LA-13155-MS

Principles of Models Based Engineering

Los Alamos
NATIONAL LABORATORY

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36.

An Affirmative Action/Equal Opportunity Employer

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither The Regents of the University of California, the United States Government nor any agency thereof, nor any of their employees, makes 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 Regents of the University of California, 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 Regents of the University of California, the United States Government, or any agency thereof. The Los Alamos National Laboratory strongly supports academic freedom and a researcher's right to publish; therefore, the Laboratory as an institution does not endorse the viewpoint of a publication or guarantee its technical correctness.

LA-13155-MS

UC-706
Issued: November 1996

Principles of Models Based Engineering

Ronald M. Dolin
Jill Hefele

Los Alamos
NATIONAL LABORATORY
Los Alamos, New Mexico 87545

Table Of Contents page

Executive Summary

This report describes a Models Based Engineering (MBE) philosophy and implementation strategy that has been developed at Los Alamos National Laboratory's Center for Advanced Engineering Technology. Models based engineering is an information management tool. Models based engineering is a key driver toward the development of adaptive product realization infrastructures. Unlike other information management technologies, models based engineering encompasses the breadth of engineering information, from concept through design to product application.

Five key assertions are put forth in this report. The first assertion is that all engineering information is interrelated and it is possible to capture all relevant product realization intent electronically and without redundancy. The second assertion is that engineering information is a hierarchy of n-dimensional model information. A third assertion is that an integrated MBE environment uses a single model based product definition within a unified information management system and therefore, with respect to engineering information, establishes a single point of failure in the concept to part process. The fourth assertion is that an optimal models based engineering environment is platform independent (both hardware and software). The final assertion is that model complexity needs to be managed so that engineers invest time and effort generating models of appropriate fidelity. Determining how much fidelity is required at various stages of product realization is discussed later in this document.

The engineering information generated in a product realization process can be thought of as a hierarchical hyper-model in n-dimensions. This hyper-model is comprised of many submodels. For example, a document or report can be thought of as a one-dimensional information model. Many aspects of design and manufacturing, such as drawings, numerical control drivers, and inspection data can be thought of as two-dimensional information models. A solid model of a product is a model in three-dimensions. Simulations involving solid models are models in four-dimensions; for example, an assembly sequence, disassembly simulation, analysis simulation, and applications of virtual reality. In this hierarchy, four-dimensional models use three-dimensional model information. The three-dimensional models, in turn, use information from the one- and two-dimensional information models.

The goal of an integrated Models Based Engineering infrastructure is unified information management and the creation of an engineering process establishing a single point of failure with respect to engineering product realization information. These are the two most fundamentally important points made in this report. With the power and availability of information generation technology it is easy for a product realization process to become overwhelmed with information that is not appropriate or necessary. The importance of controlling the fidelity of product realization information cannot be overlooked in a models based engineering environment.

Center for
Advanced
Engineering
Technology

Principles of Models Based Engineering

by
Ronald M. Dolin
Jill Hefele

Abstract

This report describes a Models Based Engineering (MBE) philosophy and implementation strategy that has been developed at Los Alamos National Laboratory's Center for Advanced Engineering Technology. A major theme in this discussion is that models based engineering is an information management technology enabling the development of information driven engineering. Unlike other information management technologies, models based engineering encompasses the breadth of engineering information, from design intent through product definition to consumer application.

1. INTRODUCTION

Models Based Engineering (MBE) is a technology that has been 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. This report summarizes contributions made in this area through research funded by the Los Alamos National Laboratory's Advanced Manufacturing Program.

This MBE research project began in October, 1994. The goal of the project is to investigate how best to evolve the Laboratory's weapons engineering infrastructure into a models based environment. This is neither the first nor the only report to consider the engineering information management issue. Nor do we expect it to be the last.

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 for the weapons program's future, not everyone agrees on what the term MBE means. In this report, 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 thus, establishe 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.

Since this MBE project's beginning, the Los Alamos National Laboratory's primary engineering division (ESA-Division), has come to recognize the importance of models based engineering in its next generation engineering vision and has launched an MBE project as one of its four technology pillars for future capabilities. The continuing efforts of this MBE Project will support the ESA-MBE project (also known as the ESA-MBE Pilot Project).

We believe that the results of this MBE project will provide useful information in future research. In the course of developing the next generation information management infrastructure presented here, we have compiled several position papers and given many presentations. We include those as appendices to this report.

The constant enemies of research are scope and/or focus. There are many issues surrounding next generation information management that we did not address in our research. That does not mean that we do not recognize their importance. Rather, this points to our continued struggle to stay focused on what we believe to be the most important issues.

One contribution this project has made to the overall discussion of next generation information management is to foster a 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. Our hope is that, if you glean nothing else from this report, you gain an understanding that, in our opinion, 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.

2. INFORMATION MODELS

The question we asked ourselves and many others this year is "what is a model?" We reviewed that question within the context of the evolution of Engineering Design and Computer-Aided Engineering (see Chapter 4). The primary hypothesis that emerged from our exploration was that every relevant piece of information an engineer generates, applies, or archives can be thought of as a submodel of *n*-dimensions, where *n* presently ranges from one to four. These n-dimensional submodels are ultimately collected into a unified product hyper-model.

This hypothesis extends the popular notion that an engineering model is only geometry and topology into the much broader regime of unified information management.

Given this definition of a hyper-model in *n*-dimensions, we subdivide model dimensionality into four spaces. In this four-dimensional space, the primary *n*-dimensional information models are:

1. one-dimensional models (documents and reports),
2. two-dimensional models (drawings, numerical control drivers, and inspection data, or other application and feedback data),
3. three-dimensional models (solid models that capture product intent), and
4. four-dimensional models (time dependent models, i.e., test data or simulations that can contain real-time feedback).

This notion that engineering information can be thought of as a hierarchy of *n*-dimensional models leads to a second hypothesis based on model fidelity. In the mathematics of geometry, model complexity goes up with '*n*.' The same is true of engineering information, as an engineering model increases in complexity (and dimensionality), more information about the design is captured. The complexity of an engineering model at any dimension is referred to as the model's fidelity. We believe that managing the generation and application of model fidelity is a very important aspect of working within an MBE environment.

One way to discuss the framework for modeling engineering information is to define this hierarchy of *n*-dimensional submodels using a cascading set of theorems built upon one another. It may seem unconventional at first, but it is a concise way to make the fundamental points.

Theorem 1.0. MBE Theorem For Minimizing Information Redundancy:

An *n*-dimensional information model should contain only enough information to unambiguously capture intended product definition without redundancies. These platform independent models should be fully integrated in *n*-space. For example, a one-dimensional information model should be integrated with the other relevant *n*-dimensional models (where n=2,3,4) so that information is only captured once and it is captured at the proper level of information dimensionality.

Corollary 1.1: Seek the lowest-dimensional model that can capture all relevant product definition information unambiguously and without redundancy.

Corollary 1.2: Information exchange increases in complexity as *n* increases

Corollary 1.3: Design information can often be more easily communicated with sophisticated information models. For example, a three-dimensional model may, in some instances, more concisely convey product information than a one-dimensional model (i.e., a picture is worth a thousand words).

Corollary 1.4: In general, the most efficient way to communicate product information is to use a combination of different *n*-dimensional submodels in some cases, product intent may best be communicated using a combination of first and third dimensional information submodels. For example, the combination of an inspection report with a nominal engineering design solid model can result in the generation of an as-built engineering model.

Theorem 2: Model Fidelity: Because engineering information can be modeled, one should always consider the most efficient way to "design" an information model with only the appropriate amount of model fidelity.

Corollary 2.1: It is usually a good practice to develop information from 1 to *n*-dimensions. In other words, always begin an information capture process in the first-dimension. Once that has been done, develop and expand that information into higher dimensions.

Theorem 3: Modeling Information: Do not over model your information. This notion is an understated theme put forward in Theorems 1 and 2 and their corollaries. The idea behind this theorem is that engineers should think about what their model information is to be used for and develop the appropriate level of model sophistication (i.e., fidelity).

Models Based Engineering encompasses all four n-dimensional information model spaces. A brief discussion of tools and technology that can be used to generate an *n*-dimensional information model is given in Chapter 4. We begin here with some background of different modeling approaches currently used within the Laboratory and some history explaining why things are done the way they are. This is followed by a discussion of useful technology development efforts that would enhance the current state-of-the-art.

3. MODELS BASED ENGINEERING FOR INFORMATION MANAGEMENT

3.1 Models Based Engineering Definition

The definition of Models Based Engineering (MBE) used in this investigation 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.

The goal of this MBE investigation is 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 disjunct. 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. See Appendix C for an in-depth discussion of this topic.

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 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.

There are many examples of engineering organizations that invested heavily into building single-platform/single-application infrastructures only to find that none of their information management and dissemination problems went away. Industrial examples include Boeing, Ford, and Chrysler.

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.

3.2 Models Based Engineering - Who It Helps

MBE makes information management across disciplines possible. MBE will become an enabling technology for all the many aspects of engineering, like archiving, design, analysis, life cycle support, process management, product management, and bringing customers into a product realization process.

At Los Alamos, the weapons program's product development process can be broken into three design activities, physics design, design engineering, and material science. Our vision of an MBE based product realization environment has all three design activities using a common information hyper-model. As Figure 3.1 shows, in addition to the design activities sharing information, post design activities such as surveillance, manufacturing, and surety share the same information as well.

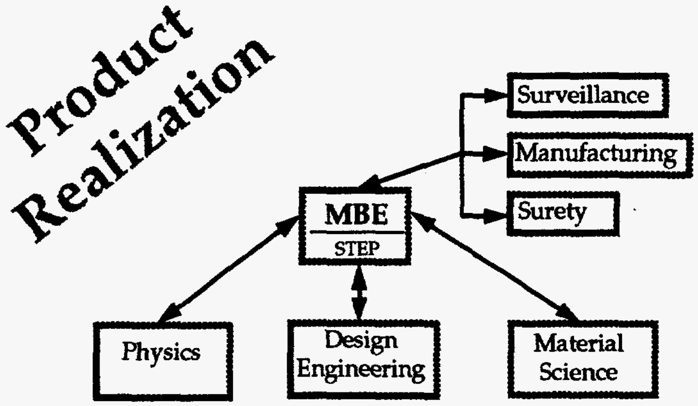


Figure 3.1. Models Based Engineering helps everyone involved in product realization.

Two important aspects of the information environment shown in Figure 3.1 are that information flows bi-directionally and the information is held in a common repository. Bi-directional flow of information is important. Members of a product realization process are at the same time allowed to access information and responsible for adding to the value and content of the information. We include post-design applications with the design activities because the need for robust design information lives beyond traditional design cycles.

Some may view the information environment shown in Figure 3.1 as a proposal for a new or different design methodology. We don't. Rather, we see it as a formalization of current design methodologies. We recognize that the one important consideration that must be diligently respected is that MBE should only be used to evolve capabilities and not to revolutionize them.

Implementations of MBE infrastructures need to reliably insure that other legacy infrastructures and our many years worth of product realization information are not compromised or left behind. Evolving to MBE environments allows engineers to retain an ability to produce product using emerging **advanced technologies** while maintaining a high confidence in their engineering **process reliability**.

3.3 Models Based Engineering - History

In the late 1970s and early 1980s engineers began to seriously begin using computers for design work. The emphasis of early computer enabling applications was for the development of engineering drawings to represent products. These initial computer aided design (CAD) tools produced two-, two-and-a-half-, and three-dimensional wire-frame drawings. Like the mylar medium they replaced, early CAD tools, while often visually complete, were seldom geometrically or topologically complete. Appendix C contains an in-depth historical perspective of the evolution and impact of computers in engineering. This perspective is from both the standpoint of how computers changed what engineers did, and how computers changed engineering itself.

3.4 Models Based Engineering And New Technology

One motivation for developing an MBE capability is that it offers a migration path that allows organizations and institutions to evolve their engineering capabilities. MBE provides the backbone for reliably considering new technologies and processes with minimal risk to mission critical activities.

Whenever new technologies or methodologies are introduced into an existing environment the question to be addressed should not be "is this good," but rather "does this enhance current ways of doing business, or provide a smooth transition path to better ways of doing business?" We believe that MBE does provide a credible and reliable transition infrastructure.

3.5 Current Engineering Process

The current engineering process used at Los Alamos, as well as in many other organizations, is serial. Many would argue that serial approaches to engineering are necessary and optimal. There are others who believe that engineering product realization can and should be parallel. Which approach is best is a very complicated subject. In the end it is almost certain that some hybrid combination of serial and parallel approaches to engineering is optimal. We do not offer an opinion on this topic, primarily because our vision of MBE works equally well with either a serial, parallel, or hybrid approach.

One aspect of the current serial approach to engineering used at Los Alamos is that by the time a product is ready for delivery to the customer there are at least five different models that can be used for some aspect of product realization. Those models are

1. **Physics Model** - used to build physics concept model,
2. **Weapons Engineering Concept Model**- the initial engineering concept model,
3. **Design Engineering Model**- generates "official" product definition drawings,
4. **Engineering Analysis Model** - the analysis model of product definition, and
5. **Manufacturing Model** - models for machining and inspection. As-built product definition.

These models are usually distinct and can become out of phase with one another as a design matures from concept to product. It is also possible that these models can capture or interpret information differently, or at the very least, with varying levels of appropriate fidelity. Another attribute of the Laboratory's current serial approach is that it leads to five separate information management activities, which is fraught with potential for information incompatibles and redundancies.

Figure 3.2 shows how our current serial approach to design works with respect to the electronic sharing of product model information. The solid lines connecting the boxes in the flow chart show the official information flow path. The dashed lines show information flow paths that are possible (and sometimes used), but not approved. Notice that the only information feedback path in this current process is from manufacturing back to design.

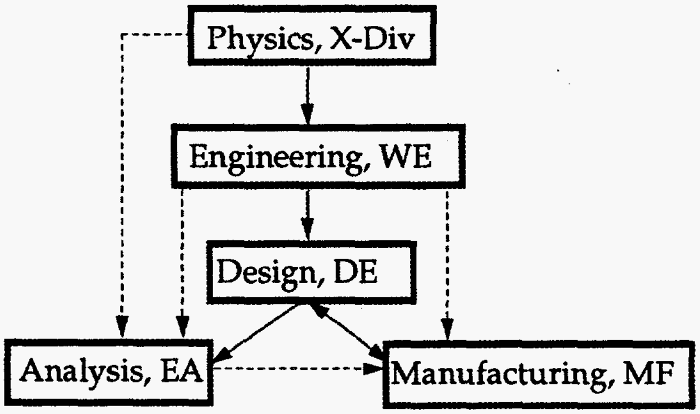


Figure 3.2. Flow chart of current product realization at Los Alamos.

One aspect of the process shown in Figure 3.2 is that there are many potential users of product information who are not part of the process. Disciplines or technologies that could provide or benefit from product information but are not part of the current product realization process include,

- the customer,
- testing,
- maintenance,
- materials,
- prototyping (physical & virtual),
- X-ray simulation,
- assembly simulation,
- computer based learning,
- inventory and scheduling,
- project management, and
- consumer related applications.

We believe that efforts aimed at developing new models based engineering environments should provide access to these disciplines and technologies.

3.6 Communication Problems That Can Be Overcome

The current product realization process used at Los Alamos is the result of many years of engineering Nevada test devices, hydro-tests shots, and stockpile components. The process is optimized for human interaction and direct personal communication. Today, however, we have access to sophisticated technologies that allow information to be developed, discussed, and exchanged electronically.

Most engineers would agree that we need to consider ways to take advantage of these new technologies. The concern, though, is how we evolve from a product realization process based on direct human communication to one based on electronic information management and exchange.

Figure 3.3 describes an actual dialog between a design engineer and an engineering analyst that recently occurred. This example is typical of information exchange within our current product realization process. In this example a design engineer wanted to have a preliminary analysis performed while a design was still in its concept stage. The initial design model was created in AutoCAD as a two-dimensional sketch (or cartoon), and given to the analyst as a starting point for constructing an analysis model.

The AutoCAD two-dimensional cartoon could not be used as input into the analyst's primary modeling tool, SDRC I-DEAS. Hence, the analyst had to port the AutoCAD cartoon into a Los Alamos developed software tool called PDT that was developed, in part, to convert two-dimensional cartoons into analysis models. Unfortunately, PDT can read neither an AutoCAD native or IGES (Initial Graphics Exchange Standard) file. PDT has an IGES translator but it cannot interpret AutoCAD's particular IGES format. Luckily, a commercial CAD system from Applicon called BRAVO can read the AutoCAD IGES file and output an IGES that can be interpreted by PDT.

Once the concept cartoon was in PDT, dimensions were verified, geometry was closed, and duplicate entities were eliminated. The model was expanded into a three-dimensional representation of the initial cartoon and the new model was passed into I-DEAS where it had material properties specified, was meshed, and was given initial and boundary conditions. The output of the I-DEAS model was used as input into the commercial finite element analysis tool ABAQUS.

The model was then read into ABAQUS and an analysis was performed. When the analysis was completed, the results were read back into I-DEAS for post-processing and evaluation.

At this point in the process, the analyst called the design engineer on the phone and suggested some design changes. The design engineer modified his AutoCAD cartoon based on the analyst's recommendations, and made a few more changes that reflected the analyst's suggestions in terms of the entire system and incorporated those changes into a new concept model.

The design engineer then informed the analyst of the additional changes verbally and the analyst modified his I-DEAS analysis model to reflect those changes.

At this point, two less than ideal situations have arisen. First, four different versions of the design model have been created - the initial concept cartoon, the analyst's suggested change model, the design engineer's design change concept cartoon, and the analyst's modified model based on his understanding of what the designer verbally told him. There are four possible places for a misunderstanding to occur and so, four points of failure with respect to the design information.

The second less than ideal situation that has arisen is that both the designer and the analyst have discovered that it is easier and quicker to convey product information verbally rather than electronically. This has a cascading negative effect. As more design changes are made, more modified concept cartoons and models will exist.

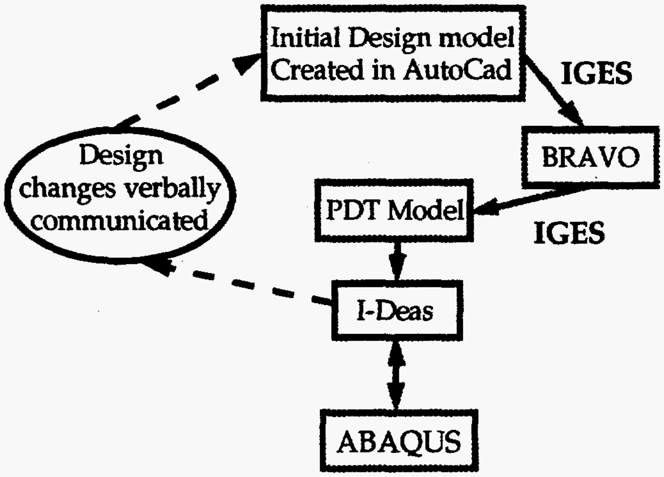


Figure 3.3. Example of information flow on a previous product.

Second, as more disciplines are brought into the problem solving exercise, more interpretations of verbally expressed design intent will have to be made. Both these phenomena increase the complexity of the design process and of the problem of managing generated information.

We believe that MBE is an enabling technology for enhancing communications within a product development environment. When an MBE environment is implemented within an engineering organization, communication problems like the ones outlined in Figure 3.3 are minimized. A lot can be said about the difficulties involved with developing a product realization process optimized for electronic information exchange and management however, we defer that discussion until later.

3.7 Developing Models Based Engineering - A Circular Approach

MBE environments should be thought of within the context of how information is developed and deployed rather than in the context of how design or engineering is done. We have often been asked what the difference is between MBE and concurrent engineering. We tend to answer that concurrent engineering looks at *how* information moves through a process and MBE considers *what* information moves through a process.

By way of metaphor, concurrent engineering is like a highway and MBE is like the cars, trucks, and buses moving commerce along the highway. Some maintain that a possible third part to this metaphor are the laws that govern how the information commerce moves along the highway. Others think that this third aspect is part of the infrastructure defined by concurrent engineering.

Most research into concurrent engineering has focused on developing new approaches to product realization based on the idea of bringing everyone involved in product realization together to simultaneously design and manufacture a product. That has required participants in a product realization process to be connected electronically, to be involved in all aspects of design, and to participate in what is optomistically called consensus engineering.

Some argue that this new utopian form of engineering is only the current in-vogue fad and does not represent an optimal approach to engineering. They maintain that if this was an optimal form of engineering it would have been the approach engineers evolved toward over the centuries. Perhaps the contexts of this discussion could be summarized by expanding our earlier metaphor. If the goal of concurrent engineering is to build the highways, then this issue of how engineering should be done is analogous to the metaphor of determining where to put the roads. Some would contend that we should pave the cow paths while others maintain that we should blaze new trails.

Luckily for us, development of MBE does not require this issue to be decided one way or the other. MBE attempts to look at engineering from an information development and deployment perspective. MBE should address the issue of what information people need in a product realization process and how they want that information managed.

In that context we believe that a MBE environment should be circular with the information hyper-model at the hub of product realization. This is shown in Figure 3.4. In this circular environment, everyone in a product realization process has equal access to all product information whenever they need it. Everyone also has the ability (or responsibility) to add value to a product definition.

Notice that we chose to call the product information hub the "Engineering Model." This was to reflect our belief that engineers should be responsible for managing product realization information in all its *n*-dimensional forms. This includes pre-design information like customer requirements and preliminary physics designs, as well as post-design information like manufacturing data and consumer maintenance specifications.

4. ENGINEERING MODEL

So far we have maintained that everyone involved in product realization should be allowed to develop and deploy product information. We also said that engineers should be responsible for managing whatever information is gathered. The next issue to be considered is what information should the overall product information hyper-model contain? At this point we are not concerned with the format of information, only its content.

4.1 STEP-The Great Interfacer?

While we do not think it overly important at this point to define information format, we recognize that in order for information to be available to the widest possible audience it has to be in a format readily accessible by many different disciplines. On the surface, it seems obvious that one-dimensional models can easily be stored and translated using the ASCII standard.

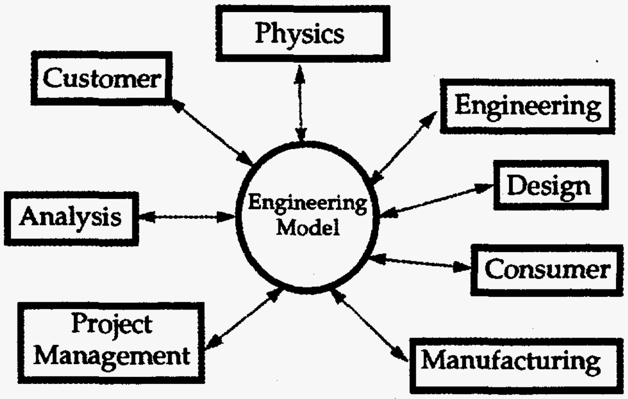


Figure 3.4. Circular Models Based Engineering environment

We believe that two- and three-dimensional information should be translated using the STEP format. STEP is an international standard whose acronym means "Standard for the Exchange of Product Model Data." STEP has the ability to encompass the one-dimensional ASCII data as well as four-dimensional simulation and test data. However, while STEP can provide a format, issues such as what information is stored within a STEP data base and how that information is interpreted and applied still need to be resolved. See Appendices C and D for further discussions.

As a data exchange standard, STEP allows dissimilar software systems to interface information. STEP, however, does not aid in information management or information content. Figure 4.1 shows a few possible product information providers that may commonly share information within an MBE environment using the STEP standard.

4.2 Models Based Engineering - As An Enabler

Models Based Engineering allows different technologies to share information in a product realization environment. Since most of these different technologies require the use of information models they can impact the content of what gets stored in engineering hyper-model. A cursory list of nontraditional technologies that could contribute to product definition in an MBE environment includes,

- X-ray Simulation,
- Selective Laser Sintering,
- Information Archival,
- Computer Based Learning,
- Analysis,
- Optimization,
- Information Perception (VR),
- Assembly Simulation, and
- Consumer Technologies.

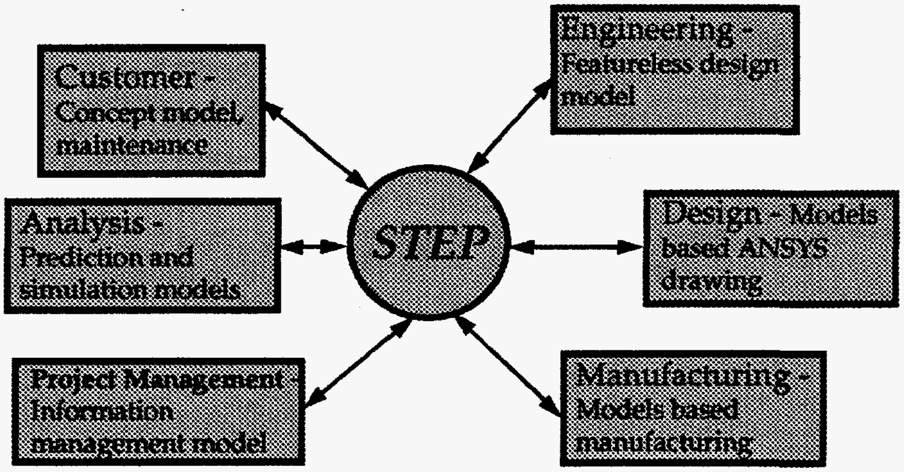


Figure 4.1. STEP as an enabling tool for Models Based Engineering.

4.3 Modeling Engineering

An important aspect of models based engineering is determining how much model information needs to be generated at each stage of product development. In other words, how much fidelity does an engineer require in a model to perform the tasks that are to be done? Even if this question seems straightforward for one-dimensional models, it gets more complicated as model dimensionality increases. Even one-dimensional models can have a complicated set of fidelity metrics.

There are actually two issues that need to be considered when attempting to answer the question of how much model information is either adequate or appropriate. They are:

1. How much information is needed?
2. When in a process is particular information needed?

Finding the answers to these questions is an ongoing research activity.

The first step in considering these questions is determining, at a high level, what it is that an engineer does. From that we can derive a matrix of the model information required. Before developing this model information matrix, an attempt is made to represent the various stages of product realization process from an information standpoint.

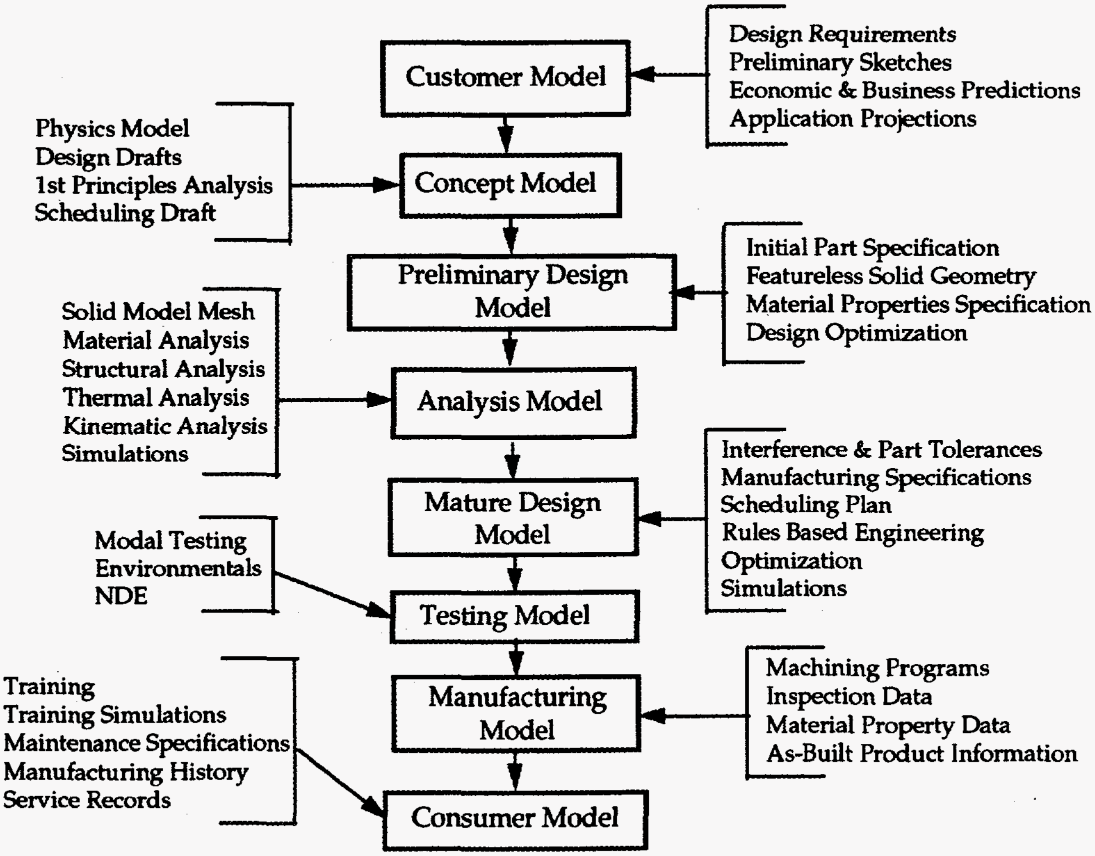


Figure 4.2 Stages of product realization in terms of evolving information.

We want to show what information is available or required at each stage. This pictorial capture of a product realization process is shown in Figure 4.2. The figure shows the stages of product realization from an information standpoint.

The serial process outlined in Figure 4.2 is subjective and should be thought of as a starting point to allow this discussion to proceed. From the standpoint of implementing an MBE infrastructure, the exact makeup of the information requirements and information flow within a product realization process are not important. One desirable attribute of MBE implementations is that they are flexible and do not require a predefined information structure.

Every different design and every different organization in a product realization process will have an information evolution different from the one shown in Figure 4.2. It is, therefore, not worth spending time dealing with how different people wish to organize their information. What is important is that information be available when needed. MBE environments need to be robust enough so that the specific organization of a product realization process does not impact how information is gathered or used.

The product realization process suggested in Figure 4.2 begins with a customer model. Information at this stage is probably very crude. Documentation will be incomplete and nondetailed. Drawings will be more artistic than technical. The customer will probably have some idea of the design requirements, an anticipated set of applications, and rough economic and business projections.

The next step in product realization is generating a concept model. The concept model contains the first technical information to be added to the product. This is the stage where physics models are generated for hydrodynamic analysis. Design engineers generate draft designs and perform some first principles analyses. Manufacturing engineers and project managers may also begin to develop scheduling plans based on emerging design candidates. Appendix C contains an alternative approach to engineering design based on more traditional metrics.

All the information generated at this stage of product development is built upon earlier, customer supplied information and is available to everyone involved in the product realization process up to this point. There will probably be one-, two-, and three-dimensional information generated.

Once the initial pool of potential designs has been narrowed down, preliminary design models are generated. At this stage initial parts specifications are formalized and material property requirements are defined. The first step in the process of building a full featured solid model of the final product assembly begins here with some featureless solid geometry models.

These featureless solid models are used to continue first principles analyses and to begin more sophisticated finite element analyses. This would also be the appropriate time to begin numerical design optimization. At this stage the design is still evolving and changing.

Everyone who has been involved in the product realization process up to this point has unrestricted access to design changes because model changes are reflected back to earlier contributors of product information.

These earlier contributors of the product realization process can review design changes against their set of metrics and criteria, and either validate the changes or suggest additional modifications. This is neither a concurrent nor a serial process, but, rather, a hybrid of both.

Once the preliminary analysis and optimizations have been performed, and the upstream participants in the product realization process have been consulted, a refined design will emerge. Attributes of the refined design can be incorporated into a more detailed, moderately featured analysis model. This analysis model can be used to perform sophisticated analysis including

- structural analyses (FEA, FDM, BEM, etc.),
- mass property analyses,
- tolerance stack-up analyses,
- kinematic analyses,
- assembly form and fit analyses,
- environmental analyses, and
- application simulations.

After these analyses are performed, the design will have matured into a near final state and full featured solid models will begin to emerge. Once a full featured model is developed, formal interference and part tolerance specifications can be made. The manufacturing process also can be specified and final scheduling can occur. This detailed model becomes the basis for the design and everything that happens to the product afterwards will be based on this model's specifications.

One application of this mature design model will be product manufacturing. This includes machining, forming, finishing, and inspection. This model will also be used for post manufacturing applications such as maintenance, training, inventory, and product management.

Perhaps the most important information contained in the manufacturing model is a definition of each individual product's "as-built" attributes. This is significant data. It is imperative that MBE infrastructures have the ability to make "as-built" product information available to upstream engineers and physicists.

Allowing engineers and physicists access to "as-built" product information versus nominal product design information has tremendous benefits in post-production environments where stockpile replacement part matching and re-engineering are critical issues. The ability to analyze "as-built" products also plays a significant role in product surety. This is important, especially in light of the increased fidelity of analysis tools (particularly physics codes) and the current government ban on nuclear testing.

Testing models also rely on the mature design model. Testing is an activity that starts before manufacturing and continues throughout the remainder of a product's life cycle. Early tests can be done in software (application simulations). There can also be a battery of physical tests performed with prototypes of varying levels of sophistication (see Appendix F). Testing information needs to become a component of product realization's hyper-model.

The generation of product information never ends. In the final stage of product realization a consumer model is generated. In this context, the consumer can be the customer who requested the product (the same person who started this process). The consumer can also be the ultimate user of the product. Regardless, the information that needs to be gathered and made available is the same.

The consumer model needs to contain training documents and some training simulation capability. There also need to be maintenance specifications and user assistance information included in the model. In return for this information, the consumer is responsible for making information they generate available to the product information hyper-model. Examples of information the consumer is responsible for providing include a history of all maintenance done on a product, discovered anomalies, the product's service records or part replacement records, and a detailed listing of all modifications made to the design in its post production life.

4.4 Fidelity in Engineering Models

This last section is for all of you who read this far and were wondering whether or not we had a point to make. The answer is yes! Our point is this, engineers should not build complex sophistication into a product model until it is absolutely required. Just because the ability to build high fidelity, full featured solids exists does not mean that doing so is always appropriate.

Earlier we attempted to define what information was needed at each stage of a product development process. In this section we attempt to formalize the notion that engineers should start with a low fidelity definition of a product and continually add value to it until they finish with a high fidelity definition of product. By moving from a low to a high fidelity definition of product we envision the information value of a product increasing in all *n*-dimensional models.

The idea of developing product model information in a logical manner with increasing complexity is not new or unique to our proposed implementation of MBE. Others in industry are also developing product realization processes based on the same philosophy. An example would be the next generation engineering project at Lockheed-Martin (see Appendix G).

At a high level of abstraction, there are four ways to use design information during product realization. They are

- physics design,
- part design,
- assembly design, and
- in-use (field or consumer) application.

We define fidelity as ranging from low to high. We use fuzzy terms like "low" and "high" because this entire discussion is subjective. We assert that a low fidelity definition contains around 25% of the ultimate product information and that a high fidelity definition contains 100%, or all of the ultimate product information.

Table 4.1 Product realization fidelity definitions

Percent Fidelity	**25%**	**45%**	**65%**	**85%**	**95%**	**100%**
Customer Model Design Requirements Preliminary Sketches Economic and Business Predictions	X					
Concept Model Physics Model Design Drafts and Rules-Based Engineering Scheduling Draft 1st Principles Analysis	X	X				
Preliminary Design Model Part Specification (featureless solid geometry) Material Properties Specification Design Optimization		X	X			
Analysis Model Solid Model Mesh Material, Structural, and Kinematic Analysis Simulations and Optimizations			X	X	X	
Mature Design Model Interference & Part Tolerances Manufacturing Specifications Scheduling Plan				X	X	
Testing Model Modal Testing Environmental NDE		X	X	X	X	X
Manufacturing Model Machining Programs Inspection Data Material Property Data					X	X
Consumer Model Training Documents and Simulations Maintenance Specifications Manufacturing history and service records						X

In between are definitions of varying fidelity.

Table 4.1 contains a matrix of what information is required during a product realization process and what the fidelity of that information definition needs to be.

The contents of Table 4.1 are not intended to serve as any sort of canonical definition of fidelity. Rather, they are meant to provide a basis for raising the awareness among product realizers that model fidelity has to be managed.

If this particular breakdown of information versus application does not seem appropriate for your product, change it. We do, however, recommend that you always develop something like Table 4.1 for your particular product.

5. CONCLUSIONS

We have presented an overview of our definition of Models Based Engineering. We presented what we considered to be the five most important aspects of MBE, namely,

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, thus, establish 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.

We defined MBE as information management. All engineering information can be structured as an information hyper-model composed of a cascading series of information sub-models of varying degrees of complexity. We showed that with this MBE framework, information models are much more than geometry and/or topology.

The question, "What is a model?" was considered. We presented an information organization system based on the notion that every piece of information an engineer generates, applies, or archives can be thought of as a sub-model of *n*-dimensions. We subdivided this model space into four dimensions and gave examples of the kinds of information that would be captured in each dimension.

We defined a set of theorems and corollaries as a means of presenting a framework for information management. We broke information down into two broad categories labeled "content" and "context." From that, MBE was defined to be more about information content (what) than about information context (how).

An MBE infrastructure was proposed. Examples were presented showing how the proposed MBE infrastructure would be structured and what kinds of information management problems it would overcome. The circular approach to engineering was proposed (a hybrid of serial and concurrent approaches to engineering) that suggested that engineers are at the center of product realization and therefore, engineers should be responsible for managing information hyper-models.

The stages of product realization were presented in terms of evolving or maturing information. The motivation for this was to emphasize our belief that managing model fidelity would not be an *ad hoc* activity. An attempt was made to demonstrate appropriate levels of fidelity that should be invested at the appropriate stages of product development.

Models based engineering was shown to be an enabling tool for engineering. It allows engineers to perform current activities in a more organized and managed manner (with respect to information). More importantly, it provides a framework that allows engineers to consider new technologies and methodologies.

In effect, MBE provides an infrastructure for enabling organizations to evolve over time. MBE will never be turnkey. It is a dynamic approach to engineering that challenges organizations to think about what they do and how they do it from the standpoint of information management. Because of this, MBE is constantly changing and moving toward more optimum modes. This is not unlike the very engineering environments that MBE seeks to enable.

This project has proposed some ideas for developing a viable MBE infrastructure. These ideas need to be reviewed and tested before implementation. Following that, the large effort of implementing MBE needs to begin. We believe that the material presented in this report contributes to this effort.

APPENDICES

Appendix A

Center for Advanced Engineering Technology

Title

Artificial Reality - Useful Applications in Engineering?

Authors

Ronald M. Dolin (505) 667-9142; email rmd@lanl.gov
Jill Hefele (505) 667-9744; email jill@lanl.gov
Fax (505) 665-5127

Sponsoring Organization

Los Alamos National Laboratory
Engineering Science and Applications (ESA) Division
Mail Stop C931
Los Alamos, New Mexico 87545

Date

March, 1995

Executive Summary

This paper asks the question "is artificial reality a useful tool for engineering?" It discusses the evolution of computer-aided design (CAD) technology and expounds a belief that artificial reality is the CAD of the new generation in engineering technology. Assumptions necessary to make artificial reality a serious engineering tool are presented, such as; 1) artificial reality can only be used to evolve engineering processes and not to revolutionize them, 2) any artificial reality system would have to run on high end personal computers or low end workstations, 3) photo-realistic simulations are not a system requirement, 4) engineers need have only enough sense of immersion to accomplish the task at hand, and 5) any artificial reality system must be cheap enough for everyone in the product realization process to afford.

The concept of models based engineering is presented and we discuss how it is a necessary prerequisite to integrated artificial reality. We look at five components of the product realization process and point out some examples of how artificial reality could be used to enhance an engineer's work. While these examples point to many powerful applications of artificial reality it should be mentioned that they have yet to be fully explored and the ultimate verdict on their benefit to engineering has yet to be determined.

There are useful applications of artificial reality to engineering. It is not clear however, that artificial reality has useful application in all areas of engineering product realization and time is needed to both mature the technology and to evolve the product realization process. Just as CAD was not immediately useful to all engineers in its infancy, we believe that artificial reality will evolve over time and become an integral tool for engineering product realization.

TABLE OF CONTENTS

1. INTRODUCTION

In the early 1980's, Computer Aided Design (CAD) was maturing into a useful engineering tool. Early CAD development efforts emphasized engineering drawings as the quintessential element of product representation. These early systems were two-dimensional, two-and-a-half dimensional (axisymetric), and three-dimensional wire frame. Early CAD systems were drawing based and, while often visually complete were seldom geometrically complete. Nonetheless, these early computer based tools revolutionized the way engineers worked.

In 1981, Los Alamos National Laboratory formed a team in their engineering division to develop specific tools using emerging CAD technology. The primary emphasis in this development effort were in the areas of engineering analysis, data translation, modeling, and data visualization. Development efforts such as these were necessary in the early 1980's because CAD tools of sufficient broad-based application were not commercially available.

Today, CAD is a necessary tool in engineering and a myriad of software tools are commercially available. Computers are increasingly being used to enhance, and in many cases replace, traditional methods of engineering product realization. Sophisticated numerical schemes are commercially available for modeling, analysis, optimization, machining, inspection, drafting, prototyping, visualization, product definition, and data perception (the essence of virtual reality). Computers have become an established tool of the engineering profession.

Virtual reality promises to be the CAD of the next technology generation. Engineering application tools developed in the future that take advantage of virtual reality technology will revolutionize the way engineers work in the same way that CAD revolutionized the engineering work spaces of the 1980's. Virtual reality offers the potential to create new visualization, analysis, and manufacturing tools for engineers. Virtual reality can allow users to interact with their data, inputting information into a simulation, modifying that information within the simulation, and obtaining sensory feedback.

Other terms used to describe virtual reality include virtual environment technology, artificial reality, augmented reality, and synthetic environments. We prefer the term artificial reality. The reason we chose not to use the term *virtual* in our description of this data perception technology is that *virtual* already has a special meaning to engineers (e. g., virtual work). Regardless of how one referrs to this technology, artificial reality is essentially a tool for enhancing one's perception of information.

The Center for Advanced Engineering Technology (CAET), at the Los Alamos National Laboratory (LANL), is working to develop useful engineering applications of artificial reality technology to support and enhance our engineering efforts in the areas of base technologies, education, and computer based learning.

The end customer for any capability developed at the CAET is the

Department of Energy's Defense Program. Like many US industries, the defense program is steeped in culture, infrastructure, and paradigms that are hard to change and impossible to ignore. Any time new technology is brought to existing processes the question that needs to be addressed is not "is this technology good," but rather "does this technology enhance current ways of doing business or provide a path to smoothly transition to better ways of doing business?"

This paper explores how the Center for Advanced Engineering Technology is going about answering the second question and discusses the criteria used to assess the value of artificial reality in our engineering product realization environment.

2. PHILOSOPHY

We started our investigation into the usefulness of artificial reality for engineering product realization with some assumptions. Some of the assumptions were based on constraints that we have to live with. These constraints include limited financial resources and a legacy computer hardware and software infrastructure.

Other assumptions were based on a conservative assessment of the state-of-the-art in artificial reality technology. Our assumptions have led to a philosophy that we use to determine if artificial reality does in fact enhance our current engineering product realization process or provide a path to smoothly transition to a better set of processes.

The first assumption is that artificial reality can only be useful as a tool to help evolve our engineering processes and not to revolutionize them. This assumption is governed by our need to ensure that we do not use new advanced technology that excludes our legacy infrastructure or our over fifty years worth of product realization information. Evolving engineering processes allows us to retain an ability to produce product while maintaining a high confidence in our engineering processes' reliability. A carefully thought-out evolutionary plan provides a path toward updating a product realization infrastructure over time.

A second assumption is that any artificial reality system developed to support engineering would have to run on high end personal computers or low end workstations. This assumption derives from our constraint of having an existing hardware and software infrastructure. Our engineers work in a distributed computing environment on networked personal computers and low end workstations. If artificial reality is to become a useful tool it will have to run on this legacy computer infrastructure.

A third assumption is that photo-realistic animation would not be a system requirement. Engineers are trained to see partially rendered geometry and infer the rest. For example, an engineering analyst can look at a mesh that displays its model geometry as facets and internally infer what the physical object looks like. Philosophically, deciding that an artificial reality system would not be expected to deliver fully rendered, photorealistic models, at 30+ frames per second allows us to consider artificial reality on low end computer platforms that are already available to most engineers.

This artificial reality philosophy is a departure from the main stream. A major thrust for developers of artificial reality technology is in attempting to "immerse" users in a synthetic environment while expecting them to suspend their sense of what is real. This approach is driven by the consuming need for "better faster graphics," which drives artificial reality developers to very sophisticated systems on high-end computers. Our approach is to not expect engineers to suspend their sense of what is real.

If the goal of an artificial reality experience is to accomplish some engineering task, we do not see any advantage in investing in the overhead required to build and run immersive environments. We want engineers to be retain the sense of being in an artificial environment.

This philosophy on the necessary level of immersion leads to a fourth assumption. Within an artificial reality experience engineers need to have only enough sense of immersion to accomplish the task at hand. That level of immersion will vary depending on the engineering task being performed, but an overriding goal should be to deliver the minimum level of immersion.

For example, if an engineer were to enter an artificial reality experience to test the functionality of a prototype design, he would only need to see the prototype in his world. Computationally expensive frills such as background scenes would add no value to the engineers ability to test the prototype's functionality. A computer in this example would be so taxed with required computations, like collision detection, that unimportant graphical computations would only slow down frame rates and response times unnecessarily.

The preceding assumptions about how engineers need to use artificial reality leads to our last assumption. Any artificial reality system developed for engineers has to run on equipment already in the engineering workplace. In other words, the entire artificial reality system, including computer, display hardware (head mounts, stereo monitors, etc.), position trackers, and interface devices (data gloves, 6DOF mice, etc.), would have to be affordable and readily available so that a system could exist at every engineers work space.

There are two reasons why this is so important. The first reason is that if a tool is not convenient, it will not be used. We learned from experiences with various CAD platforms that engineers will typically not use the "best" hardware or software; they will use the most convenient or accessible.

If an engineer has to go down the hall to use a computer, wait in a queue to run a simulation, or exit their application software to use another tool (even if that tool will enhance their work), they either won't do it, or they won't do it very often. The result is an underutilized system or a system that is not used by everyone in the product realization process. In order for any artificial reality system to be a viable engineering tool, it must work in the engineers work space.

The second reason that it is important for an artificial reality system to be inexpensive is mass distribution of technology. If artificial reality is to become an integral part of product realization it must be cheap enough for everyone in the product realization process to afford. This means the engineers as well as the production people, and perhaps even the customer. While engineers can often afford expensive hardware it is harder for small vendors and subcontractors to invest large sums of money in technology that enhances, but is not critical to, their product production process.

One potentially useful application of artificial reality is its ability to demonstrate concepts and processes to everyone in the product realization process. Through networked simulations and file transfers, the product realization process can be verified before any manufacturing resources are committed. However, that will only happen if artificial reality systems are readily available.

3. REQUIREMENTS FOR ENGINEERING APPLICATIONS

3.1 Models Based Engineering

The engineering benefits of artificial reality can only be maximized within an integrated product realization environment. If multi-platform/multi-application integration existed, artificial reality could be used to enhance an engineer's perception of design geometry, analysis data, or manufacturing processes. The Los Alamos National Laboratory's Defense Program is currently developing a concept refereed to as models based engineering. Models based engineering strives to drive an entire product realization process using a single representation of model geometry. The goal is to determine the quintessential model representation that can be used by all disciplines in the product realization process.

Models based engineering is concerned about what information needs to move through the product realization process and not with how that information moves. Models based engineering is different from the popular concept of concurrent engineering. Concurrent engineering emphasizes how information is made available to members of a product realization team, whereas the emphasis in models base engineering is on what information is made available.

Models based engineering presupposes that a concurrent engineering infrastructure is in place. Artificial reality cannot become a useful product realization tool until something like a models based engineering system is in place.

A models based approach to product realization allows engineers to seamlessly access product information. This means a lot of information in many different forms. Everything from concept geometry to test data and inspection reports. Potentially, artificial reality could be used to explore how all that product realization information is processed. This would require new techniques for data interpretation.

An example would be to consider an integrated analysis and optimization environment. Engineering designs are not always analyzed during the concept portion of a product realization process due to the effort required to develop and solve analysis problems. Many times an analyst's suggestions to improve a design come too late in the design process to be considered. Analysis is used to either pass or fail a given design and not as a tool for improving a design. In a models based approach concept model geometry would be available to an analyst, and artificial reality could be used to show a product realization team various design prototypes optimized around some set of constraints and parameters. Artificial reality could help analysts explore a design's solution space by creating new ways of visualizing the interaction that various constraint and parameter sets have on an objective function.

4. POTENTIAL ENGINEERING APPLICATIONS OF ARTIFICIAL REALITY

4.1 Artificial Reality As An Enabling Tool

Field engineers in the laboratory, and laboratory engineers in the field is a goal for next generation engineering. The Center for Advanced Engineering Technology is currently working on technologies to allow engineers in the laboratory to interact with engineers in the field. This has direct application in industrial contractor-subcontractor relationships.

We believe that artificial reality can be used to allow laboratory engineers to help field engineers assemble, disassemble, and maintain products. By acquiring information from the field engineer about the state of a product, laboratory engineers can use their resources to analyze the data, predict various scenarios and generate an artificial reality simulation that the field engineer can then use to learn necessary techniques and to practice-by-doing prior to actually working with the product.

The Los Alamos National Laboratory has always taken total life cycle responsibility for its designs. This is also a trend in industry. Using artificial reality to let laboratory engineers become part of a field engineering team enables companies to maximize their resources because artificial reality allows a company's best engineers to be in more than one place at a time. A team of laboratory engineers can be simultaneously interacting with many field engineering teams from all over the world.

4.2 Artificial Reality As A Design Tool

Engineering design means a lot of different things to different people. In the early years of CAD, the term design inferred drawings. The analogy for design was a computerized blueprint (i.e., a two-dimensional cartoon). Over time, engineers realized that drawings did not capture all the necessary design information and that computerized drafting was just a by-product of the design process and not its driving component. Computerized product realization requires a models based representation of a design that can be used by all disciplines in a product realization process.

Models based engineering requires the generation of a lot of information. That information needs to be managed as well as interpreted. The most obvious application of artificial reality to engineering design is in visualizing models in artificial environments. Artificial reality can provide a tool for enhancing a designer's ability to see a design and to potentially interact with it. This capability would add value throughout the product development process, from concept modeling to building computer based learning tools for product operation and maintenance.

Artificial reality could also be used to manage the design process itself. New techniques for project management would need to be developed. Aspects of this new project management approach would include a mature concurrent engineering infrastructure to handle how information moves around, and a concise models based engineering philosophy to determine what information moves around.

4.3 Artificial Reality As An Analysis Tool

An engineering analyst builds analysis models comprised of discrete approximations to actual design geometry, runs analysis codes based on approximation techniques such as finite element, boundary element, and finite difference methods, and post processes the analysis information. An analyst relies on numerical simulations to determine a designs reliability to a given set of conditions.

Applications of artificial reality for previewing analysis models are evident. Another potential application is using artificial reality to assess initial and boundary conditions for the analysis model. Perhaps the most promising application of artificial reality for engineering analysis is in post processing of data. Analysts generate a lot of information and making sense out of that data is as much an art as it is a science. Entirely new paradigms would be required for artificial reality post processing. For example, what would stress information look like in an artificial world? Do contour plots and color coding make sense when the power to perceive information with other techniques is available?

4.4 Artificial Reality As A Manufacturing Tool

Like design and analysis, artificial reality provides an enhancement tool for letting engineers visualize their processes. Manufacturing can be described as the integration of a series of processes. Manufacturing requires both information and product management. Artificial reality can be used to improve manufacturing simulations and in some cases, lead to new simulation paradigms. There may be more immediate benefits to using artificial reality for product management than for using it to simulate manufacturing.

4.5 Artificial Reality As A Training And Learning Tool

Computer based learning is a discipline that addresses how people learn. Computer based cognitive programs facilitate the learing process through interaction with a computer. Computer based training and learning technologies are becoming very important to product realization. Los Alamos has always taken complete life-cycle responsibility for its product. This is the current trend in industry as well. This means that training for assembly, maintenance, and disassembly are becoming increasingly important.

Computer based learning is an important tool for training and maintaining worker skills. This is especially true for highly technical skills that are not used very often.

When a person learns by doing they retain more information than when they are lectured to, or when they learn by watching. Because the immersive abilities of artificial reality allow workers to learn by doing in a simulated environment, artificial reality can be a useful tool for training and learning.

5. CONCLUSIONS

At the beginning of the paper we asked the question "is artificial reality a useful tool for engineering?" We discussed the evolution of computer-aided design technology and our belief that artificial reality is the CAD of the new generation in engineering technology. We outlined certain assumptions necessary to make artificial reality a serious engineering tool such as

1. artificial reality can only be used to evolve engineering processes and not to revolutionize them,
2. artificial reality systems have to run on high end PC's or low end workstations,
3. photo-realistic simulations are not a system requirement,
4. engineers only need enough sense of immersion to accomplish the task at hand, and
5. artificial reality systems must be affordable for everyone in the product realization process.

The concept of models based engineering was presented and we discussed how it would be a necessary prerequisite to integrated artificial reality.

We looked at five components of the product realization process and pointed out some examples of how artificial reality could be used to enhance an engineer's work. While these examples point to many powerful applications of artificial reality it should be mentioned that they have yet to be fully explored and the ultimate verdict on their benefit to engineering has yet to be determined.

It must not be assumed that artificial reality is inherently good for improving engineering. It is almost certain that artificial reality can enhance design and an engineer's ability to visualize and interact with a design in a synthetic environment. Likewise, artificial reality offers powerful potential as a training and learning tool. These two enhancements to product realization by themselves make artificial reality a serious technology for next generation engineering.

What is not as clear is whether artificial reality can provide a better analysis post processing or manufacturing simulation tool than is currently available. While artificial reality can simulate a manufacturing process with more realism, does the added benefit of enhanced realism outweigh the extra costs? This is an important question that is being asked from an engineer's perspective. For managers and customers the answer to this question is almost certainly yes, but for engineers the answer requires careful consideration.

The answer to our initial question "is artificial reality a useful tool for engineering?" is both "yes" and "we don't know yet." There are clearly some useful applications of artificial reality to engineering. It is not clear that artificial reality has useful application in all areas of engineering product realization and time is needed to both mature the technology and to evolve the product realization process. Just as CAD was not immediately useful to all engineers in its infancy, we believe that artificial reality will evolve over time and become an integral tool for engineering product realization.

Appendix B: Presentation On Advanced Manufacturing

1) **Models Based Engineering**

- Definition
- Overview
- What it means

Ron Dolin
rmd@lanl.gov

Jill Hefele
jill@lanl.gov

2) **MBE - Definition**

- Strives to drive the entire product realization process using a single representation of model geometry
- The goal is to determine the quintessential model representation that can be used by all disciplines in a product realization process.

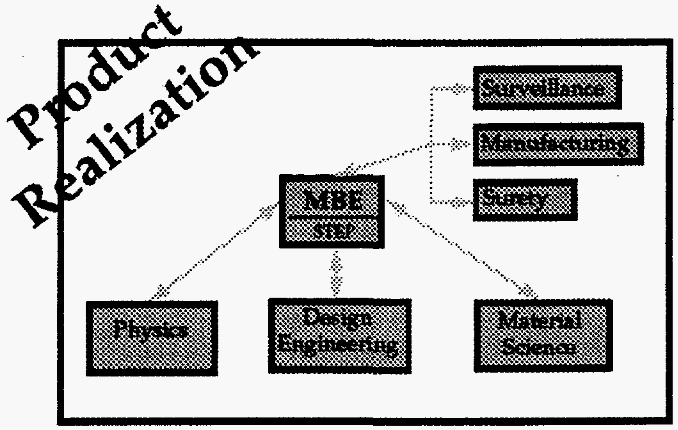
3) **MBE - Definition .....continued**

- What information needs to move through a product realization process
- Presupposes existence of a concurrent engineering infrastructure
- Multi-platform / Multi -application integration and/or interface

4) **MBE - Definition .....continued**

- Makes information sharing possible
- Makes information managment possible
- Enabling technology for life cycle support
- Brings customer into product realization process.

5) MBE - Who it helps



6) Considerations: Evolution vs. Revolution

- Need to insure that implementing a MBE approach does not exclude our legacy infrastructure or our over fifty years worth of product realization information
- Evolving to MBE allows us to retain an ability to produce product using **advanced technology** while maintaining a high confidence in our engineering **process reliability**.

7) MBE - History

- Computer Aided Design
    - Emphasized engineering drawings as product representation
    - Two-D, Two-and-a-half-D, & 3-D wire frame
    - Often visually complete - seldom geometrically complete.

8) New Technology

Whenever new technology is introduced into existing processes the question is not

"is this technology good"

But,

"Does this technology enhance current ways of doing business, or provide a smooth transistion path to better business methodologies?"

MBE - provides transition infrastructure

9) Current Engineering Process

Serial Approach

1 **X-Division** - builds physics concept model

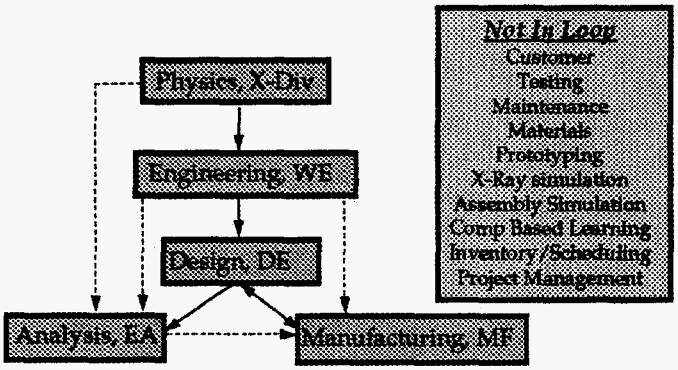
2 **Weapons Engineering** - builds initial engineering concept model

3 **Design Engineering** - generates drawings

4 **Engineering Analysis** - builds analysis model

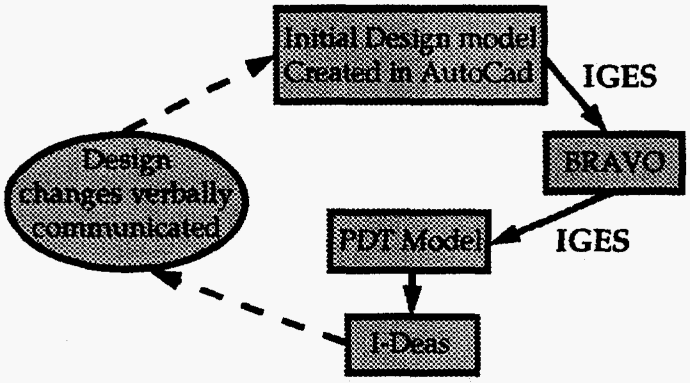
5 **Manufacturing** - **builds machining models**

10) Current Serial Approach



11) Communication Problems Example

Two Person Interface:

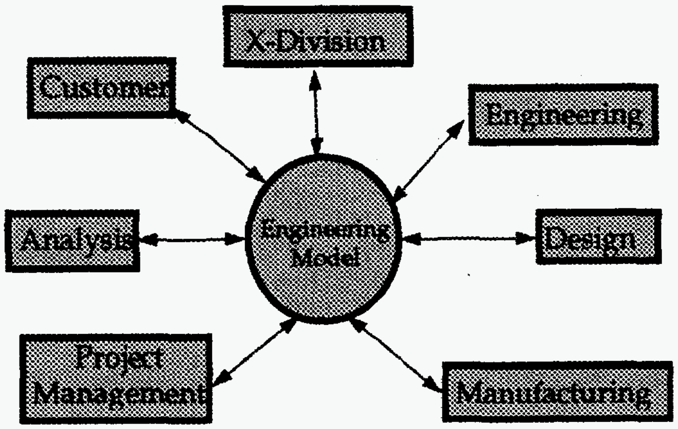


12) Developing MBE - A Parallel Approach

- Obtainable only if aspects of engineering product realization can equally share model information in a "value-added" manner

Models Based Engineering is not Concurrent Engineering - Concerned with **what** information gets managed, and not with **how** information is managed

13) Model's Based Engineering



X-Division

Customer

Engineering

Analysis

Engineering Model

Design

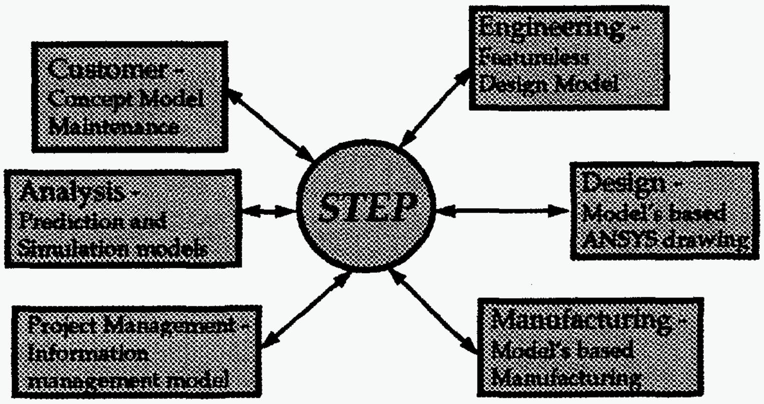
Project Management

Manufacturing

14) Engineering Model

- What does it look like?
- How is it stored?
- What are other Engineers doing?
- Enabling Tool May Be **STEP**..... "Standard for the Exchange of Product Model Data"

15) STEP The Great Interfacer?



Customer - Concept Model Maintenance

Engineering - Featureless Design Model

Analysis - Prediction and Simulation models

STEP

Design - Model's based ANSYS drawing

Project Management - Information management model

Manufacturing - Model's based Manufacturing

16) MBE - The Great Integrator?

Models Based Engineering allows integration with new technologies:

New Technologies

X-ray Simulation
Selective Laser Sintering
Information Archival
Computer Based Learning
Integrated Analysis
Optimization
Information Perception (VR)
Assembly Simulation
Industrial Technologies

17) What We've Been Doing

- Surveying Industrial Engineering
- Developing concept of MBE in parallel with the ESA-Concurrent Engineering project
- Discussing MBE philosophy with X-Div
- Developing model transfer with plants, KC this month, Oak Ridge later this year

18) Conclusions

- Models Based Engineering - quintessential element of next generation engineering
- Necessary component in a "rapid response engineering" environment
- Stability in environment where technology is advancing while expert base is diminishing
- Integrator of all aspects of weapons work

19) Technology Applications

X-Ray Simulation

- Field data acquisition integrated with analysis capabilities
- Modeling and analysis integrated with Non-Destructive evaluation
- Applications:
- Design for Inspectability, ARG/NEST,
- Stockpile support, Benchmarking software
- Archival, Training

20) Computer -Based Learning

Training and Maintenance Package for DX designed and manufactured detonator.

- ❖ Instructional Design
- ❖ Archival of engineering information
- ❖ Design, manufacturing, and maintenance
- ❖ Assembly simulation
- ❖ Prototyping

Sponsor: AMNII and Center

21) Advanced Manufacturing

- ❖ Virtual Prototype
- ❖ Remote machining
- ❖ Robotically controlled assembly
- ❖ Concurrent engineering with offsite facilitates - development and manufacturing

Sponsor: AMNII

22) Engineering Information Management

- Information Archival
  - Not how to store information
  - Rather, what information is important, how should it be shared, and disseminated.

Sponsor: Oil & Gas Consortium

LA-13155-MS
CAET-2-95-1

Appendix C

Center for
Advanced
Engineering
Technology

Title

Computers for Design - An Historical Perspective

Authors
Ronald M. Dolin (505) 667-9142; email rmd@lanl.gov
Jill Hefele (505) 667-9744; email jill@lanl.gov
Fax (505) 665-5127

Sponsoring Organization
Los Alamos National Laboratory
Engineering Science and Applications (ESA) Division
Mail Stop C931
Los Alamos, New Mexico 87545

Date
February, 1995

Executive Summary

In an integrated environment, computerized aspects of product realization, such as modeling, analysis, prototyping, and manufacturing, all operate as a cohesive system accessing a single information source. Efficient management of product realization information allows an engineer to concentrate more on a design and less on the design process. Computers are increasingly being used to enhance, and in many cases replace, traditional methods of engineering product realization. The most persistent problems emerging from this computerization of engineering are those associated with compatibility and integration.

Table Of Contents

page

1. INTRODUCTION

1.1 Motivation

Integrating the overall engineering product realization process is an enormous task. In an integrated environment, computerized aspects of product realization, such as modeling, analysis, prototyping, and manufacturing, all operate as a cohesive system accessing a single data structure. Properly managing product realization information allows an engineer to concentrate more on design and less on the design process. It allows multiple design scenarios to be easily explored. This results in a fully developed interrogation of a design's solution space and leads to a better understanding of a design's physical characteristics.

One example of how engineering design could be improved in such an environment would be to consider an environment where analysis and optimization jointly share information. Engineering designs are not always analyzed during the "what if" portion of a product realization process due to the effort required to develop and solve analysis problems. Many times an analyst's suggestions to improve a design come too late in the design process to be considered. Analysis is used to pass or fail a given design but not as a tool for improving the design.

Design optimization can be defined as the process of searching through all potential design configurations and finding the "best" set of design parameters to satisfy all the design constraints. Design optimization can be both a formal iterative exploration of some solution space defined by the design's constraint equations and parameter sets, or the informal process of a design engineer posing what if scenarios. Design optimization can occur anytime during the product realization process but design improvements are easier to adapt early in development before manpower and capital are committed to a particular design.

If analysis and optimization efficiently shared information, designs could more readily be analyzed and optimized. If these operations were run within a models based geometry system; modeling, analysis, and optimization would become one information process driving product realization.

1.2 Background

Computers are increasingly being used to enhance, and in many cases replace, traditional methods of engineering product realization. Sophisticated numerical schemes are commercially available for modeling, analysis, optimization, machining, inspection, drafting, prototyping, visualization, and product definition. Computers have become an established tool of the engineering profession.

The most persistent problems emerging from this computerization of engineering are those associated with compatibility and integration. Computer hardware and software are highly proprietary. In general, dissimilar products do not communicate with one another. If two software systems are developed to perform the same task, or the adjoining task in a product realization series, their data structures are usually different enough that they cannot share information.

Historically, software developed for the different phases of product realization are neither integrated nor compatible. One reason is that each phase of product realization uses special characteristics and requirements that make generic programs less efficient than specifically written programs. Another reason is that software venders hope to establish their codes as future defacto standards. This competition for market leadership has impeded progress toward integration and compatibility.

In the absence of integration, both hardware and software need improved compatibility. Some efforts have been undertaken to achieve this. In 1981, the first geometry data standard known as the Initial Graphics Exchange Specification (IGES) was approved as the American National Standards Institute (ANSI) standard Y14.26M. [SMIT83]

In 1986, the third version of IGES was released. It was originally called IGES Version 3.0, but was subsequently changed to the Product Data Exchange Specification (PDES). [BRAU84] The PDES committee felt that a standard product definition would lead to integrated product development. However, due the fierce competition in the computer market, the proprietary nature of the hardware and software, and the complexities involved in integration, PDES is not yet widely available. Vendors projecting PDES support in the near future appear to be supporting through interfaces and not integration.

Standards govern almost every aspect of computerized engineering. For example, in addition to IGES/PDES, other geometry standards include the Computer Graphics Metafile (CGM) standard, Graphics Kernel System (GKS) standard, Computer Graphics Interface (CGI) standard, Programmer's Hierarchical Graphics System (PHIGS), etc. [CHIN87]

CAD research in the 1980's was dominated by a believe that interfacing the many phases of product realization resulted in slow, labor intensive, error prone systems. The pervasive thinking was that considerable efficiency and accuracy can be gained by developing the theories necessary to integrate the engineering product realization process.

Discounting commercial aspects, there are major difficulties involved in integration. Foremost is the problem of developing a single data structure that can exploit the particular features of each phase of the product realization process while providing an unambiguous product definition.

An integrated data structure should define geometry so that it can be readily visualized, interpreted, and used by all engineering disciplines. At the same time, the data structure needs to be mathematically complete so that analysis, optimization, prototyping, machining, inspection and other numerically dependent operations can unambiguously access the model's topology and geometry. Finally, the data structure should be compatible with STEP/PDES for portability.

Proponents of integration felt that an advantage would be that each phase of the process would access the same data structure. There would be no need to pre- or post-process data through translators. Whenever the product model changes, each phase of the product development process would have access to those changes. The elimination of translators would improve efficiency, accuracy, and reduce ambiguity.

One difficulty involved with integration has continued to be that the computerized product realization process is not well defined. The debate goes back and forth over which phase of product realization should drive the data structure format. Even when geometry and topology drive data structure format, it is unclear whether the data should be defined in terms of Numerical Control (NC) needs [RYAN87], Computer-Aided Engineering (CAE) modeling needs [WEID84], analysis needs, or a information format suited to some other product realization need.

1.3 Approach

This investigation develops methods for bringing the informational requirements of engineering product realization into a single infrastructure. The approach is to develop what we call a “models based” engineering infrastructure that incorporates a value-added philosophy of engineering information management as opposed to the value-subtraction methodology commonly used today.

The cornerstone of models based engineering (MBE) is information management. The underlying data structure should allow geometry, topology, constraint, mesh, material property, etc., information to be stored in a concise but highly accessible manner. At issue is how can a single engineering model be defined so that its useful to every product realization discipline needing information? Instead of attempting to tackle that large question, we will look at one aspect. Namely, what are the informational requirements of engineering design? That question can only be answered by considering engineering design as a process.

2. ENGINEERING DESIGN

Problem solving exercises often appear diverse and unrelated. In fact, systematic methods can be used for solving virtually any problem. Engineering problem solving has certain characteristics that make it unique relative to other professions. Eide, et. al., defined the primary goal of engineering problem solving as the exploitation of technology for the purpose of developing a product. They considered engineering problem solving as a design process where “design” was defined as “to create according to plan,” and “process” as “step-by-step changes that lead toward a required result.” [EIDE79] Their definitions suggest that engineering design is an orderly systematic process.

E. Krick considered engineering design as an iterative process that transforms a design from one form into another while satisfying specified criterion and constraints. Krick defined criteria as the preference toward a particular aspect of a design and constraints as restrictions imposed on it. [KRIC79] In other words, criteria are those aspects of a design used to evaluate the acceptability of a design while constraints represent fixed characteristics that the design must satisfy.

A well defined design process helps divide a large problem into simpler, workable subproblems. A well defined design process enhances an engineer's ability to get a stalled design moving and insures that problem solving efforts remain focused. There is a difference between considering several solutions to a design problem and focusing on a particular solution. A systematic problem solving procedure almost always insures that the best possible solution to a design problem is found. [KRIC76]

Krick divided the engineering design process into five phases, while Eide, et. el., used nine. Both contain the same general steps. The systematic process of engineering product realization discussed in this investigation is a combination of both definitions and is divided into the following phases:

1. Identify and establish the need.
2. Define and formulate the problem.
3. Search for solutions.
4. Perform detailed analysis.
5. Decide on a design.
6. Develop specifications.
7. Communicate design.

2.1 Identify And Establish The Need

The first step in engineering product realization is the recognition that something must be done. There are several questions that need to be considered during this initial phase. For example, what is the basic problem and how much effort is going to be required to solve it? Does the potential benefit out weigh the cost? How important is the solution of the perceived problem? These are all broad questions and only general answers should be considered.

Someone involved in the product realization team must take responsibility for identifying the need and communicating it to the remainder of the product team.

2.2 Define And Formulate The Problem

The manner in which an engineering design is defined and formulated impacts the characteristics of the final product. It is essential at this phase of the product realization process that the problem definition and formulation be broad to avoid pointing to any particular solution. Narrow problem definitions and formulations have the potential for excluding desirable aspects of a design from consideration.

It is important to solve the right problem and this phase of the product realization process is where the right problem is determined. Krick suggests a "black box" approach for defining and formulating the problem. His approach assumes that details of the solution are not yet important, only a general problem statement (input) and a desired solution (output) should be considered. [KRIC76]

A general problem statement provides basic information about the nature of the final design. Some variables of the design should be identified. Broad definitions of both criteria and constraints can be made. A broad statement of the product's intended application can add insight to the characteristics that are desired.

2.3 Search For Solutions

A good way to gain an appreciation for alternative solutions is to consider known solutions from similar product realization problems. Innovative new ideas should also be considered. The number and variety of solutions should be as large as possible. It is too early to be specific and details of the design are still of no interest. The set of possible solutions to the problem is called the solution space.

Once the solution space has been fully developed, the definitions of the criteria and constraints can be applied to deliberately and systematically reduce the number of alternative designs. The surviving designs can then be further considered.

2.4 Perform Detailed Analysis

Engineering analysis uses mathematical and physical principles to evaluate the performance of a product. A product's performance is usually measured in terms of an objective function. Objective functions are mathematical equations, usually written in terms of design variables which must be minimized while the design variables are subject to specific constraints. [RAO87]

The usual areas of engineering analysis are the laws of nature (mathematical analysis), the laws of economics, and common sense. [EIDE79] There are several methods of mathematical analysis and it is up the engineer to determine which is appropriate. Commonly used mathematical analyses include structural, thermal, vibrational, acoustical, etc. These are all used to predict the performance of the product.

The economics of a design help to establish allowable costs and expenses, while predicting potential profits. These factors determine materials, manufacturing processes, etc. An engineer's common sense is used to eliminate design alternatives that prove infeasible based on a combination of mathematical, economic, and heuristic analyses.

The analysis phase of the product development process involves an iterative procedure. Given a design model, an engineer analyzes it using mathematical, economic, and heuristic considerations. The model can then be modified by changing design variables and re-analyzing. The goal of this iterative procedure is to find the best (optimal) form of a design that satisfies the specified criteria and constraints.

2.5 Decide On A Design

The iterative analysis process should result in several alternative designs that are each best in some sense. It is the engineer's responsibility to determine what trade-offs are made for each alternative design. These trade-offs need not necessarily be the same.

Engineers must evaluate and compare the alternatives. By considering the merits of each alternative, the engineer can pick the one design that best meets the specified criteria and constraints. The selected design is the solution to the original product realization problem.

2.6 Develop Specifications

The chosen design must be well documented so that everyone who needs to use and understand the design can interpret it in an unambiguous manner. In general, this requires written specifications and an electronic model. Written specifications (specs) outline materials, tolerances, and manufacturing procedures. Specs convey design intent and resolve any ambiguity in design interpretation.

Models are the language in which engineers convey ideas. Engineering models generally contain a complete and unambiguous representation of a product's geometry and topology. Engineering models are used to generate dimensioned, layout, and assembly drawings. Dimensioned drawings describe the size and topology of each part making up the design. Layout drawings delineate clearances and demonstrate the design's kinematics. Assembly drawings establish the relationships between each part in the design.

2.7 Communicate Design

It is the engineer's responsibility to insure that the final design is properly and adequately communicated both to management and craftsmen. The engineer must make sure that managers know the cost, life expectancy, reliability, etc., of the product and that craftsmen know the proper way to product the product.

3. COMPUTERIZED PRODUCT REALIZATION

The phases of engineering product realization previously discussed suggest a scientific method. G. Musgrave showed that this was not always the case. Musgrave considered the evolution of engineering design of the last sixty years by reviewing past issues of Electronic Design (and its predecessors). He showed that prior to 1958, design was most often done using experimental trial and error methods. It was only after computers were introduced to engineers that the engineering product realization process took on scientific stature. [MUSG88]

Computers allow complex analyses and simulations to be performed with relatively little effort. Computers speed up the tedious and mechanical modeling process. In many instances, computerized methods of design have become as reliable as experimental methods. Musgrave observed that through the evolution of computers, engineering design has come full circle. The speed and accuracy of present hardware and software has given engineers the ability to consider several design scenarios or, in essence, to experiment.

Many phases of the engineering product realization process have been computerized. Commercial hardware and software is available to assist engineers from the time alternative designs are first conceived until the final product is manufactured and inspected.

Currently, most phases of the product realization process are disjoint. A considerable contribution can be made by developing the theories and technology necessary to bring these computerized processes into a cohesive and automated infrastructure. [MERE88], [RYAN87], [ROUS86], [ROSE83]

In a computerized product realization processes, the engineer can explore the solution space by analyzing and optimizing alternative designs. This involves the same iterative procedure discussed earlier. Most commercial analysis systems use the finite element method (FEM) or finite difference method (FDM) of analysis to perform the mathematical (or numerical) analysis. In general, these methods require the design's domain to be remeshed for each analysis iteration. [BERN87], [DING86], [HAFT86], [SING82]

Engineering models should be optimized. Computerized optimization of engineering problems is relatively new. Most optimization systems utilize sensitivity and gradient information. This information is usually available through the FEM and FDM analyses. Using the FEM/FDM information in a numerical optimization procedure usually results in a large number of design variables. This places a large computational burden on the optimization procedure and makes posing the optimization problem more difficult. [VAND87]

Written specifications and models of a design should be developed so that an engineer can communicate the final product. In a well managed product realization environment, a mathematical model of the final engineering design should already exist. This model should have evolved during the design-analysis-optimization iterations.

Dimensioned, layout, and assembly drawings can be constructed from the engineering model. There are many commercial drawing systems currently available that interface with a model through the use of IGES translators. In general, these translators are not efficient and are prone to errors. In an MBE environment these drawings become part of the engineering model so translation is not necessary.

4. COMPUTER AIDED ENGINEERING

Perhaps the most important feature of any engineering software system is the structure of its data base. The data base is where information is stored and accessed. How that information is stored and accessed is know as the structure, or format, of the data base. [BARO80] Usually, the structure of a data base is determined by its intended application. [DUBE83]

The computerized phases of the product realization process each have special features and characteristics that drive the structuring of application dependent data structures. These dissimilar data structures generally only communicate with one another through translators. [GLAN88] The product realization process can be managed more efficiently if a single data base structure is developed that shares information freely with each customer of its information. [DUBE83] Another way to integrate the product realization process is to develop theories and technologies that allow dissimilar data structures to share product information. [DOLIN94]

4.1 History

Computers were first used in the product realization process for generating drawings. These initial systems were understandably drawing based. [DOLIN85] Characteristics unique to engineering drawing (or drafting) were the primary factors used to determine how topology would be defined and modified. The drafting process determined the structure of the data base. These early systems became known as

Table 4.1 Acronyms used to describe phases of the computerized product realization.

Acronym	Name	Application
CAD	Computer-Aided Drafting	Generate engineering drawings
CAD	Computer-Aided Design	Automate engineering design process
CADD	Computer-Aided Design and Drafting	Automate engineering design process
CAE	Computer-Aided Engineering	Automate engineering design process
FEA	Finite Element Analysis	Perform finite element based analysis
CAM	Computer-Aided Manufacturing	Automate manufacturing processes
CAM	Computer-Aided Machining	Automate machining processes
NC	Numeric Control	Numerically control machining processes
CID	Computer-Integrated Design	Automate inspection processes
CID	Computer-Integrated Design	Integrate engineering design processes
CIE	Computer-Integrated Engineering	Integrate engineering design processes
CIM	Computer-Integrated Manufacturing	Integrate manufacturing processes
CIM	Computer-Integrated Machining	Integrate machining processes

Computer-Aided Drafting (CAD) systems.

Drawings are often considered the quintessential element of engineering product realization. A tendency to regard drawings as a definition of engineering product leads to a second meaning for the CAD acronym, Computer-Aided Design. In a broad sense, Computer-Aided Design has come to represent all of the product realization phases. Generally, if a software system improves the performance tasks of at least one phase of product realization, and requires the use of a topological representation of the product, it is referred to as a CAD system.

The computerized product realization process contains many acronyms that infer some sort of operational functionality. Like CAD, most acronyms used to describe a software are ambiguous. It is usually not possible to determine what aspect of product realization motivated a software system's data structure based on the system's name.

Table 4.1 lists several commonly used system acronyms with their commonly implied applications. [GLAN88], [PARF88], [KACA86], [BEEB83], [ROSE83]

5. MODELS BASED ENGINEERING

Terminology is dangerous. Often a word or phrase takes on different meanings to different people. For example, the acronym CAD represents several different things. In its earliest form, CAD stood for Computer-Aided Drafting. Other interpretations include Computer-Assisted Drawing, Computer-Aided Design, and when spelled as CADD, has meant Computer-Aided Design and Drafting. Even within the words Computer-Aided and Design there is ambiguity.

What does *design* mean? To many, a design is a cartoon picture that represents a visual rendition of the a models topology.

The term *Engineering Model* means a lot of different things to different people. To some, it means nothing more than a formatted file that can be read into some Computer-Assisted Engineering (CAE) system. The content of the file would not necessarily matter.

To some, an engineering model means an electronic version of the classical mylar drawing. Computer drawings are kept as formatted files and they can be view but not used for many engineering applications

One aspect of 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 for the weapons program's future, not everyone agrees on what the term MBE means. In this report MBE is defined as a technology enabling the development of a managed engineering information 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 thus, 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.

6. CONCLUSIONS

Managing engineering information is not an easy task. The efforts of the 1980s to integrate the many aspects and disciplines of product realization have for the most part not worked. Models based engineering offers an alternative to integration. MBE infrastructures seek to define an information management environment that can share relevant engineering information with all disciplines in a product realization process in a value added manner.

Defining this MBE infrastructure will not be easy or done quickly. Even the seemingly simple task of using solid models to represent design requires a large evolution from traditional paradigms into new, and yet unproven ones. This long term goal is the continuing focus area of this investigation

Appendix D: STEP Training Trip Report

Memorandum

Center for Advanced Engineering Technology
Engineering Science and Applications Division
Los Alamos National Laboratory
Los Alamos, NM 87545

DATE: October 29, 1996

TO: Group Leaders, ESA-Division

FROM: Ron Dolin, Jill Hefele, Linda Dilsaver, and Brenda DeRoser **MAIL STOP:** P946
EMAIL: rmd@lanl.gov, jill@lanl.gov, dilsaver@lanl.gov **PHONE:** (505) 667-2230

SUBJECT: STEP Training Trip Report and Update

We recently attended a two day STEP training course at International TechneGroup Incorporated's (ITI) headquarters in Ohio. STEP is an international standard for product representation that was released last month after ten years of development. STEP is an acronym for Standard for the Exchange of Product Model Data (don't ask me how it translates into the acronym...someone told me once that in French it works). There is a corresponding US standard (bet your surprised!) called the Product Data Exchange using STEP (PDES). This acronym has had about four different meanings in the last ten years.

Before you read all of the gloom and doom that follows, we want to emphasize our belief that migrating to a standard environment, such as a STEP product data exchange environment, is a necessary course for ESA-Division. STEP is our only viable hope for platform and software independent product information exchange with other organizations inside and outside the laboratory. It is also a quintessential element of Models Based Engineering. A concept that you will be hearing more about in the near future.

The two most important things we learned during training was that

1) STEP will not immediately replace IGES (the current geometry transfer standard used in ESA) and

2) STEP was never meant to be "plug and play" technology.

The rest of this memo will be devoted to explaining items 1 and 2, and to lower expectations about what STEP will mean and do for ESA in both the long and short term.

STEP will not immediately replace IGES. The Initial Graphics Exchange Standard (IGES) has been in use in ESA for about twelve years. It has become a local de facto standard geometry exchange protocol within the weapons engineering community. IGES has many limitations and propensities for errors (why IGVIEW was created). The reason that IGES will continue to be a viable data translation tool is because many users will not immediately require the advanced features of STEP. Commercial CAD vendors will continue supporting IGES in the future. And STEP will take several years to become a viable data translation tool.

Continued use of IGES will persist simply because an IGES infrastructure already exists in most institutions and change costs money (always frame an argument in terms Americans can understand). Since IGES added solids and trimmed surfaces, many companies see no compelling reason to migrate their product data exchange format to STEP. Another variable in the equation is that until the solid modeling wars are over there is too much flux in models based methodologies to invest in STEP. At issue in the solid modeling wars is how will solids be represented, manipulated and parameterized. CSG systems are quickly becoming a thing of the past but even within the B-rep family of modelers, the rivalry between ACIS, ProEngineer, and others to define solid modeling standards is fierce.

STEP has yet to address how parametric models will be represented or translated in a way that preserves the model's logical structure. If logic cannot be maintained, only explicit solid model files can be exchanged and that destroys any chance of intelligent sophisticated model information sharing.

STEP will not be "plug and play" technology. Implementing STEP in our engineering process will require both an up-front resource requirement and a continuing investment in supporting local STEP expertise. We had hoped that STEP would allow us to remove ourselves from involvement in data translation but if anything, STEP will require an even greater commitment to understanding information exchange than IGES required. This is primarily due to the fact that there are many "mini" translation standards within the STEP standard. These mini standards are referred to as Application Protocols (AP's). There are currently twelve AP's, with more slated in the future. There is an automotive AP, a ship building AP, an electronics AP, etc. Every industry that thinks they're important has to have an AP......which probably means that the DOE/NWC will have to have their own AP, as well, at some point in the future. DOE-DEF might just evolve into some bizarre DOE AP for Weapons Engineering Product Realization.

Appendix E STEP Conference Trip Report

Memorandum

Center for Advanced Engineering Technology
Engineering Science and Applications Division
Los Alamos National Laboratory
Los Alamos, NM 87545

DATE: October 29, 1996

TO: Group Leaders, ESA-Division

FROM: Ron Dolin
EMAIL: rmd@lanl.gov
HOME PAGE: http:/scylla.esa.lanl.gov:8000/www/caet3.htm
MAIL STOP: P946
PHONE: (505) 667-9142

SUBJECT: **International STEP Product Data Exchange Meeting Trip Report**

Last week I attended the International STEP meeting - a forum for product model exchange people from around the world to discuss and develop product model information management standards. This meeting had a large number of European participants, about a dozen people from Japan, and a few folks from Australia. I met one person from South America (Argentina), but nobody from Africa, Russia, the Middle East, or a nonJapanese Pacific Rim country.....draw your own conclusions.

As the only Los Alamos participant I felt obligated to expose myself to as much as possible. I started out with subjects I knew best (i.e., IGES, geometry, topology, shape representation, and parametrics) and moved into unexplored areas like configuration management, aircraft manufacturing, and ship-building (a stretch I know, heard the sea call ya might say).

What follows is a collage of thoughts and impressions from my week of meetings, hallway interactions, and meal-time discussions. Instead of writing in neat sentences and paragraphs I've decided to be unstructured. My hope is that this "free-flow" format gets points across compactly (hey don't blame me I just use caffeine, I didn't invent it). I don't expect people to read this entire report so I have highlighted topic areas....find something that interest you and skim the rest.

The meetings were interesting but like most technical gatherings the real value was in talking to other participants 'off-line' and trying to get a feel for the pulse of the international product data standards community. I wrote extensively, starting and ending each day at the neighborhood coffeeshop. I hope the following random thoughts have something useful for everyone. If not, oh well, I can't be responsible for the random chaos rambling around inside my head......at least not while I'm drinking East Coast water and breathing clogged sea level air.......

Lesson Learned From ISO And How That Can Help Us:

IGES and STEP both have protocols for piping. The question is, "Why?" And how does understanding that provide us insight into what we should be considering as we begin a multi-year process of developing a Models Based Engineering infrastructure?

The piping protocols that exist today for both IGES and STEP are the result of a heavily endowed Navy SeaWolf project that never got the technical peer reviews or user evaluations it needed. The data translation and interoperability attitudes for many SeaWolf project managers contained that dangerous mixture of arrogance and ignorance. There was a large contingent of the product development players that thought that what they were doing was so unique to their product that use of standards would be a hindrance. There was just as large a contingent of "belt-way bandits" who needed to justify their importance to the project and were more than willing to help foster those beliefs.

The result was an entire mini-standard within IGES and STEP for the ship building industry. With the door to this philosophy opened, the construction, automotive, shipbuilding, and airline industries soon followed with their own mini-standards (I have discussed this issue in earlier memos). This became a software tools consultant's bonanza - instead of selling one STEP product, an entire suite of products could be marketed with no 'catch-all' inclusive STEP tool available. A substantial effort at this meeting seemed to be in trying to do what they euphemistically call 'harmonizing' this divergence.

The entrepreneur in me sees all kinds of opportunities to become a very rich person in STEP. I talked with several other entrepreneurs who also see the same opportunities. Even within ESA there is an opportunity to solidify long-term job security by becoming a STEP expert (in case any of you are losing sleep over your insecurities).

We as a division need to work within the STEP framework and seek harmonic implementations of this standard as we strive for a multi-platform, multi-system infrastructure. Don't ya gotta like that term "harmonic?"......so 90's. STEP is more than just the only game in town - it's a solid, credible attempt to address a very serious road block to evolving engineering technology. ESA needs to re-involve itself with STEP. Now is the time.

The Status Of Parametrics:

Where are parametrics going? From the last meeting in Sydney, Australia, it seems unclear within STEP. Everyone seems to think they know what parametric modeling is and that it is both the wave of the future and the obvious neglected technology in STEP (I like hanging with these guys). No one can agree on how parametric modeling should be done or what the language constructs should look like. Not that you asked, but in my opinion it is too early for STEP to weigh in. Parametric modeling technology (or variational modeling if you like to say 'tomotto' instead of 'tomayto'), is only now being made widely available. The engineering community needs to work with the technology for awhile and define how they want to use it. It is STEP's job to make parametric model transfer possible, not to define how parametric modeling should be done.

Why is this important? Because CyberGod says so.........if you want to build a parametric model, a model based on equations and relationships, (e.g., lineA=2*lineB+radiusC) that can be shared across platforms while preserving the parametric logic, you need this. If parametrics are not preserved during model data transfer you end up passing 'explicit' model data (e.g., lineA=14, lineB=6, radiusC=2), and making downstream model changes more difficult.

Parametrics is the single most important aspect of next generation engineering within ESA. Without parametrics; MBE, rapid response engineering, advanced manufacturing, virtual technology, model reconstruction, computer based learning, and all the other next generation technologies the Center is exploring are compromised. Need more data.

It is very good that ISO is addressing this long term need and these are the right people to be defining parametric modeling data transfer technology. However, there is a mighty fine line between defining a technology implementation strategy and defining an information exchange standard. They just need to be clear about which they are addressing.

Information: Who is the customer of product design information? Not the customer of the product - the product information? Big question...Answer, of course, is everyone in the product realization process..... but that's the easy answer. We need to determine when who becomes the information customer and what information they need........this is an important issue that needs to be addressed in MBE.

Platform Integration: Observations, Impressions and Personal Opinions: --> **Boeing** now believes that their philosophy of forcing vendors to use only their CAE system (CATIA), so that everyone involved in product realization worked in a homogeneous environment, was a corporate and technical mistake (this from a Boeing engineer and not a corporate spokesperson......not that they asked, but I concur). Working in a homogeneous environment eliminates the obvious problems of talking to different machines and different software systems but does not address the much more profound issues of what you are talking about. Sorta like having four people who speak different languages agreeing to communicate through voice and then wondering why they can't understand each other......or more subtle, having an Irishman, Englishman, Australian, and American define football.

Dictating a single-platform, single-system environment creates many unforeseen. It seems like an appealing solution to people who don't fully consider the enormity of the problem they are attempting to solve. Sorta like the classic "treating the symptom and not the cause." Gotta love a company who can take ownership of their mistakes.

A guy from **Chrysler** and I talked about Boeing's confession and what happened to the auto industry's when they followed Boeing's lead. He said that the auto industry did not fully understand what problem they were attempting to solve when they forced subcontractors to use their hardware and software tools. He said that the car industry made the same mistakes and reached the same conclusions as Boeing, but for them it was going to be harder to correct. The problem in the car industry is that their "homogeneousvender" philosophy not only created product realization problems, but redefined the very business foundation for how cars are made in America. He had been with Chrysler for twenty-eight years and had some fascinating insight into the car industry. In his opinion, the car industry will never recover from this mistake because now the entire nature of automotive product realization process has changed.

To summarize, what's happening within the auto industry is a micro managers worst nightmare. The subcontractors have gained control of the process because they now control the information......and in this new era of communication, information is power. The servants have seized control of the castle and anarchy reigns (oh be still my beating heart). He gave me an outstanding lesson in business history, economics, and what can happen when managers make technical decisions based on nontechnical metrics. For me, this one conversation was worth the entire trip......

Oak Ridge and Allied Signal Kansas City are already using STEP. They have translators (commercial and some in-house), and have done benchmarking on real geometry and topology (Scott's done some....waiting on translators...PO's bottled up in administration....storm the castle!). They have not made it a production tool yet. Sandia is moving rapidly toward full STEP implementation. No one seems to know what Livermore is doing.

If **the Division's goal for MBE** is to simply map our current engineering methodology into three-space, we can grab any old CAE system, send the drafters to training to learn how to draw and dimension in three-space, and be done in three months.........MBE is a lot more than building 3D geometry....it's about modeling information.....it's a new methodology and a philosophy for doing engineering and for intelligently developing, managing, and using engineering information.......there must be a windmill around here somewhere eh?????

Mechanical Design: An ad hoc group for **Rapid Prototyping** is meeting at the next STEP meeting in Grenoble, France, in October. A group for **Mechanical Design using Form Features** will meet there as well. There will be a **one-day workshop** at Gernoble on FEA modeling, harmonization with geometry, and from feature modeling.

Model: An engineering model is the result of an optimization process whose objective is to capture all the necessary and/or relevant design information (more than geometry and topology) with the least amount of complexity. I use the optimization axiom because, in almost all instances, these two goals (i.e., capturing all relevant information and least complexity) compete and move in different parameter spaces. A model does not necessarily always have to be a fully featured three-dimensional representation of product, although NIST and the UK aircraft guys disagree with me........ It's the least complex information model that satisfies the needs of the information customer.

Geometry versus Topology: What is more important to the model?....to the engineer?.... to the information customer? Where should constraints and parameters be applied? The answer is - not clear. Need to be able to specify constraints and parameters long before you commit to geometry, so, way before you commit to topology (but that is only my humble opinion of what a MBE process should be like).

Geometry is different than topology. Geometry is mathematical representations of manipulatable simple shapes (curves) and topology is the use of geometry (representation) to form surfaces and complex features. For example, in a B-rep system, solids are formed from surfaces, which are pieces of topology, and surfaces are formed from curves, which are pieces of geometry. **Bottom line** --- geometry and topology are different beasts (someone asked me that question the other day).

Virtual Reality: Industry lead interest group being formed. Just had a meeting at Boeing. Attendees included Ford, Alcoa, Kodak, GM, NIST, Sanida, etc. UK aircraft industry very interested in joining. I was invited to join as well. I was also invited to join the **STEP Simulation subgroup**. It's for assembly simulation today, but definitely for virtual reality in the future. The UK is very involved in virtual reality simulations in engineering (last year's SIGGRAPH). I told them that I would join VR industry interest group but did not believe that LANL had the funding or interest to allow me to make a commitment to the STEP Simulation subgroup. I base that on the fact that the once strong LANL presence in STEP has been reduced to zero.

Information Vs. Data: Talked with several people from NIST and the UK about the definition of "data" in product realization. The consensus seemed to be that 1-D data is a concept schematic of little value (from an information standpoint). Two-D data is a document, and 3-D data is a model. "If that were true," I asked, "what is n-D data?" I shared my ideas about perceiving data in what Jill and I call "perception-space." The Europeans in our discussion group seemed comfortable with the idea of n-dimensional data perception. It's exciting to have abstract discussions with people who think outside of the same box as you do?

Features and Parametrics: Can features be kept in a callable library? The answer had better be yes, or my ideas about MBE are in a world of trouble (is that the sound of a flushing toilet?????). Need to determine how to determine what is base-line geometry and topology, and what is a feature................. kinda like trying to determine if my lack of sleep is last night's problem or this morning's.

Must separate features from geometry and topology. Shape and Parametrics committees agree. When Richard, Scott, Jill, Dwight, and I were part of Lou Salazar's ProEngineer evaluation team five years ago we talked about that being a good approach.......do I gotta good memory or what?

Generalization of the current STEP CSG data structures would allow parametric model translators. We want EXPRESS based methods for constraint information transfer. We need to have features standardized. Need to determine how important CSG modeling will be in MBE.

If you had a good parametric model, could you simply pass parameters around to update model changes? What would this nongraphics language look like? What would be the impact of this approach to engineering in a MBE environment?....Al Gore will wanna know. In a virtual simulation, could you send someone the model *a priori* and then send updates during the simulation by only sending parameter changes? Would that get around the network bandwidth problems? Could internet be consistent in model refresh transfer packets? Would a parametric nongraphics information model solve our data transfer problems in MBE? Could Scotty be transported from the Bridge down to Engineering in one piece???? Need to find the answers...or at least find out if these are the right questions.....

Engineering Analysis - Formerly the Finite Element Subgroup: Had a great discussion over breakfast with some NIST and UK folks about the maturing attitudes of the analysis community and the role of analysis in product realization. We talked about the power and potential of someday performing high level analysis in the geometry domain instead of the classic discretization domain (is that another windmill I see out there?). We talked about the Sandia paving algorithms and some personal ideas about implementing analysis in the geometry domain for optimization that were given in my 1990 ASME paper. These are the first people I found who wanted to talk about this stuff since I left Purdue five years ago. Do I smell a revolution???

The Finite Element subgroup changed their name to Engineering Analysis to symbolize their realization that FEA is only one of an entire portfolio of analysis tools available to engineers today. We talked a lot about how FEA has evolved way beyond it's ligament place in an engineer's arsenal of analysis tools into some kind of canonical, all-inclusive, tool with a following whose dogma has become "finite elements - the monolithic tool for solving every engineering problem."

The Engineering Analysis subgroup recognizes that FEA is only a tool, and not the only tool, that can provide engineers with insight into product features and performance attributes. I am not sure when the last time LANL formally evaluated analysis as a process. We should use the MBE initiative to take a close look at how we do analysis, why we do it the way we do, who performs analysis, and what other tools beside FEA are available to enhance our ability to understand product.

Configuration Management: Way---WAY beyond the scope of my limited capacity..... but given the reverence everyone here talks about it, it's gotta be a big deal. I need to have Scott and Jeff give me a lesson on what CM is, what it does, and why it's important. Better understand it so that I too can become more reverent.......

Interfacing+Integrating = Linking + Harmonizing: New term for interfacing is linking. For example, "we link design with manufacturing." Same thing as last year's lexicon which was "to interface design with manufacturing." If anything linking looks like a reduced form of interfacing with slightly modest expectations. But if it looks like a duck..... New term for integrating is harmonizing (near as I can tell). For example, "we are going to harmonize product model design with analysis." The Geometry subgroup is trying to get the Engineering Analysis and Manufacturing subgroups to coordinate activities. I am sure this new nomenclature is more a result of STEP being international than it is them trying to overtly develop their own anthropology.

Mathematically, design and manufacturing can never be integrated (throw tomatoes now). This is primarily because they have competing needs, expectations, and languages. Most engineers have known this for many years but have had to wait for the glory-boys to wear themselves out from seeking the "grand unification theory of engineering" (that email address is "bass_earnest_t@mayberry.rfd"). Better to think about linking/interfacing.

Engineering Anthropology: STEP nomenclature, language, and anthropology very daunting......Big ARPA project. STEP is beginning to realize that this is a big deal.....Jill and I have been trying to educate people about this for two years now. Joe Kindel and Ken Lee seem to understand it's significance. We've just been too far ahead of the technology curve on this issue......kinda like computer based learning.

Engineers share information space, but each engineering discipline uses that space differently. For example, a structural engineer uses a model differently than a project engineer would. Some information they can share (and so should) and other information is unique to their particular task. The primary problem that MBE should address is how do different disciplines share design information? What is the lowest common denominator, and how can each user of product information add their value to a model without disrupting the model that will also be used by other disciplines? This is one issue of anthropology.

How are we going to resolve the differences in language structure and competing needs between disciplines who interpret, add parametric nomenclature, and value to a model? For a million dollars I'll give you my answer....ok, for a beer at the Inn I'll tell you my lies.

The Ship Building Subgroup see training and 'design for maintainability' as big deals (see it pays to roam outside of my geometry/topology comfort zone)

EXPRESS programming language: Version I, II, III,.....,N --> get a score card. Where is the ISO going with this tool? What is it really for? No opinions here, just observations. Division will need an EXPRESS expert.

ProEngineer: Discussed as something like "the problem child." If some data translation problem from some CAE system doesn't seem to make sense, the model probably originated in ProEngineer.

BRAVO: Has the best constraint solver on the market (NIST guy's opinion....who'da thought BRAVO eh?). The BRAVO solver is not set up for simultaneous equation solving though. That limits it's use as an optimization tool. I told the guys at Applicon three years ago to add simultaneous equation solving. They didn't think I knew what I was talking about (easy mistake) and now NIST and STEP are looking for a first to market company and BRAVO is not ready....shoulda listened to me! Need to survey CAE industry to get more inf. on this.

Committee Bureaucracy: STEP's got plenty. "Who's job is it to do what around here?" They seem to function on formality and that seems to make things move smoothly and in an organized manner. I'm not sure, but there my be a message in that for me somewhere.

Dinner On The Potomac: Going to STEP meetings is such a sacrificial endeavor......Sat at a table with the head of ISO STEP, some NIST people, British folks, a Rockwell Engineer, and two software integration guys from Boeing. The consensus was that STEP will be integrated at Boeing, Rockwell, and the UK aircraft companies within eighteen months. Boeing just announced last Friday that they would immediately move to STEP and that all their vendors would have to communicate product information with them via STEP (but no platform requirements would be specified).

While on my third glass of wine I started on this tangent about how now was the time for the ISO to begin thinking about the next STEP replacement (they said they already were). Then I gave them some ideas about how the next product standard should not be based on geometry or topology.....that product information was much more than visual models....that drawings and models was a media that served engineering well for a long time but that it was now time to consider new paradigms. I gave them my ideas about what the next paradigm should look like (no pun). They seemed to agree with my basic premise. I don't remember the details.....that's the problem with real time concept development. I remember one of the British guys saying that the person who defines the next product information philosophy will become the new Bill Gates. I agreed......but who wants to be a billionaire anyway?.......I can't even successfully manage being a hundredaire......

DEC recently joined Japanese version of STEP. Don't know if that means anything? Buy or sell DEC stock? Who can say.

Attendance: Oak Ridge, Sandia, and KC geometry guys, the same ones who always show up at things like this. I've been hanging with these guys for twelve years now. Boeing was very well represented. Sandia presence was large. KC and Oak Ridge had a strong attendance. Los Alamos interest small (muy corto.....just little old me). Livermore not in attendance near as I can tell. Sandia has five members on the ISO committee. Los Alamos has none.

International attendance at least equal to US attendance. The French seem to be thought of as the ISO Nay-sayers. The Japanese move, walk, and eat as one collective unit. Germans, British, and Australians like Robert's Rules of Order (can I get a second on that...).

Australian guy talked about someone in Sydney burning the French Embassy to protest the French Government's decision to test nuclear weapons again. No one seemed to have any sympathy for the French.

Ran into Ed Clapp - he's at AutoDesk now. He still remembers the days when Dwight and Rob Oakes were cowboying things in these committee meetings.

General: Can't decide how much of what these folks are doing is related to information transfer and how much is related to developing a standard for defining how industry should be doing modeling. Dangerous difference..... "a mighty fine line," as Eric Clappton would say.

They are spending more time talking about how to change model geometry and topology then they are talking about how to store, interpret, and transfer the model. These two objectives are not linked in my mind.....

In the mix of the new information age, how are you going to jump on board and how are you going to play? Answer: find a niche....become an expert - same as always. Geometry? Visualization? Process modeling? -old ponies. Math - not as exciting as it once was. Information modeling....catch the wave....

Appendix F

Center for
Advanced
Engineering
Technology

Title

Next Generation Engineering Technologies Enabling Manufacturing for the Nuclear Weapon's Complex

Authors

Ronald Dolin,	ESA-EA,	rmd@lanl.gov
Lyle Edwards,	ESA-WE,	ledwards@lanl.gov
Jill Hefele,	ESA-EA,	jill@lanl.gov
Doug Hemphill,	ESA-WMA,	dhemphill@lanl.gov
Rick Hinckley,	ESA-DE,	hinckley@lanl.gov
Paul Lewis,	ESA-MT,	lewis@lanl.gov
Art Nobile,	ESA-TSE,	anobile@lanl.gov
Scott Parkinson,	ESA-FM,	sdp@lanl.gov
David Stupin,	ESA-MT	stupin@lanl.gov
Dan Varley,	ESA-WE,	varley@lanl.gov
Octavia Vela,	ESA-MT,	vela@lanl.gov

Sponsoring Organization

Tim Neal,
Program Manager for Materials and Process Technologies
Nuclear Weapons Technology Program Office

Date

December, 1995

ABSTRACT

This report was commissioned by Tim Neal, Program Manager for Materials and Process Technologies in the Nuclear Weapons Technology Program Office. The investigation had four goals; understanding what the current manufacturing capabilities of the engineering division at Los Alamos (i.e., where we are), predicting what manufacturing capabilities will be needed to support weapons programs in the future (i.e., where we need to be), developing strategies that suggest how the Laboratory can transition from where we are to where we need to be, and reviewing capabilities development and assessment activities on-going at Sandia in the area of product realization.

The report is broken down into five chapters. Chapter One introduces the project and provides some background on our current manufacturing processes and technologies that would be used today to make replacement stockpile parts. Chapter Two provides an assessment of ESA Division's capabilities. The third chapter reviews what Sandia has done to position itself for future manufacturing needs. We discuss what Sandia did, and is doing, to transition into the future. Chapter Four takes a futuristic look at advanced manufacturing. Chapter Five summarizes our customers' views about their future challenges and how ESA Division is preparing to meet those challenges.

The process that led to the compilation of this report was an eye-opening experience for ESA Division. The Division is already taking steps to better position itself to meet the challenges that will face its customers in the future as a result of this study.

TABLE OF CONTENTS

The rest of this report is available upon request from
Ron Dolin (505) 667-9142, or rmd@lanl.gov

Appendix G

Center for
Advanced
Engineering
Technology

Title

Rapid Prototyping - Physical And Virtual

Authors
Ronald M. Dolin (505) 667-9142; email rmd@lanl.gov
Jill Hefele (505) 667-9744; email jill@lanl.gov
Fax (505) 665-5127

Sponsoring Organization
Los Alamos National Laboratory
Engineering Science and Applications (ESA) Division
Mail Stop C931
Los Alamos, New Mexico 87545

Date
September, 1995

Executive Summary

This paper discusses why rapid prototyping (or physical prototyping) and virtual prototyping are really components of a broader Advanced Prototyping technology. While advantages of physical prototyping are obvious, there are things that a physically prototyped component cannot do. There is a limit on the number of "what if" scenarios that can be attempted with physical prototypes and there are time delays. This means that physical prototyping's ability to influence design is limited. Physical prototyping will always be just an end-user of design information. Virtual prototyping has the potential of overcoming the short-comings of physical prototyping and enhancing an engineer's ability to utilize the potential of prototyping for design.

1. INTRODUCTION

Virtual prototyping is an enabling tool that can bring customer, consumer, and manufacturer together to help develop, test, manufacture, and use a product without being geographically collocated or without the product ever physically existing. In order for this vision to be realized applications must be able to run over wide area networks (e.g., internet) and the necessary virtual reality hardware must be both affordable and readily accessible.

Virtual prototyping can play a pivotal role in enabling the DOE/NWC to evolve its technology and manufacturing capabilities into the future. Virtual prototyping can become a powerful technology for product development-to-deployment. While a lot of attention is currently given to rapid physical prototyping technology, we believe that physical prototyping and virtual prototyping are really components of a broader advanced prototyping technology capability.

2. PHYSICAL PROTOTYPING

The power and advantages of being able to rapidly produce physical prototypes are obvious. But there will always be things that a physical prototype cannot do. For example, physically prototyped parts can never be used for structural, thermal, dynamic, kinematics or destructive evaluation (unless your actual part is going to be made from the same material as the prototype).

There will always be a limit to the number of "what if" scenarios that can be attempted with physical prototypes and there will always be time delays (it may be hours or days but still delays). This means that physical prototyping's ability to influence design is limited. Most importantly, physical prototyping will always be just an end-user of design information. Even if an engineer learns something about his/her design after building a component prototype, there is no convenient way to feed that knowledge back into a product realization process in an integrated or electronic manner.

Efforts are underway to address some of these short comings in physical prototypes. For example, the automotive industry has shown that when parts are prototyped using bi-refringent material, they can be photoelastically evaluated and the results can be matched with finite element analysis predictions.

There is also active research into using scaling laws, mainly for frequency evaluation, so that physical prototype parts can be used as modal test models.

Virtual prototyping can however, provide analogous capabilities using simulations and at the same time address the other short comings mentioned above. Perhaps most important, virtual prototyping can allow unlimited "what-if" scenarios and provide an integrated information feedback loop from product back to design.

3. VIRTUAL PROTOTYPING

Virtual prototyping is a technology drawn from the highly popularized methodology for data perception called virtual reality. The principle of virtual reality is that within an immersive computer simulation users can suspend their recognition of the physical world and supersede it with a computer generated synthetic world in which nonphysical tasks can be safely, easily, and repeatedly performed.

Virtual prototyping can play a pivotal role in enabling the DOE/NWC to evolve its technology and manufacturing capabilities into the future. Virtual prototyping can become a powerful technology for product development-to-deployment. While a lot of attention is currently given to physical prototyping technology, we believe that physical prototyping and virtual prototyping are really components of a broader advanced prototyping technology capability.

Virtual prototyping allows engineers to consider applications that were never possible with physical prototypes. The following sections discuss some potential applications.

3.1 Virtual Prototyping As An Enabling Tool

Field engineers in the laboratory, and laboratory engineers in the field is a goal for next generation engineering. Virtual prototyping is an enabling technology that allow engineers in the laboratory to interact with engineers in the field. This has direct application in industrial contractor-subcontractor relationships.

We believe that virtual prototyping can be used to allow laboratory engineers to help field engineers assemble, disassemble, and maintain products. By acquiring information from the field engineer about the state of a product, laboratory engineers can use their resources to analyze the data, predict various scenarios and generate simulations that field engineers can then use to learn necessary techniques and to practice-by-doing prior to actually working with a product.

The Los Alamos National Laboratory has always taken total life cycle responsibility for its designs. This is also a growing trend in industry. Using virtual prototyping to let laboratory engineers become part of a field engineering team enables companies to maximize their resources because it allows a company's best technologist to be in more than one place at a time. A team of laboratory technologist can be simultaneously interacting with many field teams from all over the world (or from all over the DOE/NWC).

3.2 Virtual Prototyping As A Design Tool

Product design means a lot of different things to different people. In the early years of CAD, the term design inferred drawings. The analogy for design was a computerized blueprint (i.e., a two-dimensional cartoon). Over time, engineers realized that drawings did not capture all the necessary design information and that computerized drafting was just a by-product of the design process and not its driving component. Computerized product realization requires a models based representation of a design that can be used by all disciplines in a product realization process.

Models based engineering requires the generation of a lot of information. That information needs to be managed as well as interpreted. The most obvious application of virtual prototyping to engineering design is in visualizing and interacting with models in artificial environments. Virtual prototyping can provide a tool for enhancing a designer's ability to see a design and to potentially interact with it. This capability would add value throughout the product development process, from concept modeling to building computer based learning tools for product operation and maintenance.

Virtual prototyping could also be used to manage the design process itself. New techniques for project management would need to be developed. Aspects of this new project management approach would include a mature concurrent engineering infrastructure to handle how information moves around, and a concise models based engineering philosophy to determine what information moves around.

3.3 Virtual Prototyping As An Analysis Tool

An analyst typically builds an analysis model comprised of discrete approximations to actual design geometry, runs analysis codes based on approximation techniques such as finite element, boundary element, and finite difference methods, and post processes the analysis information. An analyst relies on numerical simulations to determine a design's reliability to a given set of initial and boundary conditions.

Applications of virtual prototyping for previewing analysis models are evident. Another potential application is using virtual prototyping to assess initial and boundary conditions for the analysis model. Perhaps the most promising application of virtual prototyping for engineering analysis is in post processing of data.

Analysts generate a lot of data and making sense out of that data is as much an art as it is a science. Entirely new paradigms would be required for post processing. For example, what would stress information look like in an artificial world? Do contour plots and color coding make sense when the power to perceive data is available? With virtual prototyping, how would an analysts interact with his/her information?

3.4 Virtual Prototyping As A Training And Learning Tool

Computer Based Learning, or Cognitive Science, is a discipline that addresses how people learn. Computer based learning programs facilitate the learning process through interaction with a computer. Computer based training and learning technologies are becoming very important to product realization. Los Alamos will continue to take complete life-cycle responsibility for its product. This means that training for assembly, maintenance, disassembly, and customer education will continue to be an important activity.

Computer based learning is an important technology for training and maintaining worker skills. This is especially true for highly technical skills that are not often exercised. When a person learns by doing they retain more information than when they are lectured, or when they learn by watching. Because the immersive and tactile abilities of virtual prototyping allow workers to learn by doing in a simulated environment, virtual prototyping can be a useful tool for training and learning.

4. CONCLUSIONS

There are many applications for virtual prototyping of both products and processes. Virtual prototyping can be applied to any product, allowing the designer to have a model based rendered product that they can hold, manipulate and exercise in simulation. This allows a designer to 'cheaply' go through revisions faster than ever before.

Similarly, prototyping a system, a part or a process will allow an engineer to put a system through its paces in software. This may include things like making sure that a virtual part fits into a given assembly. Other applications may include verifying the inspectability and the maintainability of a part in a assembly before the part is ever made. More importantly, a virtual part could be viewed and revised by a committee of engineers from different specialties and locations simultaneously for better synergism on complex projects.

Virtual prototyping can promote the use of model based engineering by capitalizing on the wealth of design/manufacturing information generated by an interactive virtual prototyping methodology.

Manufacturing simulations of products would help American industries keep pace in the expanding and quickening global market. This technology could allow a system engineer to start simulating an entire manufacturing process from raw material to finished product.

Virtual technologies will become more adaptive than conventional approaches to manufacturing and product development in the future. Software methods for modeling and verifying products will become cheaper, more reliable, and more robust as a suite of tools and visualization technologies are developed.

The information generated on parts in a virtual design and manufacturing process can be more easily stored in computer based archiving systems. Models can be archived. Simulation results can be used for training and or maintenance concerns. Computer generated renditions of a system or assembly can be used for test or product advertising and promotion (use something before you buy it).

Two proof of principal demonstrations were developed. Both applications were in support of actual Los Alamos projects. The first was an assembly/disassembly simulation of a Slide Actuated Laser Armed Detonator (SALAD). In this simulation the user is able to select and pickup the SALAD parts and assemble them.

The second project was the simulation of a tractor and trailer operation in a room. This demonstration was in support of the Nevada Test Site, Device Assembly Facility (DAF), deployment of the AL-L6 shipping container.

Appendix H: Lockheed-Martin Engineering Through Simulation Trip Report

Ron Dolin, rmd@lanl.gov, 667-9142, and
Jill Hefele, jill@lanl.gov, 667-9744
12/11/95

Carolyn Mangeng had recently attended a Trident briefing given by Lockheed Martin Missiles and Space Company where it appeared that Lockheed was utilizing Models Based Engineering (MBE) techniques. Carolyn felt that Lockheed's computer visualizations were impressive and that it appeared as though their engineering model(s) were used to infer how a particular failure evolved and transpired. Jill and I were asked to investigate Lockheed's approach to electronically integrated engineering and to determine if Lockheed indeed had a capability to infer failure modes through simulation.

We visited Lockheed's Sunnyvale facility and met with Philip Robidoux and his team of engineers. Philip is project leader for a team developing next generation engineering capabilities. This team currently consists of 24 engineers (12 FTEs), and will double in January. The team's goal is to develop a virtual prototyping capability. This capability would include advanced information management and presentation, graphical user interfaces, solid modeling technology, and an integrated design-analysis-manufacturing-testing environment.

The Lockheed team is currently using SDRC-IDEAS as their primary integrating tool and SGI Performer for simulation and presentation. This is a good combination of software tools. It was not surprising to us that they chose IDEAS for design given the success of IDEAS Master Series and SDRC's gaining market share. Two examples of SDRC's recent successes are Ford's planned procurement (announced but not yet formalized), and the licensing of Boeing's highly prized rendering technology to SDRC (at least that's the late breaking story we've uncovered and if true, is significant).

Like any advanced technology program, the Lockheed team is starting small while thinking big. They have decided to focus initially on two parallel thrust: integrating design with manufacturing, and integrating design with analysis. This is slightly different from our primary focus, which has been on integrating design with physics and design with manufacturing. The Lockheed team's primary emphasis is on uses of solid models for closed-loop manufacturing. Down the road they plan to consider other highly valued advanced technologies, such as optimization, rules-based heuristics, and virtual testing (is this a visionary team or what?).

They have spent a great deal of time considering varying levels of model complexity. This was exciting to us since it is fundamentally the same approach we've been advocating. They have invested a lot of time and money in determining the right levels of model complexity and have agreed to share their findings with us. We talked at length about the need for engineers to consider what it is that they want to do with a solid model and to not always assume that a 100% detailed, diamond-stamped quality model is necessary or appropriate.

The Lockheed team has an ambitious virtual flight test scheduled for deployment in 2003. We talked a lot about the complexities and challenges that this schedule would have to overcome. New technologies, such as virtual prototyping and virtual testing, would have to mature considerably. Jill and I were pleased that they had reached the same philosophical conclusions we had regarding virtual reality technology. We all felt that while graphics is an important tool for conveying information to users, it is not as important to a simulation as proper management of the physics, math, and engineering.

This conclusion is very much akin to the lessons learned from the CAD renaissance of the 1970s and 1980s. Early CAD development was dominated by a perceived need for better faster graphics. This need was based on a belief that a picture was the quintessential component of design intent. Ultimately that notion was replaced with an understanding that mathematical issues of geometry, topology, and information management better captured design intent. This metamorphism is best highlighted by noting the extinction of CAD (Computer-Aided Drafting) and the emergence of CAE (Computer-Aided Engineering).

In answer to the question we were asked to investigate, Lockheed does not currently have the technology to infer failure modes and failure histories through simulation. That is their goal and they have a good start toward achieving it. Lockheed understands the importance and potential impact of engineering through simulation. They also have a good understanding of models based engineering and what is involved with moving an organization from a drawing-based environment to one that is models based. It would be useful and beneficial to continue to discuss issues related to these topics with the Lockheed team.