

TITLE: Enhanced Product Realization Techniques Using As-Built and Model Reconstruction Technologies

AUTHOR(S): Ronald M. Dolin, (505)667-9142, e-mail rmd@lanl.gov
Jill Hefele, (505)667-9744, e-mail jill@lanl.gov
Cynthia S. Tsai, (505)667-2230, e-mail cstsai@lanl.gov
Gene J. Maes, (505)667-6567, e-mail gjmaes@lanl.gov

SUBMITTED TO:

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED *ph*

By acceptance of this article, the publisher recognizes that the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes.

The Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy.

Los Alamos Los Alamos National Laboratory
Los Alamos, New Mexico 87545

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, make any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Center for Advanced Engineering Technology



Title

**Enhanced Product Realization Techniques Using As-Built and
Model Reconstruction Technologies**

Authors

Ronald M. Dolin, (505) 667-9142, e-mail rmd@lanl.gov

Jill Hefele, (505) 667-9744, e-mail jill@lanl.gov

Cynthia S. Tsai, (505) 667-2230, e-mail cstsai@lanl.gov

Gene J. Maes, (505) 667-6567, e-mail gjmaes@lanl.gov

Date

October, 1995

ABSTRACT

Los Alamos National Laboratory's Center for Advanced Engineering Technology has developed a product realization process designed to enhance the complexity and comprehensiveness of the information fed back to the designer after the analytical and manufacturing operations have been completed. This process uses principles of As-Built Engineering and Model Reconstruction in a Models Based Engineering environment, allowing optimization in the manufacturing and assembly operations and providing information as to the As-Built configuration to engineering and physics designers for evaluation.

As-Built Engineering is a product realization methodology founded on the notion that life-cycle engineering should be based on what is actually produced and not on what is nominally designed. It enables customization in mass production environments and questions nominal based methods of engineering. As-Built Engineering recognizes that there will always be errors in manufacturing that cannot be controlled but need to be captured in order to fully characterize each individual product's unique attributes. It provides actual product information to designers and analysts, enabling them to verify assumptions using actual part and assembly data and allows optimization of new and re-engineered assemblies.

Model Reconstruction provides the capability of subjecting a design to adverse conditions within the computer aided environment and building a stereolithography model and simulated radiograph from the analytical finite element information of the simulated damaged part. With this simulated testing, visualization of the resulting data is intuitive and comprehensive and validation of the analysis method is provided.

Models Based Engineering is an information management tool and a key driver toward the development of adaptive product realization infrastructures. It encompasses the breadth of engineering information, from concept through design to product application. A Models Based Engineering environment uses a single model-based product definition within a unified information management system and establishes a single point of failure in the concept to part process.

INTRODUCTION

Government agencies and low-production industries have discovered that a product realization infrastructure is required where every individual characteristic of a particular product is captured and stored in electronic form to effectively deal with maintenance and surveillance issues. The characterization of a product includes all of a product's deviations from its nominal design that occurred during manufacturing, maintenance modifications, and application effects, along with a record of how the product has aged and matured. All this information must be gathered into a product data management system storing all relevant information pertaining to the product, characterizing the product using a single model, and using enhanced visualization techniques to validate analysis and tests; thereby verifying the design process.

In the product realization process the designers and engineers begin with a simple model and set of performance parameters to develop a design solution. This design usually exists in the form of a solid model. Nominal design parameters are used to represent an ideal product. This nominal design is used to perform physical and mechanical analysis simulations and specify manufacturing procedures.

Because the design is nominal and the design is still in a conceptual stage, a single solid model can be used to represent the product. This single solid model is essentially the ideal design specification containing no flaws or inconsistencies. It is the model that will determine how piece parts will be manufactured and against which they will be evaluated. However, once manufacturing begins, small deviations start to creep into the design during manufacturing and assembly and while the product goes through its service life. These deviations are design inconsistencies that can reduce the validity and relevance of the nominal solid model. The nominal design represented what we aspired to manufacture and assemble but does not capture the definition of what was actually manufactured and assembled.

Once the manufacturing process begins, deviations appear in the product. The amount that each part deviates from nominal is captured in the inspection. Because each part is different, each part's as-built definition must be characterized with a description of its current state. Historically, people on the shop floor have made modifications and added features to designs "on-the-fly" with no documentation of the changes that were made to the nominal design. These changes were necessary to make the design functional or to aid in manufacturability, but documentation of the changes made is not usually executed. When the product is taken in for maintenance or to fix a problem, the lack of documentation of the changes made causes delays and mistakes in the maintenance procedures.

At various stages of production the manufacturing engineer generates as-built information. Design engineers and physicists can use this as-built information to determine through analysis how to locate features so as to mitigate the effects of manufacturing deviations from nominal. Analysis is also used to adaptively customize mating parts during manufacturing to compensate for existing deviations.

Using as-built engineering principles, the assembly engineer is able to optimize the assembly of each system through analysis in order to come as close as possible to obtaining the performance parameters of the nominal design in each system. Because each system has been custom manufactured and assembled in an as-built environment, a unique model is generated for each system to capture the as-built characteristics of the product.

When the as-built model of the fielded system is available to the maintenance engineer, he/she is able to accurately monitor the physical and phenomenological changes of every system in the stockpile or inventory during routine maintenance and surveillance. These changes can include generalized effects of aging but also the very system-dependent changes that occur as a result of the various environments each system is exposed to. The as-built model contains the state of the system being surveyed at the time it was last inspected. Using this information maintenance engineers can measure any changes that have occurred. By tracking changes in the form of an evolving set of as-built models, engineers begin to understand what effect different environments have on various piece-parts in the assembly. This models-based log of each system's maturation also contains maintenance work history and all repairs, replacements, and modifications. Using an electronic product data management system is essential due to the massive amounts of data generated.

As systems begin to be retired, many piece parts are inventoried for possible re-use and re-engineering. Each inventoried piece-part has an associated solid model describing its current state. When a system comes in from the stockpile to receive a new part, engineers use the inventory of as-built models in a post-production analysis and optimization simulation to determine which individual piece-part is best suited to be used in the system to optimize design and performance parameters. When the system is returned to the stockpile or warehouse, its as-built state is represented and the level of untested reliability and confidence is quantified.

The primary aspect of implementing As-Built Engineering, Models Based Engineering, and Model Reconstruction in the product realization process is the principle that the only measure of importance is the quality of the final product and final assembly, both of which can be measured. This approach is not concerned with the details of how a product is produced because the product's quality can be measured at various stages of production. In a robust manufacturing environment, how you make something is of no real consequence. The only benchmark is the quality of the end product.

AS-BUILT ENGINEERING

As-Built Engineering is foremost a methodology for allowing customized product realization at mass manufacturing speeds, prices, and flexibilities. Customized product realization is a significant philosophical deviation from the popular approach to design and manufacturing that has been used for the last fifty years. In fact, As-Built Engineering is a significant deviation from the manufacturing approach used through out the world since the beginning of the industrial revolution.

As-Built Engineering methodology is rooted in the notion that a product's life-cycle support should be based on what was actually produced and not on what was idealistically or nominally designed. It is not possible to consistently manufacture a product to the exact specifications of a design. Also, it is not possible to predict or control the amount of deviation a manufactured part will have relative to a canonical nominal design specification. The dictionary defines nominal as "existing in name only; not real or actual; theoretical; so-called." Engineers not comfortable with thinking of manufacturing deviations in these terms chose instead to develop an entire approach to engineering that made uncontrollable deviations an acceptable part of a design solution. This approach to engineering is referred to here as nominal based engineering. Nominal based engineering seeks to create a design that is impervious to small errors in manufacturing. These small acceptable errors are referred to as a part's tolerance and can vary on both the positive and negative sides of nominal. Once nominal based methods of engineering were adopted they began to affect even how design itself was done.

As-Built Engineering involves a re-examination of methods of nominal engineering in light of advanced technologies. In our estimation, engineering technology has matured to the point where it is now possible to do customized product realization in a mass production mode. This, in essence, brings product realization full circle. Before Eli Whitney and his contemporaries revolutionized engineering with mass production and the concept of interchangeable parts, manufacturing was based on highly customized design. Since the industrial revolution, engineers have sought solutions to problems based on nominal designs because they did not want the added constraint or cost of customized manufacturing, even though in some instances a customized solution to an engineering problem can be more optimal and result in better performance characteristics of a design. Today, engineers have the ability to do customized manufacturing using advanced technologies. This returns engineers to where they were before the industrial revolution philosophically.

As-Built Engineering is not a radical new way of design or manufacturing, but is a new way of thinking about the solution space of product realization problem solving and the opportunities created by emerging technologies. There will always be errors associated with manufacturing. Those errors should not be dismissed under the protected umbrella of manufacturing tolerances, but should instead be acknowledged and incorporated into the product realization process and used to help build an optimum product.

Products can and should be fully characterized using solid models. Each individual assembly should possess its own separate engineering model depicting the assembly's unique characteristics. This in turn can be used to feed as-built information to designers and analysts for higher fidelity simulation, and to monitor the changes that occur in a product in its life-cycle. Customized product realization allows piece parts to be assembled in an optimum way. This approach minimizes rejected parts in production because it provides a way to accept parts that otherwise would have been unacceptable. It enables a mechanism for optimizing performance characteristics during assembly and for knowing logically which piece-part in an inventory is the best one to be used in a particular assembly.

This does, however, suggest small modifications in current manufacturing processes. Suppose, for example, that you were making two axi-symmetric parts that mated together. Assume one part had already been manufactured but that it did not have the same mass property characteristics as those specified by the nominal design. In other words, the mass, volume, center-of-gravity, and inertia properties deviated from nominal. Now suppose that the mating part's machining is broken into two independent steps, the turning operations and the milling operations. Once the second part has been turned, it can be inspected, and an as-built model can be reconstructed from the inspection data. The off-axis features of the second part can be incorporated into this as-built model and the engineer can start performing analysis on the two as-built models to determine the optimum configuration for achieving an assembly with mass properties as close to the design specification as possible.

At this stage, the second part's as-built model is a hybrid with the turning portion represented by as-built data and the features represented by nominal data. The engineer is locating the second part relative to the first. Since the second part has not yet had any off-axis features milled out of it, it is still axi-symmetric and can be rotated relative to the first part so that design parameters are optimized. In essence, this operation is akin to dialing in the desired performance parameters, which in this example means taking advantage of both parts' deviations from nominal to minimize the effects of manufacturing inconsistencies. This is what is meant by assembly optimization. This locating operation in turn indicates to the manufacturer where to locate the off-axis features on the second part to optimize the assembly.

This approach maximizes part reuse in post-production by providing a logical way for determining what optimal piece parts to use in an assembly from an inventory of possible piece parts.

Many traditionally human intensive aspects of manufacturing can be automated in an as-built environment. For example, in As-Built Engineering every piece part is inspected--not just when it is completed, but at every crucial stage of the value-adding process of going from raw material to finished product. Things such as loading stock and locating features can all be automated. The as-built environment is robust enough to allow parts to be manufactured directly off of a solid design model. Because of the "inspect-often" philosophy, manufacturing can be done reliably using multiple software tools and platforms on different pieces of manufacturing equipment.

In this environment the way parts are inspected must change from the way it is done today. Engineers need to generate more product information faster than was previously required. They also need to be able to reconstruct a model from inspection data and measure manufacturing deviation relative to the design specifications. This will be possible using emerging technologies. Decision analysis that has traditionally required human interaction can be automated using heuristic based methods. Whereas before design engineers often had to physically go to the manufacturing area to look at a particular part, in an as-built infrastructure, a part is fully captured and characterized electronically. That electronic model can be sent to the design engineer for review, analysis, and modification. The computer model of the as-built part can be used to determine the next steps in a part's manufacturing. Advanced technologies will enable all of this without creating a manufacturing bottleneck.

As-Built Engineering provides a methodology for the monitoring of an assembly's maturation. The only way to understand how a system is aging and wearing is to know its state at any given moment. The current method of having a single engineering model of some nominal system to represent all the actual systems of that design is not practical. As-Built Engineering is based on the premise that each system in an inventory is different and, hence, needs its own individual model. Having a separate model for each individual system allows all post-production activities involving a product to be defined and captured in the as-built model. As-built models contain the high fidelity product history information that can be used for maintenance, simulations, and quality assurance.

MODEL RECONSTRUCTION

One important aspect of any design process is determining if a given design can withstand the environments to which it will be subjected during its life cycle. These environments include mechanical and thermal insults, as well as loads due to acceleration and impact. These probability and risk assessments are increasingly being made using models created with the use of computer aided engineering tools. These tools have the ability to define a model in solid geometry, create a topological definition of the design for analysis, perform an analysis of the design in virtually any simulated environment, and post-process the results into two-dimensional flat screen projections for the analyst to review. The analyst can then provide feedback to the designer as to the feasibility of the use of the design within its intended environment. However, the ability of a designer to comprehend all the subtleties of the actual state of the design in its intended environment is, more often than not, deficient at this point with the current suite of commercially available technology. What is needed is a method whereby a designer can readily visualize a distressed model in a tactile three-dimensional mode. This tactile visualization is usually achieved by building a physical model and testing it under the specified conditions. This is a time consuming and expensive process.

The ability to fully visualize and comprehend damage in design models subject to environmental conditions is an important capability for the Los Alamos National Laboratory as well as, the entire Department of Energy's Nuclear Weapons Complex. The international ban on underground nuclear testing has made damage simulations an ever increasing asset. We are no longer permitted to perform the full assembly tests that historically has provided designers the verification that a particular design will function as predicted. Reverse engineering projects, such as the one described in this paper, were started to provide new advanced engineering technology to the Accident Response Group. The Accident Response Group needed a capability that would allow them to practice manipulating damaged nuclear weapons within the safety of digital environments and to respond to actual emergencies where critical assessments concerning the safety of a damaged nuclear weapon must be made quickly with the utmost caution. Time is of the essence when the Accident Response Group is called to a nuclear accident, and as much information about the system, the accident scenario, and the level of damage is needed to be effective in such situations.

In 1994, the Los Alamos National Laboratory's Center for Advanced Engineering Technology, which is part of the Engineering Sciences and Applications Division, began exploring capabilities development possibilities that might meet the needs of the Accident Response Group. Like most of the Center's projects, we sought to develop only what we could not acquire either commercially or from our industrial and academic collaborations. Our goal was to develop a capability that would allow our engineers to build both a digital as well as a physical model of a damaged design.

The approach taken began with the construction of an undamaged model using a commercial engineering design software package. We then subjected the design to adverse conditions using commercially available mesh generating and finite element analysis tools. The result of this step

was digital representation of our damaged design. However, in most commercial mesh generating or analysis tools, the deformations that occur in a mesh as the result of simulation are not incorporated back into the model. That is primarily do to the fact that it is often difficult to update mesh geometry after an analysis. Also, until recently there has been little need for producing a damaged model. Most commercial tools that have analysis post-processing capabilities display the damage incurred during an analysis by taking the undamaged mesh geometry and displacing each node point by its deformation. But, the mesh itself is never updated. In our work, we have developed the algorithms that update the topology of a deformed mesh. Our algorithm includes many complex capabilities like adding thickness to shell elements and compensating for element cross-over. The main reasons for wanting to be able to generate a damaged digital model is so that we can construct a selective laser sintered model as well as a simulated radiograph of the damaged design. Our motivation for wanting the rapid prototype model and the simulated radiograph of the damaged design is that it allows for a much more intuitive and comprehensive perception of the current state of the design than is currently available with simple computer displays.

MODELS BASED ENGINEERING

Models Based Engineering (MBE) is a technology catching the imagination of many scientists and engineers. There is increasing recognition that engineers need to evolve their information management infrastructure toward more advanced 'next generation' capabilities. One aspect of implementing MBE that has proven difficult is that it has come to mean different things to different people. While many agree that MBE is a critical enabling technology, not everyone agrees on what the term MBE means. In this paper, MBE is defined as a technology enabling the development of an integrated engineering infrastructure.

The five most important aspects of this definition of MBE are

1. Engineering information is a hierarchy of n -dimensional models.
2. MBE infrastructures use a single model-based product definition within a unified information management structure and establishes a single point of failure with respect to design information.
3. Engineers need to manage product model information so that models contain the appropriate level of fidelity.
4. Engineering information can be captured and applied electronically.
5. Optimum MBE environments are platform independent.

MBE is founded on the belief that all information generated, applied, and archived in an engineering environment can and should be thought of as a single unified hyper-model comprised of many submodels of n -dimensions (where n presently ranges from one to four). Given that as a fundamental hypothesis, we assert that engineers generate a lot of information that is neither geometry nor topology. Models based engineering is information management. All engineering information can be structured as an information hyper-model. The term "model" includes a much broader class of information than simply geometry and topology.

The definition of Models Based Engineering (MBE) used in this paper is that it is primarily a methodology that strives to enable product realization processes using a single representation of engineering information. That single representation should consist of n -dimensional submodels of varying levels of fidelity. These submodels comprise a unified hyper-model that contains all relevant product information. Work is being done the Center for Advanced Engineering Technology to determine the content and context of the submodels and hyper-model so that product information can be used by all disciplines in a product realization process. The information captured at each dimension of submodel complexity, and the appropriate level of each submodel's fidelity need to be determined.

An important aspect of defining MBE is determining *what* engineering information needs to move through a product realization process (i.e., information content). This should be the first consideration for any effort aimed at evolving a current engineering infrastructure.

We do not consider *how* information moves through an engineering process (i.e., information context). The complexities of physically (or electronically) getting information from one place

to another are large. We leave this complex area of research to those investigating concurrent engineering technology.

This is not to say that we think that MBE and Concurrent Engineering are disjoint. In fact, our approach to MBE presupposes the existence of a concurrent engineering infrastructure. The anticipated concurrent engineering infrastructure should be built around a philosophy of supporting multi-platform and multi-application environments. We believe that striving for an integrated engineering environment is not a reasonable or cost effective goal in engineering and that emphasis should be on creating an engineering environment that allows for diversity in both hardware and software. Ironically, this philosophy brings engineering information exchange full circle. In the early days of computer aided design, vendors, software developers, and engineers were forced to implement only interface schemes because the technologies and methodologies for integration were not available. However, in the last ten years, great emphasis has been placed on integrating both hardware and software. In the area of engineering applications, this approach has not been successful. Developing integrated environments is costly and time consuming. At the same time engineering tools are changing rapidly and those attempting to integrate environments spend all their time catching up.

Another reason that integration has not proven itself to be valuable is that the grand hope that integrated environments would make information management seamless to the engineering was never realized. That is because, in the great rush to integrate, most of the emphasis was placed on *how* information moved through an environment and little attention was paid to *what* information was disseminated. Our research into MBE methodologies has emphasized determining *what* information is important to a product realization process and *what form* that information should take. Our goal is to develop information management schemes that allow sharing of information between dissimilar platforms and tools.

PROJECT DESCRIPTION

In fiscal year 1996 the Center for Advanced Engineering Technology collaborated on a distributed manufacturing pilot project illustrating the principles of As-Built Engineering, Model Reconstruction, and Models Based Engineering. The pilot project had two primary goals. The first goal is to demonstrate that it is possible to

- a) fully characterize a product using existing technologies,
- b) perform assembly optimization, and
- c) feed As-Built Engineering information back to designers for re-evaluation of hydrodynamic and structural analysis.

The second goal of the collaborative manufacturing project was to demonstrate that in a robust models-based manufacturing environment information is captured and used more effectively. We demonstrated that the frequency and duration of visits required by engineers from the DOE design labs to the manufacturing plants can be reduced. We also demonstrated that the complexity and interactivity of information being exchanged between design laboratories and manufacturing plants can be increased.

The primary benefit of the project was to allow the DOE/NWC to work more closely together using "as-built" engineering information. This project developed and demonstrated capabilities that allow DOE/NWC parts to be designed, engineered, and manufactured electronically (i.e., without generating any paper based information such as drawings or reports). The project leveraged existing DOE efforts while seeking to enhance the capabilities of those efforts. The overall benefits to DOE from this project include faster concept-to-part throughputs, minimization of information redundancy, and an ability to simultaneously involve all product development disciplines at all phases of product realization.

In this project, two design agencies (Los Alamos National Laboratory and Lawrence Livermore National Laboratory) concurrently engineered a nominal models based design and sent that design to a production plant in an electronic form. Los Alamos and Livermore each independently engineered separate halves on an unclassified part that was to be mated together. The production plants manufactured and inspected the products using only the solid model, electronic information exchange, and models based manufacturing methodologies. Once the parts were made and inspected, the production plants sent the inspection data to Los Alamos where necessary as-built model information was generated. The design agencies took the as-built model information and reconstructed an As-Built Engineering model. This as-built model used to define how to optimize the assembly (i.e., locate the piece parts relative to one another), to fully characterize the as-built product (i.e., individual archiving), and provide as-built model information to Engineering and Physics for higher fidelity analysis and simulation. The solid model information was also used by engineering analysts to create a finite element analysis model and simulate a devastating environment for the model. The resulting deformed mesh was used to construct a rapid prototype using Model Reconstruction techniques.

CONCLUSIONS

The project described in this paper was successfully completed and illustrated the enhancements that the implementation of As-Built Engineering, Models Based Engineering, and Model Reconstruction adds to our organization's way of doing business. The application of Model Based Engineering philosophies saved us time and money. We were able to optimize our manufacturing and design processes and characterize the performance of our design more completely using As-Built Engineering techniques. Models Reconstruction provided enhanced visualization for our analytical techniques.

Los Alamos National Laboratory's Center for Advanced Engineering Technology has developed a product realization process designed to enhance the complexity and comprehensiveness of the information fed back to the designer after the analytical and manufacturing operations have been completed. Most importantly, these improvements are not based on radical new ways of engineering design or manufacturing, but rather are based on new ways of thinking about the much larger issues of enabling a complete product realization infrastructure.