial and, government satellites, and strategic and tactical missiles.
- Technology Services is comprised of businesses providing federal services, energy programs, government and commercial IT, and aeronautical/aerospace services lines.

To support this LMC business structure and its diverse product lines, a series of councils exist that serve to facilitate communication between personnel serving similar roles throughout the corporation. Perhaps the most extensive of these council structures is the Engineering Process Improvement (EPI) Program.

2.1 Engineering Process Improvement Program

The EPI Program began in mid-1989 within what was the Aerospace Division of General Electric (now a part of Lockheed Martin). The primary objective of the EPI Program is to continuously lower product development costs by improving engineering design productivity and reducing duplicated effort through propagating common bets practices.

In addition, EPI considerations include improving the quality of designs and associated deliverables, enhancing the ability of LMC to insert emerging technologies, and improving integration with other business functions organizationally interfacing with Engineering.

Organizationally, the EPI Program takes its direction from the participating operating units through the Technical Operations Management Council (TOMC). The TOMC is made up of senior executive engineering managers and is supported by a series of discipline-specific (Mechanical, Electrical, Engineering Project Management, Software, Systems) Subcouncils and interdisciplinary (Affordability, Commercial Technology Insertion, Design for Six Sigma, PWB/CCA, Supportability) Process Groups / Focus Teams.

Supporting the council structure is the EPI Center. The EPI Center provides program management and facilitation services for the EPI Program. It also supplies a number of dedicated technical resources to support the EPI engineering process, transfer engineering best practices, and facilitate computer-aided design tool implementation.

3 Reassessing Product Definition

Worldwide, the Aerospace Industry is reassessing the processes that generate, and the data that constitutes, mechanical product definition. LMC is no exception. This reassessment is being driven by a variety of factors in the business environment. Principal among these factors are efforts within our customer base toward more "network-centric" concepts of operations characterized by initiatives such as Simulation-Based Acquisition and Networked Systems-of-Systems Simulation. In LMC, this effort is being broadly addressed through an initiative known corporately as Model Centric Design (MCD).

The broad concepts of the Mechanical Subcouncil's MCD initiative are common across the engineering departments of LMC. We refer to “Model Centric” as a focus on requirement driven behavioral representations of our design intent that includes transformation of objects and data managed, information documented, performance and processes modeled.

3.1 Mechanical Model Centric Design

MCD can be depicted, in part, through the hypothetical spiral development process.

Throughout the product development life cycle, for each phase of the spiral, generalized representations of product behavior are transferred from discipline to discipline through a common foundation of a configuration-managed data model.

The EPI Mechanical Subcouncil’s vision of Model Centric Design is to allow product definition data to flow seamlessly throughout the enterprise. For a mechanical model centric process, the three-dimensional solid model must be the portal to the geometric definition, as well as processes, specifications, and key design characteristics.

Given the formality dictated by the customers of the Aerospace and Defense industry, this vision is a large departure from the processes enabled by the Mechanical Computer Aided Engineering tools commercially available today. Consequently, LMC perceives reaching its vision as an evolutionary process.

Over time, the 3D model will be used to capture increasing amounts of the design information. At the current time, the majority of datasets are comprised of many objects. The fundamental objects are both a fully detailed three-dimensional model of nominal geometry and a reduced dimension drawing (RDD). In this state, the RDD contains key design characteristics and inspection criteria only. Also within the dataset are a number of task specific artifacts – sub-discipline derived abstractions or views of the dataset. These abstractions are augmented with additional annotations and attributes characteristic of the sub-discipline. Versioning and precedence of each object within the dataset must be formally configuration managed.

The initial level of evolution of Product Definition is the traditional engineering drawing. It has been the basis of mechanical product definition datasets throughout the history of design. In the defense industry, the requirements are largely dictated by MIL-STD-100. The drawing contains all the information needed to fabricate the product through a two-dimensional representation (2D) of the physical requirements. Product configuration management is based on the concept of the drawing serving as the definitive record of authority. Unfortunately, very little of the design rationale and complex relationships between product phases and product representations from different disciplines is captured in a drawing. Furthermore, any of this information that is available is locked in drawing symbology and a limited set of parametric values.

The second evolutionary level is an RDD dataset. An RDD dataset contains a drawing and a model. Product configuration management is based on a dataset rating system that portrays order of precedence regarding the definitive record of authority – model over drawing. While the model likely contains all the information needed to fabricate the product through a three-dimensional representation (3D) of the physical requirements, the typical topics of collaboration between manufacturing, inspection, and engineering are represented as critical characteristics and dimensions or textual information on the simplified RDD. The 3D model serves as a portal to these product representations from other disciplines. Even though the relationships are complex, simple abstractions are used with integrations to provide more transferable information.

The third evolutionary level of Model Centric datasets is the Dimensionless Drawing. In the case of the Dimensionless Drawing, all collaboration between manufacturing, inspection, and engineering is via the 3D solid. The solid is the controlling entity for all product definition, with process and specification information available in both the 3D and 2D representations. At this stage, the 2D representation is largely a remnant of the product configuration process.

The final evolutionary level of Model Centric datasets is the Model Only state. At this state, no drawing exists. All product definition collaboration between manufacturing, inspection, and engineering to represent geometric, process, and specification critical characteristics is available from the 3D model. All geometric, process characteristics, and specification information is available in the 3D model. All product configuration management is based on a model as the definitive record of authority.

As traditional drawing-based datasets are replaced with 3D-model-based datasets, there is an opportunity to make more of the design rationale and complex relationships between product representations from different disciplines more accessible. Additionally, the contents of the traditional drawing symbology can be exploited for truly integrated engineering process implementations envisioned by our customers concerned with Simulation Based Acquisition.

This future model also acts as the control point for information required by all enterprise users. The model will either directly contain the information needed or serve as a portal to associated, derivative models that complete product characterization. Users will be supported by a number of discipline-specific views of the dataset. Accordingly, tools must support the extraction and data management of simplifying levels of abstractions. Abstractions are dataset views that target both specific user roles and tasks. In this final form, design intent will be both more accessible and more efficiently valuable to everyone in the enterprise.

Today, not all this vision is achievable. There are limitations with many of the CAE tools used in the Mechanical Engineering process. Most of the near-term limitations are centered around points in the process where data must move between tools dedicated to the tasks of the various sub-disciplines of Mechanical Engineering. Also significantly, Mechanical Engineering lacks a standard modeling language to describe the mechanical products. Modeling languages have become common in other disciplines: Systems is developing SysML; Software has developed UML; and Electrical has been using an HDL for a long time.

If a language were formally defined, then perhaps the Mechanical Engineering design process would evolve toward the synthesis of design product definition. It certainly would better convey the design intent, the analysis, and behavior, in an expressed context. Some have suggested that TechnoSoft's Adaptive Modeling Language (AML)® has the potential to be such a universal language for Mechanical Engineering.[1] While AML® is quite robust, at this point it lacks the industry wide endorsement characteristic of the more standard languages of the other engineering disciplines.

But today, data is not as functional after it has left the context in which it was originally authored. These limitations often exist within "integrated" tool suites from the same software supplier.

4 Lessons Learned Improving the Process

Throughout LMC, as we are examining Mechanical Engineering process improvements that allow us to leverage the 3D model, we are using the simplified Mechanical Engineering process. In the following sections, this paper will discuss the implementation of Model Centric Design within several stages of this process. (Note, for brevity, process steps that have shared lessons are considered together.)

Over the years of evolving the Mechanical Engineering process and motivating the tools suppliers toward our model centric vision, many lessons have been learned. Example lesson themes include tool functionality gaps, impacts on the supply chain, customer readiness, long-term archival, quality challenges, and the associated efforts of industrial standards organizations such as AIA, ASME, and ISO.

Some of the most important lessons based on the ongoing efforts of Lockheed Martin's

Mechanical Model Centric Design initiative, and other piloting efforts throughout industry, are highlighted in the balance of this paper. Both business benefits and barriers are reviewed.

4.1 LMC's Capability and Maturity Model for Mechanical Model Centric

In spite of many man-hours of effort to achieve this vision, many of the LMC business sites remain unclear what tasks they need to complete in order to successfully adopt a Mechanical Model Centric design process.

Accordingly, LMC has been developing a transition plan maturity model with the objectives to eliminate duplicated development of site-specific plans and reduce the learning curve for transition. The model is structured as a spreadsheet-based interview tool to assess "Is my business ready for a Model Centric Engineering process?" The model is, in concept, based on Aerospace and Defense Industry required capability maturity models such as those used by the Carnegie Mellon Software Engineering Institute (SEI℠) to assess Integrated Capability and Maturity Model (CMMI®) levels. (The SEI℠ is a federally funded research and development center sponsored by the United States Department of Defense (DoD). SEI℠ CMMI® ratings are a competitive requirement for defense contractors developing software intensive systems for the DoD.)

We have identified the most important high-level characteristics of success (configuration management, training, quality, among others) Subtopics questions are being written for each characteristic with examples of "Objective Evidence" and "Listen for Themes" listed as potential answers.

"Objective Evidence" is a tangible example or demonstration of a concept. It consists of qualitative or quantitative information, records, or facts pertaining to the implementation of a process characteristic. It is based on observation, measurement, or test, and can be verified. "Listen for Themes" are less tangible expressions of a concept, largely based on interviews. To make reasonable judgments regarding an organization's implemented processes relative to the CMMI® models, appraisal teams base their judgments on the collection of evidence for each characteristic. [2]

These subtopic questions of the capability maturity models are also being mapped to a seven-level model centric dataset rating system. The seven-dataset levels refine the levels of product definition. Each level signifies a rising suitability for the direct use of 3D data by downstream users. The 3D data in the lowest level dataset may not be used at all. In contrast, in higher-level datasets the 3D data may be used directly by manufacturing without referring to the drawing for any product definition.

The dataset ratings are used with standard dataset content requirements. Each content requirement addresses: applicability of the dataset for use; examples of intended use; required and potential optional dataset content; dataset authority for the basic form, location, orientation, and dimensional characteristics of all design features; the degree to which the dataset complies with internal dataset standards; and any known use restrictions.

4.2 Proposal and Concept Design

The design stages that make the most effective business impact are Proposal and Concept Design. It is well accepted that early design decisions have 70-80% impact on the downstream life-cycle costs related to development, production, and maintenance. This significance is due to the complex relationships between product development phases and product development disciplines. [3]

It is essential to explore the highest risk relationships and develop a real understanding of the multi-discipline interdependent sensitivities early in the life cycle to avoid illconceived, sub-optimum designs, or excessive costs. There is an obvious need for an integrated approach that provides robust analyses of design variables across interdisciplinary models. However, the practicality of early multidisciplinary trade studies based on these interrelationships poses a large problem: Few of the details needed to model downstream effects on critical design points are known.

For example, manufacturing models were traditionally developed after the fully refined detailed designs existed. However, at this traditional point where the design data was available, crucial decisions had already made significant impact to schedules. Such decisions are costly to change and might have other far-reaching consequences. Early feedback based on the implications of design decisions would enable more informed decisions at early crucial process points.

Given this desirable holistic approach to design, an idealized solution is to enable rapid trade studies that can play a significant role in improving design success and lowering costs. However, rapid trade studies have proved impractical due to the nature of the current design techniques and CAD modeling paradigms. Today's CAD simulations, manufacturing process, and cost models tend to be too resource intensive due to their size and complexity. Consequently, LMC draws on the concept of levels of abstractions to idealized systems models to address these issues. [4]

Standard abstractions are used to provide simplified, yet representative, models from all disciplines of product development. At LMC, we define abstractions as representative models of the essential characteristics and properties of the design item (for example, system, element, component, process, cost, and so forth). We also define levels of abstraction as the degree of model fidelity to which the details of a "real world" problem are simplified within the modeling environment. Primitive abstractions, such as the simple beam and plate structural models, or primitive volumes for component space claims, can provide useful feedback. These abstractions formalize design assumptions that also form a set of invariable design rules that can be continuously re-verified as the design models mature. Furthermore, as the design matures and data increases in complexity, so do the complexity levels of the abstractions. This further underscores the need for a standard Mechanical Engineering language. Such a language could define and transfer the taxonomy for these various levels of abstractions. Without a standard taxonomy, there can be no understanding the intention or limitations associated with each abstraction.

Even when most of the details are known, there are many advantages to abstracting the model to higher levels of simplicity. Additionally, the level of abstraction can vary from one discipline to the next, allowing multidisciplinary system-level fidelity tailored to higher resolution on specific areas while relaxing the level of detail relating to others. Multiple level models enable evolution and adaptation, as needed, depending on parameter sensitivities. This shedding of unwanted overhead often consists of removing unneeded parameters or as-yet unknown/undecided details with low impact or sensitivity. The characteristics, behaviors, and sensitivities remain intact albeit at lower resolutions. The most important gain is perhaps the speed of changing trade study analyses. We recommend distilling the essence of heavily detailed models by capturing only the most fundamental behavior.

4.3 CAE Pre- and Post-Processing

Today, at LMC, analysts still spend an enormous amount of time in pre-processing design data to abstract a model appropriate for analysis. Pre-processing consists of removing unwanted or unneeded small features, repairing undesirable geometric entities, creating a mesh, cleaning the mesh, assembling any associated assemblies, and adding loads, boundary conditions, and material properties. However, if we look at the process in terms of a product value chain for tool integration pre-processing adds little real value to the product. The opportunity for time and cost savings in this area is huge. The inordinate time spent in preprocessing easily diverts the job focus of the analyst from providing technical insight and expertise to mesh making, obscuring their key function.

If much of the analysis models are still manually developed, errors are inevitably introduced regardless of the analysis diligence. According to presentations at our internal Mechanical Analysis Conference (MAC02), CFD pre-processing at one LMC business takes up 95% of the analyst's time (i.e. 5% of the analyst's time is actually spent doing analysis) and at another, FEA preprocessing takes up to 90% of the analyst's time. Nearly all of the different fields of mechanical analysis (FEA, CFD, Thermal, Optics, and the like.) require their own manual and personalized pre/post-processing to create a specific model for that analysis tool. This underscores the need for automation of the abstraction pre-analysis process. [5]

LMC learned many lessons regarding the automation of the pre-analysis process through one of our early model trail-blazing experiences with design-to-analysis (D-to-A) integration. This program focused on exploiting the integration of the D-to-A process for structural dynamics simulation. In 1997, the initial D-to-A processes on top-level assemblies investigated the use of a PTC's Pro/ENGINEER® geometry-based finite element mesh. Later, in 2000, a redesign was started in support of this same program. During 2000, many hardware configurations were considered, resulting in numerous updates to the models. In 2001, as the design hardware configuration was frozen, the D-to-A process began a full-system finite element modeling of the weapon.

The top-level assembly consisted of more than 450 individual parts distributed among a team of seven people by sharing subassemblies. One person was required to maintain the top-level assembly. The team members had expertise on several different tool suites, but a varying level of experience with the D-to-A process. The team determined the initial requirements of the analytical model.

The same Pro/ENGINEER® model was used for both the design and analysis geometry through geometry simplification. Special analysis features and layers were created to help manage the analysis mesh geometry, as needed. A significant amount of planning went into the documentation of the intents and limitations of these abstractions.

Not only did the planning considerations include geometry, it also addressed element types, quality metrics, and size to be universally used in the top-assembly mesh. Furthermore, additional planning revolved about standard definitions of the mesh interfaces. Mesh interfaces were defined at the connection between each major sub-assembly. Each finite element modeler was required to create their mesh to conform to all of the rules. When completed, the full-system model contained more than 1.3 million elements.

This total effort took the analysis team a little over one year. The initial review of the Pro/ENGINEER® model by the analysis team took a month, including time to reorganize and manage the model hierarchy. The models were then transferred to data management and allocated to the analysis team members. It then took the analysis team three months to appropriately simplify the models under data management. Finite element modeling and material assignment for the parts took six months. The subassembly model verification, through modal analysis took an additional month, and the final structural analysis took about 2 months. [6]

However, even as tightly integrated as these design and analysis models were, the overall D-to-A process used was a traditionally serial progression. Furthermore, in this type of process, we still see too much non-value-add design activity before the model is ready for actual analysis. There are many opportunities for the automation of the abstraction process. Even in this well-planned and executed program, design engineers tend to use the majority of the available development schedule to develop their designs, leaving the remainder between the analysts and test engineering. The impacts of any problems found become magnified so late in the design process. As part of the model centric process change, LMC advocates analysts providing early abstraction simulations. Early feedback based on the simulations of design decisions empowers analysts and overall better informs the decisions of the integrated project teams.

Ideally, the object of every project team is to get the best design possible at the earliest time in the design cycle. Until recently, optimization has happened in a serial process in which designers complete their work, move it to analysis, and wait for the changes that may flow back in a very simple feedback loop. With this process, at best, one or two of the most logical iterations can be accomplished before time and resources run out. Accordingly, if designers and analysts were enabled to do optimize design possibilities across a multitude of disciplines early and efficiently through the use of model abstractions, it would be a very powerful process improvement. With new expedited processes, even those ideas that may have seemed illogical or impractical may be studied, and perhaps might even lead to beneficial design insights.

The analyst's world is also changing toward more integrated models in which multi-physics simulations/analyses will be developed. The model will be maintained as a result of integrated model associativity and real time collaboration between representatives of all affected disciplines. When a design engineer changes a CAD model that is associated to complex analysis models, with all loading and boundary conditions, results should associatively flow to and automatically modify higher-level system analyses. Ultimately, multidisciplinary optimization will allow for the upfront inclusion of analysis and the study of a multitude of parameters across many design concepts. Test data will be rapidly combined with the analysis-centric model for validation of the simulation and for use in related analysis studies. [7]

4.4 Documentation and Detail Engineering

As stated earlier, LMC's vision is to have all product definition data available through the 3D solid model. At LMC, we see the August 2003 release of the American Society of Mechanical Engineers (ASME) Y14.41-2003 standard for Digital Product Definition Data Practices as a major milestone in that effort. Y14.41 is the first standard that establishes requirements for stating and interpreting dimensioning, tolerancing, and related annotations for use in datasets based on engineering models and not drawings.

Y14.41 builds upon the previous ASME standards for two-dimensional drawings. The standard explains how annotations are to look, are to behave when a user interacts with a model, are to be oriented with respect to a model, and additionally how models and associated drawings may be used together as a dataset. As depicted in Figure 1, all annotations are displayed planes parallel to the model surfaces.

While Y14.41 is straightforward, no CAD system fully supports the new standard yet. Most CAD systems have construction planes that can be used for sketching, but adding dimensions and tolerances to such planes as described by the ASME standard is difficult.

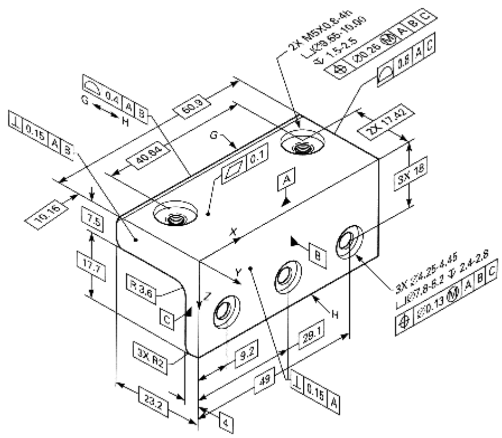

Fig. 1. Y14.41 Model with all annotations displayed.

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Y14.41 brings about many implications. It directly impacts developers of CAD tools by providing guidelines for software improvements related to modeling, dimensioning, tolerancing, and data interrogation practices. Indirectly, existing standards dealing with data exchange and archiving will also feel the influence of Y14.41's approach for Model Centric design.

LMC sees a convergence of the current efforts of the various industry and standards groups being driven by Y14.41. First, LMC has encouraged our current CAD suppliers to implement Y14.41 in a manner that it is fully compliant with ASME Y14.5's geometric dimensioning and tolerancing (GD&T).

Also, we are advocating that Y14.41 be implemented as the presentation requirements for Edition 2 of International Standardization Organization (ISO) 10303, the Standard for the Exchange of Product Model Data (STEP) Application Protocol 203. LMC, as a board member of PDES, Inc, is committed to the use of STEP as a data exchange and archive format for 3D product definition. (PDES, Inc, is the North American consortium concerned with accelerating the development and implementation of ISO 10303.)

Furthermore, LMC has endorsed the use of the STEP AP 203 Edition 2 format as the basis of an archival approach compliant with the Draft Aerospace Recommended Practice (ARP) 9034-2003 entitled "A Process Standard for the Storage, Retrieval and Use of Three-Dimensional Type Design Data" recently published by the Americas Aerospace Quality Group (AAQG) committee of the Society of Automotive Engineers (SAE). (Note - "Type Design Data" is Federal Aviation Administration vernacular for the technical product definition needed to attain an airworthiness certification for an aircraft.). ARP 9034 began as an AIA-sponsored, FAA-focused document and is currently being extended to address the broader Aerospace Industry. Accordingly, this document is expected to evolve into an ISO-recognized, International Aerospace Quality Group (IAQG) sponsored Aerospace Standard in the future.

ARP 9034-2003 sets a number of process standards that allow data to be successfully archived, retrieved, and used for the life of a type certificate (50+ years). Specifically, it relates to digital type design data found in three-dimensional models along with accompanying data such as tolerances, specification call-outs, product structure and configuration data. ARP 9034-2003 itself is based on NASA's Consultative Committee for Space Data System's Open Archival Information System (OAIS) process model. OAIS is a conceptual framework for an archival system dedicated to preserving and maintaining access to digital information over the long term. The OAIS process model is described by ISO 14721:2003. As such, it is likely that OAIS will be a highly visible component of the ongoing effort to address the challenges of preserving digital information.

LMC has begun discussing retention needs for our various programs. In order to achieve our goal of the three dimensional model centered design process, a reliable and effective archive system is critical. Since Model Centric eliminates all traditional drawings from the engineering design process, an electronic archival system must be developed to meet regulatory, legal, contractual, and business requirements. Through efforts of industrial standards organizations such as AIA, ASME, and ISO, LMC plans to address long-term data archival of Model Centric Design data in a process consistent with SAE/AAQG ARP9034.

Another useful reference to understand many of the common requirements and processes needed to support long-term data archival of product data is a white paper written by the European Association of Aerospace Industries (AECMA). AECMA's LOng Term Archiving and Retrieval team (LOTAR) developed its white paper to delineate the general approach and strategic recommendations regarding long-term archiving. The white paper contains a description of use cases, processes, data, mapping, system architecture, consolidation of the main requirements, scenario descriptions, and description of the general methods for long-term archiving.

The LOTAR team, and its North American counterparts, the PDES sponsored Long-Term Archival Requirements team and the SAE/AAQG ARP 9034-2003 team, are developing additional methods, case scenarios, and process descriptions to support the development of a merged ISO and Aerospace Industry standard for long-term archiving.

Unfortunately, in general the implementations of STEP AP 203 by our current CAD suppliers remain incomplete. These incomplete implementations currently limit options related to data exchange and prohibit the use of STEP as a long-term archival solution. For example, the CAD tools suppliers' current implementations of AP 203 generally support geometry well, but do not address some existing configuration and data management requirements.

4.5 Procurement

LMC has been using CAD models as part of the product procurement process for decades. Unfortunately, much of the use was handled only by individual engineers and was done without the direct involvement of our procurement and quality professionals. Recently, we have attempted to formalize these processes.

The justification for the formalization effort can be traced in part to successful experiences working with the Validating Advanced Supply-chain Technology (VAST) program. The F-22 Program Office sponsored the VAST program to address the key issues facing the Air Force in an era of increased outsourcing and reliance on supplier capabilities. The purpose of the VAST program was to help drive affordability concepts throughout the defense industrial supplier base by validating and stimulating improvement in small and medium sized enterprises (SMEs).

The VAST Program focused on two technology activities for SME supplier improvement: 1) use of Lean Deployment principles, and 2) digital communication of the Technical Data Package (TDP) data to the SME.

The program selected a single provider of sheet metal parts to research. They found a 44% cycle time reduction and a sizable cost avoidance for the F-22 Program. While these results may be insignificant when taken in the context of a single SME, when taken across the broader F-22 SME base or the larger SME base, the results were significant. The selected SME was one of sixty-three similar suppliers supporting F-22 production. From the single SME supplier, this cost avoidance projected to be 10-times larger for the collected five LMC fighter aircraft programs. When these cost avoidances are estimated across the entire LMC F-22 SME business base, the results are over $1M per year in cost avoidance for the program.

Details of this and other business cases can be found in the VAST final report prepared for the Air Force Research Laboratory at Wright-

Patterson Air Force Base, under Cooperative Agreement F33615-00-2-5541.[9]

Under the auspices of the EPI program, LMC has periodically administered a survey to measure the Model Centric readiness of our downstream functions, such as our Procurement and Mechanical Manufacturing partners. Generally, the survey asks the partners to address some company-specific preferences regarding:

- Infrastructure
- CAD/CAM Tools
- Preferred Product Definition Media
- Model Centric Experience
- Business Processes

Included with each question, there is a section where the partner is encouraged to contribute additional comments, such as future developments and current capabilities.

Our findings in our latest version of the survey have remained mixed. While almost all of the companies responding had some CAD experience and more than 75% had some experience with high-end CAD tools (Pro/ENGINEER®, CATIA®, I-DEAS Master Series®, or Unigraphics®), only 60% of our respondents characterized their companies as CAD/CAM capable with 3D data. Most do not consider themselves ready to accept model centric data as the sole depiction of product definition.

Interestingly, this readiness self-assessment seems to be counter to their own experience self-assessment: More than half of the companies reported that their commercial and military customers are using some type of Model Centric product definition. Many of these customers were using only models, and 75% were using RDDs.

Significantly, there was no measurable difference in preference for the use of IGES or STEP. However there was an experience difference; 2/3 had used IGES while only 1/4 used STEP.

Finally, these companies seem capable of handling model-based inspection. Of the companies that responded, 75% had Coordinate Measuring Machine (CMMs) capability and a majority also indicated that they had some sort of Dimensional Measurement Interface Software (DMIS). LMC believes that the combination of CMM capability and DMIS tools is probably sufficient for creating a valid inspection process based on Model Centric product definition data.[10]

4.6 Fabrication, Verification and Validation (Inspection)

The functionality available in mechanical CAD software has enhanced the capabilities of designers to produce complex hardware. CAD software has also improved the design engineer's ability to produce product definition datasets. All the high-end CAD suites LMC uses to develop product definition have some integrated CAM solution. Almost every CAM solution on the market today has an associated simulation solution. Given ready access to an existing library of model parts, tools, machining centers, and material data, CAM systems can realistically simulate the CNC fabrication program developed by a manufacturer.

Establishing consistent ground rules for the use of model centric techniques for design documentation, manufacturing, and inspection phases are difficult given the evolutionary status of design tools. Models contain excellent representations of a design's geometric requirements. However, many models lack geometric dimensions and tolerances or other data that is needed to fully define the product. Currently, manufacturing engineers must blend the geometry contained in the CAD file with the product specification contained in the other forms of engineering documentation. This necessity to use multiple representations to communicate a design is the greatest limitation faced by CAD/CAM/CAI users.

Many of the CAD and CAM suites use, or optionally make available, Vericut™ from

CGTech. Vericut is so widely used that it is practically an industry standard. Manufacturing tools like Vericut can typically simulate up to 5-axis milling, drilling, turning, and wire EDM operations in combination.

In a CNC program simulation, a part model is graphically used to verify the accuracy of the tool path and make certain the finished part matches the design model by representing the material removal process directly from CNC programming data. LMC has found that these simulations are invaluable when they depict machining errors and discrepancies that can corrupt the cutting process. These simulation tools can also be used to dramatically boost productivity on the shop floor by providing automated or user-selectable settings to optimize the material removal process.

As discussed earlier, the establishment of a dataset rating system is fundamental. The rating system is used to communicate a design's compatibility with standards and manufacturing requirements. The purpose of the dataset rating system is to communicate the intended use the model data to the manufacturing, procurement, and inspection organizations.

In the Aerospace and Defense industry, many components are highly complex and have very tight tolerances. Fabricating complex, tight tolerance components requires not only a precision machining capability but also a precision inspection capability.

Corporate experience has indicated that many of our most complex parts would take weeks to manually verify. Furthermore, the complexity of these parts might require much more than manual inspection in order to ensure design intent is achieved. In order to address inspection repeatability, reproducibility, and increased efficiency when compared with traditional manual methods, LMC must insist on computer-aided inspection (CAI). There are two types of CAI methods in common use: coordinate measuring machines and non-contact scanning interferometers. Expectedly, with the benefit of interfaces to the major CAD systems, each CAI method improves the total inspection efficiency when compared to manual inspection. Unexpectedly, this process improvement is possible even though the commercial systems currently available are not capable of interpreting the allowable tolerances directly from the 2D or 3D CAD data.

CMMs are the most popular alternative to manual inspection, and are available at many of LMC's suppliers. CMMs decrease inspection costs and improve inspection capabilities, and accordingly quality. The most widely used CAI interface for CMMs is Brown and Sharpe's PC-DMIS®. PC-DMIS® supports all of the major CAD tools and industry interface standards, allowing users to program the inspection of a part based on data imported directly from the CAD file. Likewise, Geomagic® is a very popular CAE tool to program non-contact scanner interferometers. Non-contact scanners share many of the advantages with CMMs in comparison to manual inspection.

The major distinctions between CMMs and scanner-based systems are as follows: Scanners are often faster at data gathering than CMMs; Scanners are non-contact and consequently can be used on fragile parts; CMMs probe a discreet number of contact points, driven by the inspection-dimensioning scheme, while scanners measure the part everywhere and compare data to the nominal CAD geometry; Scanners provide enhanced graphical comparisons by collecting a large "point cloud" of data and providing a clearer picture of the actual size of the parts.

For example, experience on the F-22 fighter program indicated that high-speed measuring accuracy was a very important factor in the total cycle time of fabricating of parts. Verifying a medium-to-high complexity part (150-200 features - 1000 dimensions) might take 8 hours, manually. In comparison, to probe 1000 dimensions with high-speed CMMs, inspection could be reduced to minutes.

Furthermore, with a high-speed non-contact laser interferometer, the whole part could have been captured in about the same time.[11]

5 Conclusions

At present, even at LMC, engineering drawings remain the most common way to communicate product specifications. This is true even though almost all of the designs developed in the last decade have 3D models as their basis. LMC is currently working to change this reality, because as CAD technology is maturing, models are being more widely used to effectively accelerate product design.

There are issues using the 3D data for the manufacture and inspection of the product, but time and experience will provide solutions. Today the accuracy of the product design is unparalleled, and the future will provide the users of the design data and all the tools needed to interrogate that data which controls the design.

Our customers are slowly becoming more accustomed to model data being part of the deliverable dataset. Today it is not unusual for designs to be documented using one of the model centric dataset forms in place of traditional drawings.

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