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Advanced Engineering Environments for Small Manufacturing Enterprises: Volume I

Steven J. Fenves
National Institute of Standards and Technology; Manufacturing Engineering Laboratory
Ram D. Sriram
National Institute of Standards and Technology; Manufacturing Engineering Laboratory
Young Choi
Chung-Ang University; Mechanical Engineering; Formerly, National Institute of Standards and Technology; Manufacturing Engineering Laboratory
Joseph P. Elm
Software Engineering Institute; Carnegie Mellon University
John E. Robert
Software Engineering Institute; Carnegie Mellon University

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Steven Fenves (NIST)
Ram Sriram (NIST)
Young Choi (Chung-Ang University/NIST)
Joseph P. Elm (SEI)
John E. Robert (SEI)

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The report identifies candidate commercial off-the-shelf (COTS) products for the software components relevant to SMEs. The list of candidate products presented is by no means exhaustive; in the rapidly moving CAD/CAE/CAM software product market, only a few representative products could be identified. COTS components other than those mentioned here are available. The components listed herein are intended only as a sample of available technology as of the date of this report. Inclusion in this report is not an endorsement of these components by the National Institute of Standards and Technology (NIST), the Software Engineering Institute (SEI[SM]), or the authors of this paper.

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Executive Summary

Small manufacturing enterprises (SMEs) can gain efficiency by integrating advanced design and engineering tools into the product development process. Such integration may involve not only the acquisition of the tools and training of the personnel to use them, but may also require changes to the SME's design processes. Careful attention to issues such as tool integration with the design process, compatibility between multiple tools, appropriate design protocols, and data storage standards can maximize the interoperability between the tools and facilitate the creation of an advanced engineering environment (AEE). Such an environment can maximize design efficiency and accuracy through reduction of redundant efforts and enhancement of design data sharing.

AEEs are defined as "computational and communications systems that can create virtual and/or distributed environments functioning to link researchers, technologists, designers, manufacturers, suppliers, and customers." [**NRC 99**] Typically, they consist of design tools (e.g., computer-aided design (CAD), computer-aided engineering (CAE),), production tools (computer-aided manufacturing (CAM)), project management tools, data repositories (product data management (PDM), product lifecycle management (PLM)), and networks. AEEs can vary greatly in comprehensiveness, from a *basic* configuration utilizing limited CAE functions built into a CAD system, to a *comprehensive* configuration, maintaining a common database of design information accessible by all relevant design and analysis tools.

An SME may benefit from adopting an AEE from both an internal and an external perspective. From an internal perspective, an AEE can offer benefits to the SME such as:

- **Schedule reduction.** Product development and production schedules may be shortened by minimizing redundant work, enabling parametric design (i.e., a change in a design parameter such as a physical dimension producing a design embodying that change), minimizing the number of design iterations, maximizing reusability of designs, enabling collaboration, and improving communication;
- **Product quality improvement.** Product quality can be improved by optimizing product design via analysis and simulation and by enhancing communication throughout the organization; and
- **Cost reduction.** Production cost and product development cost can be reduced through design optimization, early problem detection and correction, and encouragement of a design-for–manufacturing approach.

From an external perspective, AEEs can improve the SME's interface to the world outside the company, providing the flexibility and responsiveness needed to quickly respond to the evolving global market. AEEs provide effective communication with customers and suppliers via collaboration tools and catalog facilities.

When adopting an AEE, SMEs must consider business, technical, and organizational issues to achieve successful adoption and realize the business benefits. Key factors for success are:

- clearly identified business objectives and metrics;
- the readiness of the organization for the technology;
- suitability of the product structure;
- executive commitment to the adoption;
- interdepartmental communication practices;
- AEE technology literacy and computer literacy of the staff;
- skill levels of the design staff; and
- risk identification management.

The first step in successful AEE adoption is to analyze the current state of the organization. Once the organization's current baseline is understood, the SME can define the targeted end state for AEE adoption . From this effort the SME will define the new design processes, a communication plan, a technology plan, a training plan, and strategies to effectively apply the AEE. In implementing the AEE, the SME should choose the level of AEE capability based on operational goals and business constraints. An evolving AEE that gradually expands in both scope and breadth is often the desired approach, but this can be difficult given that AEE tools are not always interoperable. Therefore, selection of the specific AEE elements will be based on a careful correlation of the technical requirements of the SME and the capabilities of candidate commercial off-the-shelf (COTS) tools.

AEEs for SMEs are most often constructed through the integration of COTS information technology (IT) tools such as CAD, CAE, simulation, and design optimization tools. A key aspect of the use of COTS components is interoperability, the ability of data to be shared among tools. Standard communication protocols and translation capabilities included in many tools are not always sufficient to ensure interoperability. This is often a limiting factor in the creation of AEEs using COTS components. Stand-alone translation tools and translation services are also emerging to address this need.

A sophisticated AEE offers the SME access to improved design synthesis techniques. Iterative experience-based design methods can be replaced with formal design methods (e.g., axiomatic design theory, the Theory of Inventive Problem Solving, Quality Function Deployment, Design of Experiments) and knowledge-based CAD. An AEE also encourages collaboration. An inherent feature of AEEs is that virtually all data is stored in an electronic format. This makes it easily transportable to and available at many locations. This, in turn, encourages collaborative effort on design and production activities, with team members accessing a common design database and exchanging knowledge in real time.

The optimization of manufacturing processes is also a powerful part of the design effort in an AEE-enabled environment. Virtual environments and simulation are useful tools to aid the designer in this process. COTS tools compatible with the other elements of the AEE are available to visualize and simulate workflow, operator working conditions, equipment utilization, etc.

For many SMEs, the acquisition cost of the AEE components can be prohibitive. In response to this, the field of application service providers (ASPs) is growing. An ASP typically hosts AEE applications on a server and offers fee-for-service access to those applications to clients via the Internet. Through ASPs, SMEs can gain access to advanced IT tools on a pay-per-use basis without major capital investment. Today ASPs exist to provide services such as CAD file translation, engineering analysis services, data repository services, and parts catalog services.

Abstract

Advanced engineering environments (AEEs) are computational and communications systems that can create virtual and/or distributed environments linking researchers, technologists, designers, manufacturers, suppliers, and customers, providing for the orderly integration of tools used and data developed during the design phase of a product. AEEs consist of design tools (e.g., computer-aided design (CAD), computer-aided engineering (CAE)), data repositories (e.g., design databases, supplier catalogs), and the networks linking these components and other enterprise processes.

Although AEEs can improve the productivity of small manufacturing enterprises (SMEs), a key barrier to SME adoption is a lack of awareness of AEEs. This report provides an overview of AEE technologies for SMEs, starting with a description of the levels of AEE capability and a summary of the benefits of AEE technology.

AEEs for SMEs are most often constructed through the integration of commercial off-the-shelf (COTS) information technology (IT) tools, but successful adoption of these tools requires planning and commitment. This report provides SMEs with an overview of technical considerations for AEE adoption to enable such planning. Interoperability of these tools and efficient communication between the users of these tools is also discussed.

1 Introduction

Today, in many organizational settings, the concept of performing engineering tasks without a computer is almost unthinkable:

- Project proposals, memos, technical reports, etc., are generated through word processing;
- Technical research is done via the Internet;
- Communication with customers and suppliers is accomplished via email;
- Project schedules are developed and monitored using computerized scheduling tools;
- Project budgets are generated and project costs are tracked using enterprise resource planning (ERP) systems;
- Computer-aided drafting (CAD) tools are used to generate engineering drawings;
- Computer-aided engineering (CAE) tools are used to analyze the behavior of product designs;
- Product performance is evaluated prior to construction via modeling and simulation;
- Engineering designs are realized using computer-aided manufacturing (CAM);
- Electronic design automation (EDA) tools are used to generate schematics and lay out printed circuit boards;
- Computer-aided software engineering (CASE) tools are used to design and manage software development;
- Configuration control is maintained using product data management (PDM) systems;
- Materials are purchased, received, and distributed using a materials requirements planning (MRP) system; and
- Production workflow is planned, tracked, and managed with manufacturing execution systems (MES).

The software tools used have radically changed the life of the engineer.

If the difficult task of integrating these tools can be accomplished, the result is a powerful advanced engineering environment (AEE), as depicted in Figure 1. A synergy develops that makes the combination of these tools greater than the sum of their individual capabilities. Properly interfaced tools enable the user to transfer product models developed in three-dimensional (3D) CAD directly to CAE tools for analysis, eliminating redundant model building. Printed circuit board designs may be transferred from an EDA tool to a CAE tool for thermal analysis. The results of preliminary CAE analyses are imported into word processors and embedded into sales proposals, increasing their impact on the customer. High-bandwidth communications between members of the organization encourages collaboration and reduces the importance of coworkers being co-located.

These and other factors arising from the introduction of an AEE can have far-reaching effects on all aspects of an organization's structure and operation.

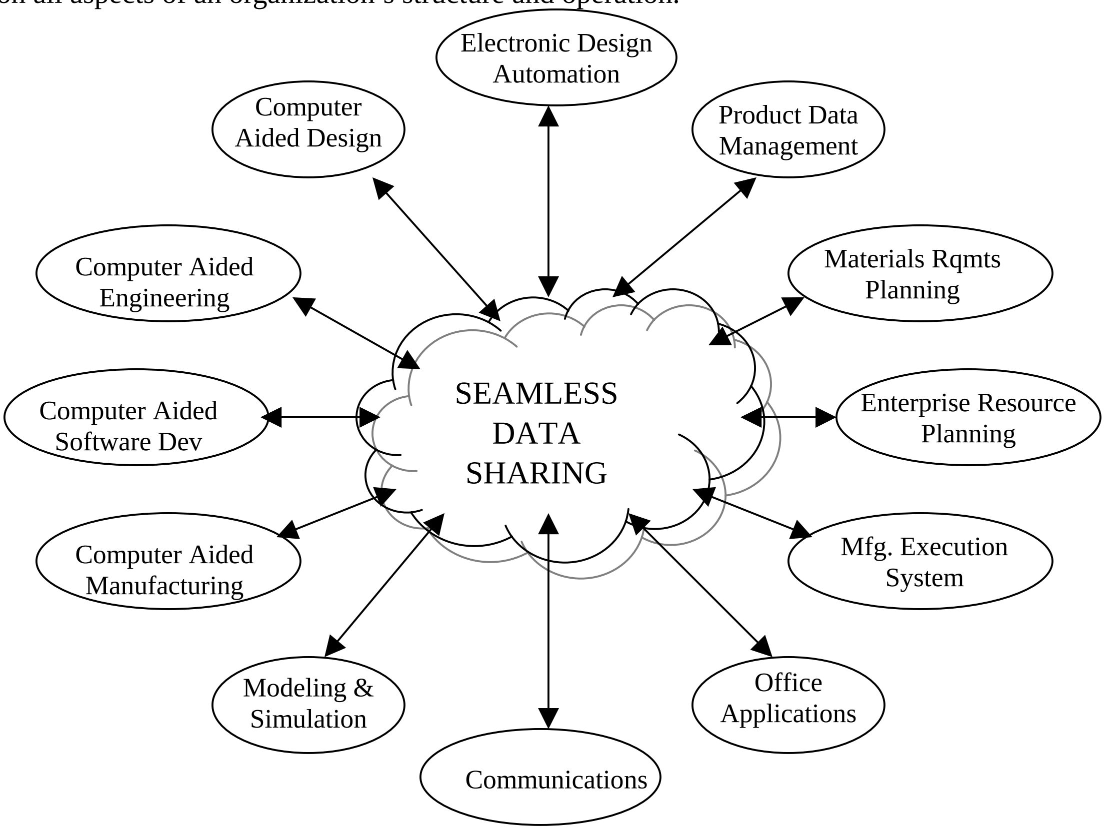

Figure 1: AEE Tool Integration

Adoption of a new technology is challenging for any organization, requiring commitments of capital and manpower. For new technologies these commitments are often substantial. Because large companies are more capable of meeting these challenges, they are typically the early adopters of new technologies; however, as the technology matures cost is often reduced to enable penetration of larger markets. When this occurs, the technology becomes accessible to SMEs. A recent study of SMEs ranging in size from 20 to 500 employees found that 75% use CAD tools and 62% use CAM tools [**SPIRC 03**].

1.1 AEE Definition

AEEs are integrated toolsets that enhance the productivity of participants in product development and production. AEEs are defined as "computational and communications systems that can create virtual and/or distributed environments functioning to link researchers, technologists, designers, manufacturers, suppliers, and customers" [**NRC 99**, **NRC 00**]. The physical elements of AEEs are:

- **Design tools—**e.g., CAD and CAE tools;
- **Project management tools—**a workflow management system used to plan, monitor and modify as necessary the various activities during the lifecycle of a product;
- **Data repositories—**a design evolution database containing the complete description of the current product design and its design history, and a design repository database containing past product designs;
- **Networks—**a design network linking the design tools and data repositories, with a planning gateway linking the AEE to the enterprise business functions, a production gateway linking the AEE to the downstream production processes, and a client gateway linking the AEE to the end user of the product

1.2 History

As stand-alone engineering applications of the 1960s and 1970s began to be integrated in the 1980s by means of shared user interfaces and/or shared internal information models, the term "environment" and variations such as "integrated design environment" came into common usage to refer to such custom-built, domain-specific collections of tools and capabilities [**Fenves 90**, **Fisher 89**]. As the need for tools for building such environments became apparent, the term "framework" came into usage to refer to sets of domain-independent tools and components designed to assist in the construction and maintenance of environments [**Sutton 98**]. Environments and frameworks have continued to expand in number and scope as user needs for tighter integration increased and as strides in computing and information technologies vastly increased the range of possibilities.

In anticipation of the next wave of developments, and to provide direction to these developments, the National Aeronautics and Space Administration (NASA) commissioned the National Research Council (NRC) to produce two reports on AEEs [**NRC 99**, **NRC 00**]. NASA and its major contractors have done considerable work on AEE components, but it must be emphasized that the AEEs described in these reports, when they are developed and made operational, will *fully* apply only to NASA and the largest of its prime aerospace contractors. Small manufacturing enterprises (SMEs) are clearly small players in this array of participants, occupying a place along the supply chain of the prime NASA contractors, where they would be linked into an AEE developed by the prime.

While full-fledged AEEs as described by the NRC reports appear only as a vision today, SMEs have urgent computational and communications needs that require immediate attention. Furthermore, SMEs have an increasing role in the supply chains of larger manufacturing companies that are clearly moving toward the AEE vision. Therefore, it is reasonable to present architectures of engineering environments—whether advanced or not—suitable for deployment by SMEs today that will enable transition to the engineering environments of tomorrow.

1.3 Purpose of Report

This report is the first in a series of two reports addressing AEEs and their application to SMEs. The purpose of this two-volume report is to build awareness of the AEE concept and assist SMEs in evaluating the desirability and feasibility of incorporating AEEs into their business operations.

Chapter 2 of the report discusses candidate architectures for AEEs and comments on their applicability to SMEs.

Chapter 3 presents the benefits that may accrue to an SME from the adoption of an AEE in terms of internal and external effects. This chapter also discusses the technical considerations that affect the decision to adopt or upgrade an AEE.

Chapter 4 discusses issues that an SME must consider when incorporating an AEE into its operation, such as:

- evaluation of the current state;
- definition of goals and strategies to achieve them;
- definition of the AEE scope to be adopted;
- specification of the requirements for the AEE components; and
- selection of appropriate COTS components.

Chapter 5 describes the general characteristics and capabilities of architectural elements or components for AEEs. The scope of the research leading to this paper was limited to geometry-centric design efforts. As such, the listed components reflect only geometry-centric design tools. These components are currently available or will be so in the near future.

2 Advanced Engineering Environments

2.1 Classification of AEEs

The functionality of AEEs can vary widely. In this report, we utilize a three-level categorization, classifying AEEs as basic, intermediate, or comprehensive. Detailed descriptions of these levels are found in this section.

2.2 Basic AEE

2.2.1 Overview

Many SMEs design and manufacture products in a mode in which the product's form is determined first. Analyses to determine whether the product's behavior matches the intended function are performed only later as a verification of the completed design. Of course, the initial form definition does not spring from a vacuum; it may come from a preliminary analysis of a highly abstracted sketch of the product's form or from the designer's prior experience with similar products. Typically neither the designer's experience base, abstract sketches, nor preliminary analyses are recorded in computer processable or retrievable forms. As such, the design support environment persists as if the form had been designed first.

An SME employing this operational mode needs only the most basic form of engineering environment. Such an environment can be configured from no more than a CAD system and one or more CAE analysis tools. The product form is captured by the CAD system. This form may then be transferred to the CAE system for analysis of behavior. Within the CAE system, this model may be subjected to a process of idealization—the abstraction of the model to a form suitable for analysis. This often requires the simplification of the model, removing design detail that is appropriate in the CAD model and needed for production, but not significant to the analysis process. An illustration of idealization is seen in Figure 2.

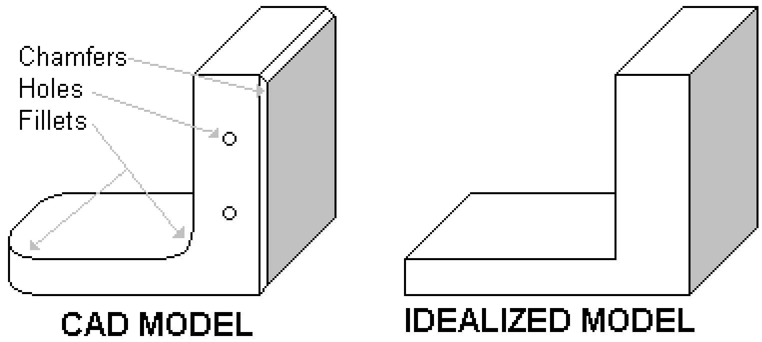

Figure 2: Model Idealization

This basic engineering environment can serve as a starting point of technology insertion for even the smallest SME and can be, in time, migrated to the intermediate level, as experience and expertise develop. Later sections of this report discuss the available alternatives, technical considerations, paths, and strategies involved in the migration.

2.2.2 Components

As shown in Figure 3, a basic AEE consists of the following components:

- **CAD system.** The CAD system provides a comprehensive set of tools for generating, manipulating, and updating the geometric form of the product being designed. In this architecture, it also provides persistent storage of the current, as well as previous designs.
- **Embedded analyzers.** Many, if not most, CAE tool providers provide limited-capability versions of their full-strength analysis tools embedded in the CAD tool. The advantage of these embedded versions is that they are directly accessible from the CAD tool interface and thus require considerably less setup time and user training. This makes it attractive and practical to invoke functional analyses at early stages of spatial design and use the analysis results to guide further design decisions.
- **Compatible analyzers**. Embedded analyzers are often restricted in capacity and scope. In many cases, it will be necessary to eventually use a complete, full-capability CAE tool, particularly in the detailed design stage. If both the embedded and compatible CAE tools come from the same COTS vendor, transition from the former to the latter can be quite simple and natural. A CAE tool is deemed compatible with the CAD tool if it is capable of seamlessly receiving the spatial representation of the product to be analyzed from the CAD tool through a shared representation, a neutral file, or a translator. Since the CAD model is intended to provide information for production operations, it often contains more detail than is necessary for or compatible with CAE tools. The process of abstracting and simplifying the CAD model to make it suitable for CAE is called idealization or defeaturing. Idealization may be performed either within the CAD tool or within the CAE tool after the spatial model has been transferred.

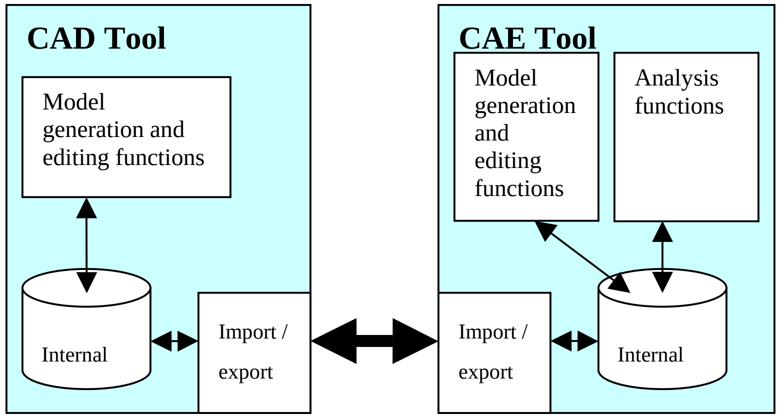

Figure 3: Basic Engineering Environment

This is the simplest AEE possible, and is suitable for implementation by even the smallest SME with little or no previous experience in computer-aided design and analysis. With appropriate planning and choice of tools, the AEE can, in time, be upgraded to the intermediate level or higher.

2.3 Intermediate AEE

2.3.1 Overview

A potential intermediate-level AEE architecture emerges from the Core Product Model and the Design-Analysis Integration projects in the NIST Design and Process Group (DPG) ([**Fenves 03**]). The product model architecture envisions a master information model containing all information about the product being designed, and multiple views of portions of that data relevant to specific functional domains or design disciplines.

Two kinds of transformation occur between the core information model and the domain-specific views:

- Models for functional analyses are extracted from the core model by idealization; and
- Spatial models and other results generated by the analyses are transformed back to the core model by a process called mapping.

The information architecture is based on two premises:

- It is possible to idealize analysis models for all functional analysis domains of interest from the information in the master model and to update the master model based on the mapping of the analysis models; and
- Design can be initiated from any one of the functional analyses and the master model can be initialized from the information mapped to it from the functional analysis model.

Spatial design (traditional CAD) is just another "functional" design domain. The CAD model generated is just another view that can be mapped to the core model.

2.3.2 Components

The information architecture presented above can be readily converted to a component-based AEE architecture by defining the components responsible for generating and maintaining the information models described above, as illustrated in Figure 4.

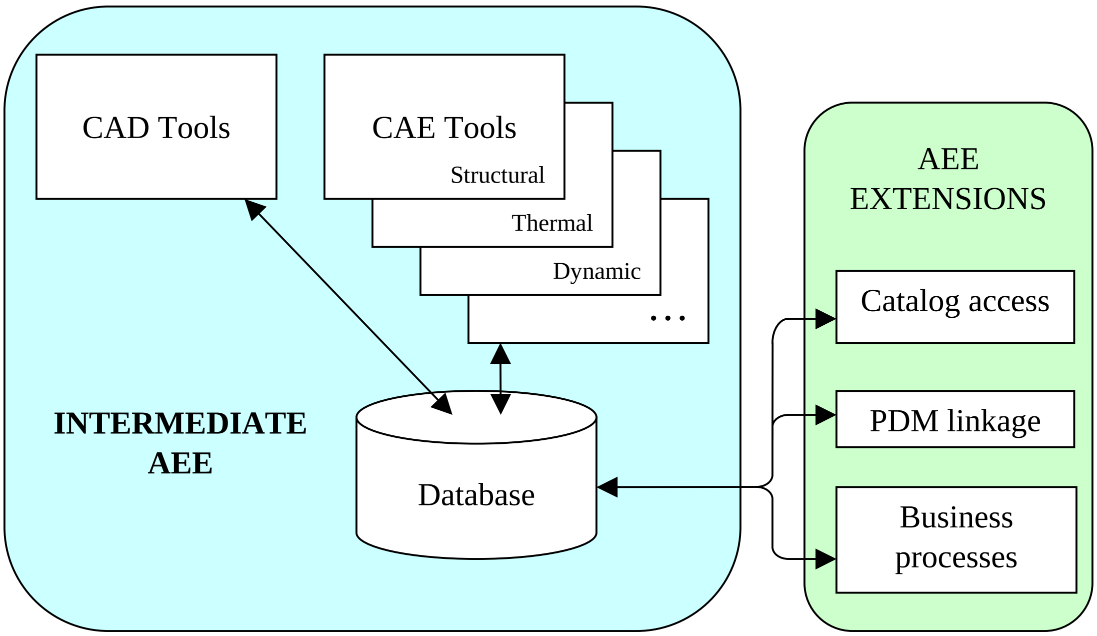

Figure 4:   Intermediate-Level AEE Architecture

Database. The database contains the common master information model and supports all concepts and data structures shared by the tools used in the design process. It is expected that all necessary translations can be grouped under the categories of idealization and mapping discussed above. Existing translators and/or standard protocols such as STEP AP 209 (**[ISO 94], [PDES 99]**) may be used to support idealization, if not mapping.

CAD system. Even though in the information architecture the spatial design or CAD model is treated as just another "functional" model, the reality of modern CAD-based design is that the CAD tool and CAD model play a key role in the design process. CAD systems provide comprehensive tools for generating, manipulating, and updating geometric forms, so that a predominant mode of design today is to create the geometric form first and later evaluate its behavior and compare it to the intended function. The information architecture supports this mode of design by allowing the geometric model and the CAD model to be one and the same; i.e., the idealization and mapping transformations between the CAD and core models are identity operators.

CAE tools. A variety of discipline-specific CAE tools, such as finite element analyzers, thermal analyzers, computational fluid mechanics simulators, etc., can interoperate with the CAD system and each other via the database. As stated before, the CAE tools receive the spatial representation of the product from the CAD system by way of the database. This occurs through idealization, which may remove features irrelevant to the analysis at hand (defeaturing) but may also make major modifications of the spatial model; e.g., replacing a solid by its medial axis transform. The CAE tool will typically build its own internal model. If this representation is to be returned to the database to reflect changes made in the design of the product, mapping, which in a sense is the inverse of idealization, needs to be performed. A simpler architecture results if no spatial changes are mapped back directly to the database and all spatial modifications are entered through the CAD system.

2.3.3 Possible extensions

Three extensions can be readily incorporated in the intermediate architecture.

Catalog access facility. Short of a full-fledged function-to-form knowledge-based conceptual design tool or a design repository, designers in SMEs would be well served with a much simpler catalog access tool. SMEs could use it to access manufacturers' and suppliers' on-line catalogs for searching, browsing, and extracting component data in a form suited for direct entry in the database for representing product components.

PDM linkage. A linkage to a PDM system that allows for (*a*) tracking the design process itself and (*b*) linking the completed design to the downstream manufacturing processes would be of great benefit to most SMEs. A further link to a Product Lifecycle Management (PLM) system could extend the linkage to the full lifecycle of the product, from conception to operation and disposal.

Linkages to business processes. Any number of linkages to the organization's business processes may be accommodated. Common linkages include:

- A bill of materials (BOM) from the CAD system may serve as input to an MRP system;
- Drawings from the CAD system may serve as inputs to an MES; and
- CAD drawings may serve as inputs to a subcontract solicitation process.

2.3.4 Applicability to SMEs

The intermediate-level architecture is applicable to most SMEs with significant mechanical or electromechanical design activities. It differs from the basic level primarily in the scope and sophistication of the CAD and CAE tools. A common configuration includes a CAD system and multiple interfaced CAE tools. The database function is often provided by the

CAD system's native database facility. The user enters and modifies the spatial representation only through the CAD system user interface. With proper planning, this configuration can be extended in a number of ways, including:

- adding further CAE tools;
- implementing a common database independent of the CAD system's facilities;
- providing the extensions discussed above; and
- providing mapping capabilities to convert the CAE tools' internal representations to the shared database representation.

2.4 Comprehensive AEE

2.4.1 Overview

The comprehensive-level AEE is illustrated with the NIST DPG AEE architecture. This architecture was developed primarily to serve as the basis for defining the standardization needs at the interfaces of the various component classes comprising a comprehensive AEE [**Sriram 01**]. This emerging engineering environment is seen to be distributed and collaborative, where designers, process planners, manufacturers, clients, and other related domain personnel work, communicate, and coordinate using a global web-like network. Designers may be using heterogeneous systems, data structures, or information models, the form and content of which may not be the same across all disciplines. Hence, appropriate standard exchange mechanisms are needed for realizing the full potential of sharing information models. The various applications are coordinated by a workflow management system using a product realization process (PRP) manager. The applications are connected by a design net, which provides the infrastructure for high bandwidth communications. The applications retrieve design data and knowledge from distributed design repositories and the evolving designs are stored in a database that provides snapshots in time of the evolving design, with design artifacts and associated design rationale stored at various levels of abstraction. Finally, design applications communicate with other manufacturing applications through various nets, such as the production, process planning, and user networks as shown on Figure 5. The classes of AAE components are further described below.

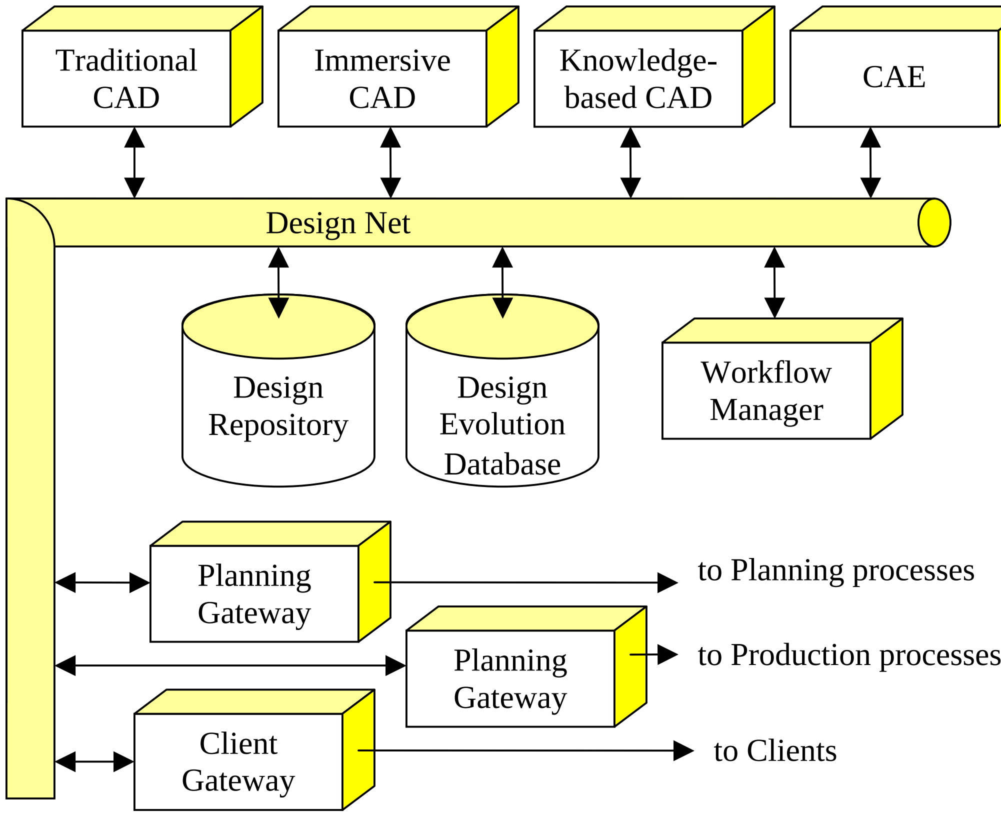

Figure 5: The NIST DPG COMPREHENSIVE AEE Architecture

2.4.2 Components

2.4.2.1 Applications

The applications comprising the comprehensive AEE are as follows:

Traditional CAD. Traditional CAD systems initially evolved out of attempts to provide better drafting aids. In these systems, the designer uses a computer to develop either two-dimensional (2D) or 3D spatial models of the design. The drawback of traditional CAD systems is that they only aid in generating geometric forms. This limitation encourages designers to come up with the form of the product first and think about satisfying its intended function later (i.e., design by form-to-function transformation), an approach that can result in non-optimal designs.

Immersive CAD. In immersive CAD applications, the human being becomes part of the design by using various immersive environments, including virtual displays and haptic interfaces (e.g., an instrumented glove providing input as well as force feedback, visual, and speech). Immersive CAD systems can aid in the evaluation of the operability and manufacturability of designs. With appropriate interfaces, designs can be directly modified to reflect the designers' experience in manipulating the virtual prototype.

Knowledge-based CAD. Tools are needed to help designers to think in terms of function first, so that form subsequently results from function (i.e., design by function-to-form transformation). Some knowledge-based design or synthesis systems implement this paradigm by first focusing on the symbolic aspects of design and later mapping the symbolic structure to a geometric model. Such systems can also capture the various semantic relationships between design objects.

Analysis (CAE). CAE analysis tools such as finite element analysis tools, which focus on the analysis and evaluation of behavior, are closely integrated with traditional CAD systems.

Work flow manager. The workflow management system acts as a project manager. It is used to plan, monitor, and modify as necessary the various design activities during the design lifecycle of a product and to establish and monitor project milestones. In addition, the workflow management system tracks the status of design documents and databases and enforces version control over them.

2.4.2.2 Repositories

Two repositories are envisioned in the comprehensive AEE, as follows.

Design evolution database. The representation of the design as it evolves, together with all relevant documentation, is maintained in a design evolution database. In rare cases, the entire database may reside in one place and be homogeneous. More frequently, it will comprise distributed and heterogeneous systems, data structures, or information models, whose form and content will generally not be the same across all applications participating in the design process. Nevertheless, the design evolution database must present every user with the information he/she needs in the format that user familiarly uses. This may necessitate syntactic as well as semantic translations of information passing to or from the database.

Design repository. The design repository, the future form of historical design databases, replaces traditional file cabinets of drawings and documents defining past designs. The design repository stores descriptions of past designs, together with their rationale, in a form suitable for browsing and retrieval for direct use in the active design process. Since design descriptions contain the products' hierarchical decomposition, parts and components of previous products can be readily extracted for reuse.

2.4.2.3 Networks and Gateways

All elements of the AEE are linked via network connections. The design net is the active link between the diverse agents and repositories, which may all be geographically distributed.

The process planning gateway links the design environment with the downstream activities. The link is bidirectional: not only are design decisions communicated downstream, but information from manufacturing process planning and other tasks are brought upstream to bear on the design.

The production gateway links the design environment with the production environment in a two-way fashion so that, for example, production experience on a previously designed product can be recorded in that product's description in the design repository for future browsing or use.

The client gateway links the engineering environment to the product's users. Customer needs, specifications, requirements, and evaluations flow from customers to designers, while engineering specifications, proposals, prototype designs, etc. flow from the designers to the users.

2.4.3 Applicability to SMEs

The NIST DPG comprehensive-level architecture, like the NRC AEE architecture, is not directly applicable to SMEs who wish to develop an AEE for their own internal use. As comprehensive-level AEEs evolve from current prototypes in large aerospace and automotive manufacturing organizations, SMEs will eventually become connected into an AEE of the scope described above. This, however, would occur as they become incorporated into the supply chain of a major prime contractor. In such a case, the SME would link to the AEE designed and implemented by the prime through the appropriate network(s) described above. Hosting of the AEE elements could be distributed between the SME and the prime contractor, with the AEE elements used most intensively (e.g. traditional CAD, CAE) being hosted at the SME's site. Data repositories could also be distributed or replicated at multiple sites.

2.5 Usage scenarios

AEEs may be used in a variety of ways by a design organization. Some possible usage scenarios are illustrated below.

The simplest scenario is the retroactive analysis scenario, as illustrated in Figure 6. Unfortunately, this non-optimal process is followed much too frequently. In this scenario, the spatial design is completed before any functional analysis is undertaken. The candidate design is advanced through the preliminary and detailed design stages based on designer experience and knowledge. The designer validates the design via analysis only after the completion of the detailed design stage. To accomplish this, he idealizes the model by eliminating information not needed for analysis, either due to limitations of the analysis tools or because the mass of detail may hide important aspects of the design's behavior. If the analysis results are satisfactory or nearly satisfactory, the designer completes the final design as planned. If the analysis results are unsatisfactory, the designer must return to the detailed design or even preliminary design stages to resolve the deficiencies. Another iteration of analysis then follows. This retroactive analysis approach may result in overdesign—to reduce the expense or delay of design iterations caused by inadequate behavior revealed by analysis—and/or multiple cycles of prototype building, testing, and modification.

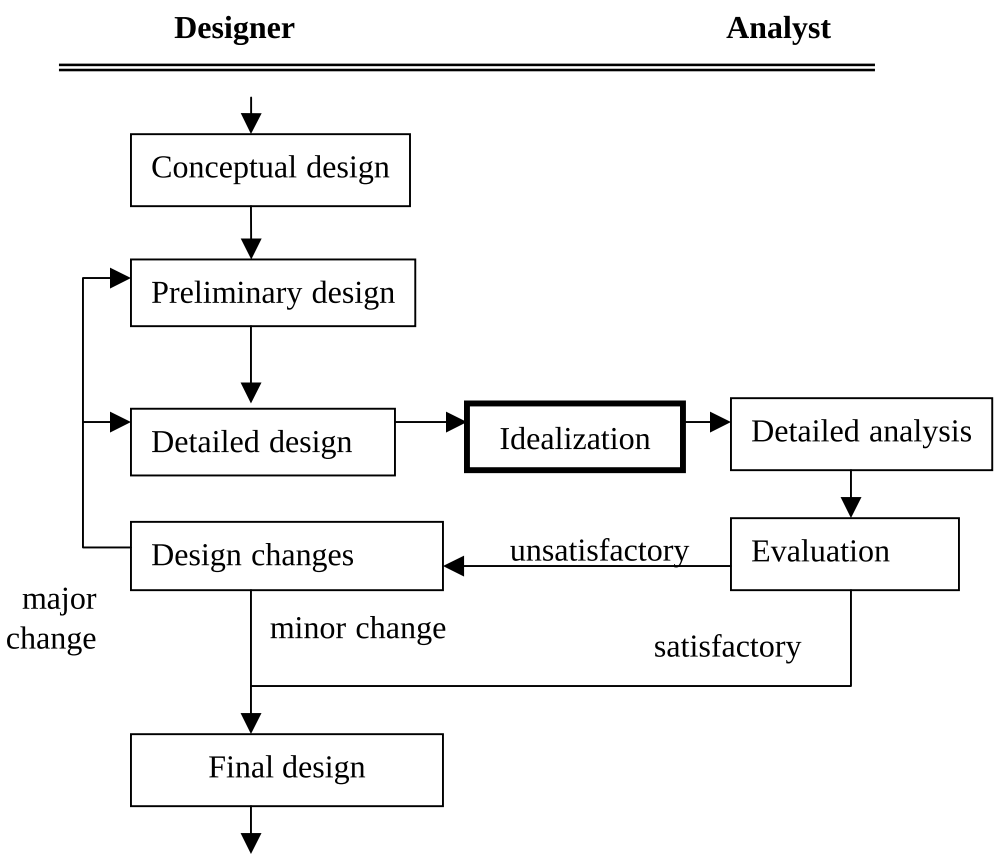

Figure 6: Retroactive Analysis Scenario

A more proactive and more effective scenario involves analyses at earlier stages so that analysis results may guide subsequent design decisions, as illustrated in Figure 7. As users develop more analytical experience and judgement, they often evolve from the retroactive analysis scenario to this one. In this integrated design-analysis mode, the designer analyzes the product throughout the design process. After completion of the preliminary design, the designer idealizes the model as it exists at that stage and analyzes the performance. If the performance is satisfactory, the designer proceeds to the detailed design stage with confidence. If not, he revises the preliminary design and reiterates the analysis. Due to the absence of detail in the preliminary design stage, design modification/analysis iterations can be performed quickly. In the detailed design stage, the designer adds the necessary model detail to suit the needs of the production processes. This detail addition causes significant expansion of both the complexity and size of the product model. At the completion of the detailed design stage, the designer again analyzes the product performance. To accomplish this, he must suppress much of the added design detail and idealize the model to make it suitably simple for analysis. If the analysis predicts satisfactory or near satisfactory performance, the designer may complete the final design. If not, he must repeat the detailed design stage; it is highly unlikely that he/she will have to revisit the preliminary design stage to correct the deficiencies. The chances of major redesigns indicated by analyses of detailed designs can thus be significantly reduced.

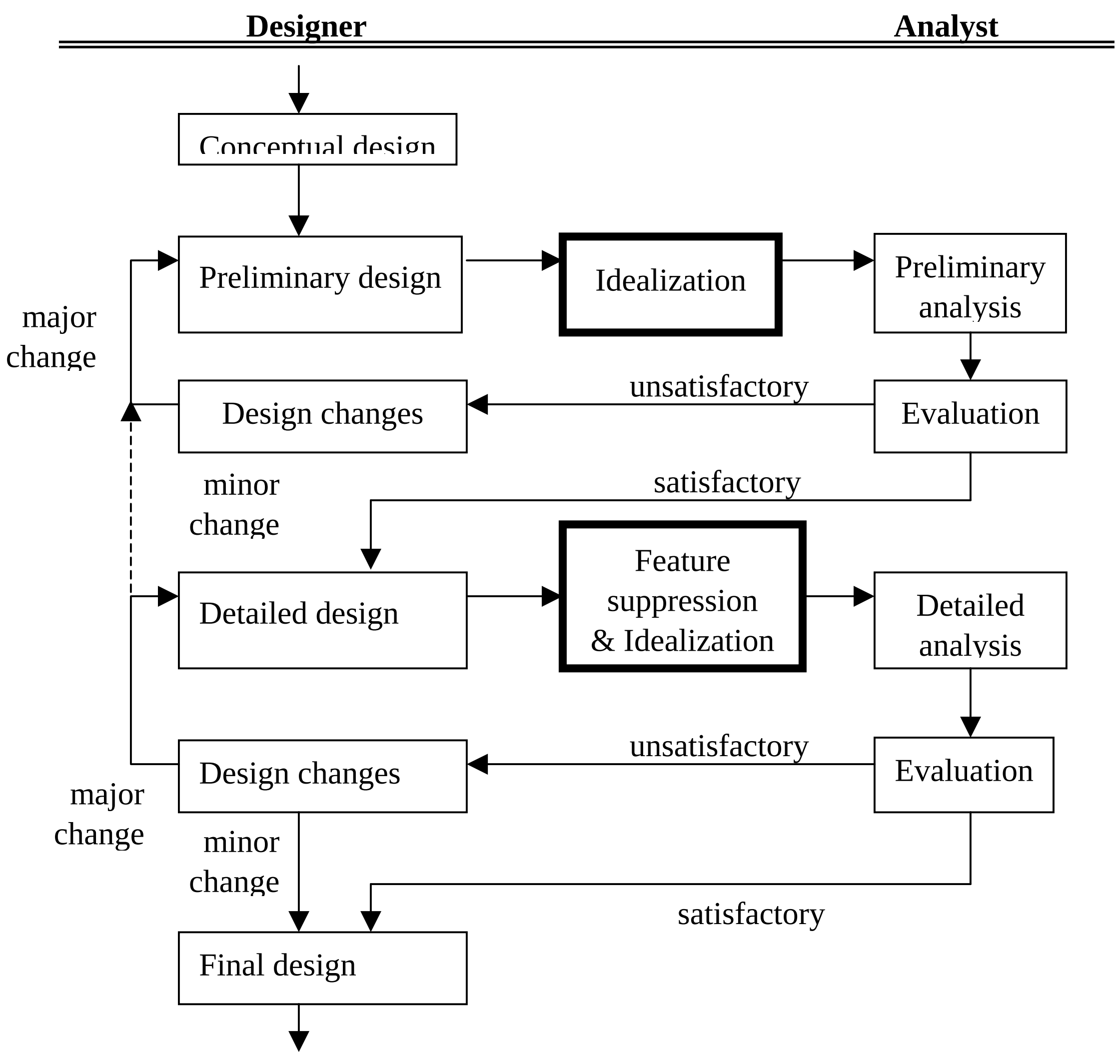

Figure 7: Integrated Design-Analysis Scenario

The scenarios shown in Figure 6 and Figure 7 only use idealization transformations; changes to the spatial model are made only through the CAD system. If it is desired that spatial changes be made through the analysis models as well, then mapping transformations need to be implemented. If one or more of the functional analysis tools are converted to conceptual or preliminary design tools, the scenario of function-driven design shown in Figure 8 emerges. In such a function-driven design mode, the product engineer begins with a functional design of the product, rather than with a form-based design, and translates the functional design into a physical form. This form becomes the starting point for the product designer. He proceeds with the preliminary and detailed design efforts much the same as in the integrated design-analysis mode.

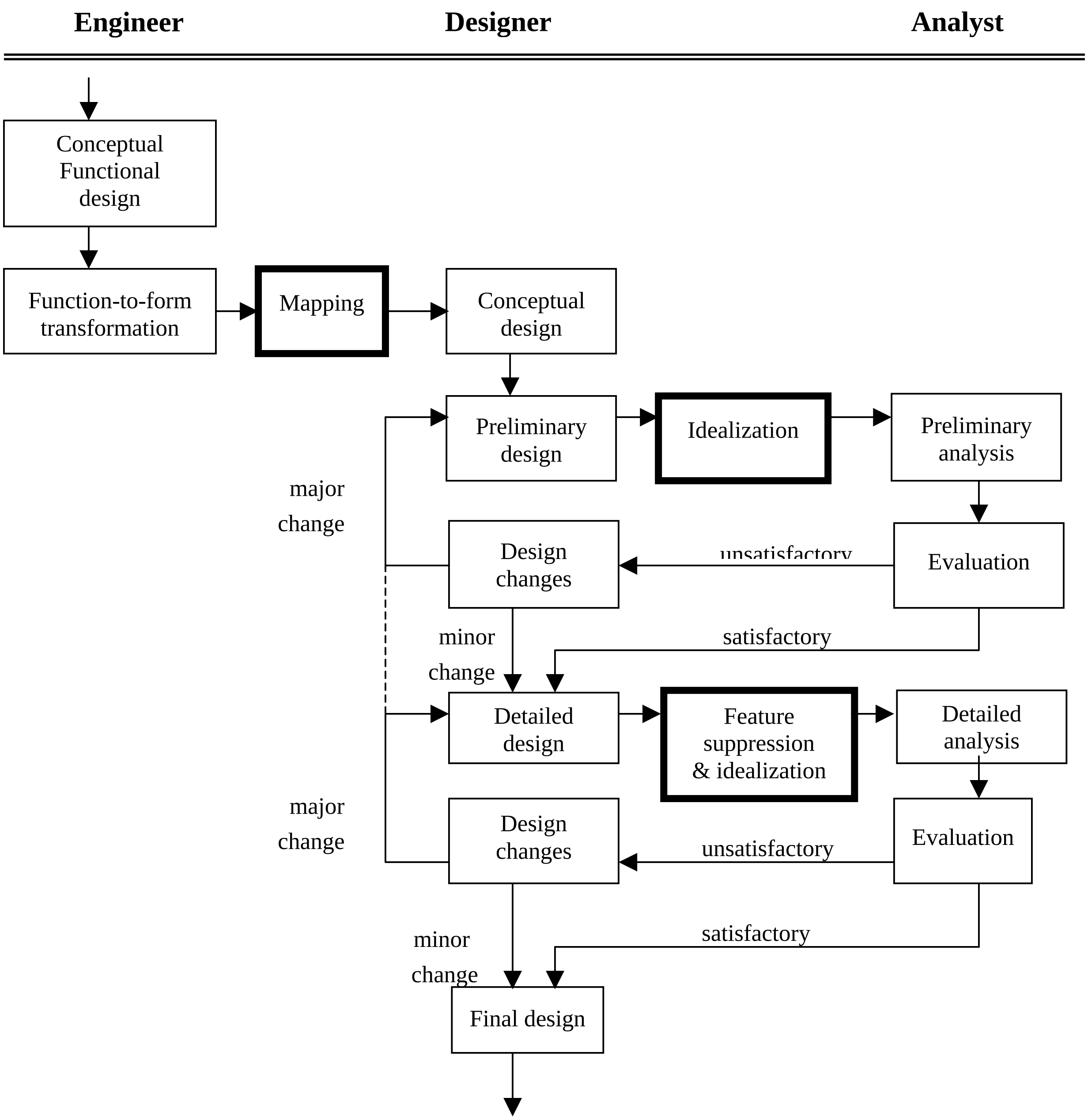

Figure 8:   Function-Driven Design Scenario

Finally, multiple functional analyses (structural, thermal, dynamic, etc.) may be introduced, in parallel or sequentially, resulting in the scenario shown in Figure 9. Like the function-driven design scenario of Figure 8, this multifunctional design-analysis scenario begins with a conceptual design to meet specified functionality. This functional design is mapped to a physical conceptual design and then subjected to various analysis processes. More detail is added to the design as it progresses through the conceptual, preliminary, detailed, and final design stages. Within each design stage, the functionality of the design is analyzed and evaluated with respect to specified requirements and, if necessary, the design is iterated before proceeding to the next stage.

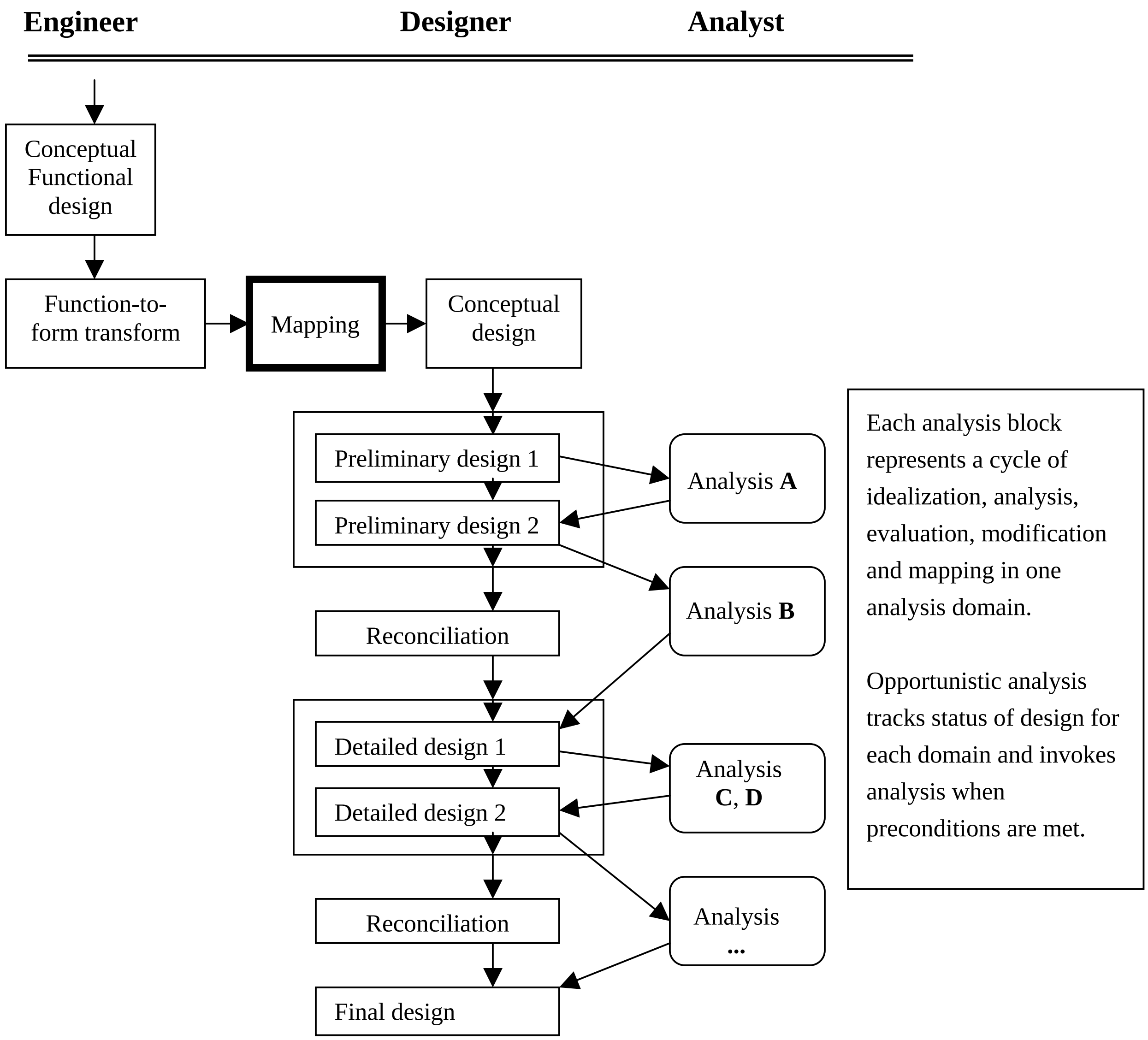

Figure 9: Multifunctional Design-Analysis Scenario

2.6 Summary

Three levels of architecture of AEEs have been presented. The basic level is easily implemented by the smallest SME and requires nothing more than two well-matched COTS software products. The intermediate level can also be implemented by SMEs, but requires some data integration. Architectures of similar complexity have been implemented by and are operational in many large and medium-size manufacturing entities, albeit without the tight data integration presented here. The comprehensive level, like the AEE described in the NRC reports, has not been fully implemented anywhere and serves primarily as a roadmap of future developments and standardization efforts at the component interfaces.

3 Benefits of AEEs

3.1 Benefits Internal to the SME

The adoption of an AEE affects many aspects of an SME's business both in the short- and long-term perspectives. The short-term benefits may be more easily measured, quantitatively or qualitatively, than long-term benefits. Although there are many areas of business where introducing or upgrading an AEE has an impact, the operational benefits can be generally classified into three categories:

- product development and production time reduction;
- product quality improvement; and
- cost reduction.

3.1.1 Product Development and Production Time

AEE components, singly or in combination, can significantly reduce product development and production times via the following methods:

Provide accurate and rapid response to RFQs. In the current globally connected business environment, rapid and accurate response to a customer Request for Quotation (RFQ) is one of the crucial elements to remaining competitive in the market. The use of rapid design tools and catalog search facilities can help to respond quickly to requests from customers. Integrated analysis tools are also useful to quickly assess whether the proposed configuration meets the key engineering requirements from the customer.

Minimize duplicated and repetitive work. Substantial amounts of product development time can be saved by eliminating, or at least minimizing, duplicate and repetitive work in the design process. Parametric design technology not only facilitates the initial design process, it also provides great convenience if redesign with minor modifications is needed later. PDM and PLM tools for managing the design process and data are also useful for facilitating reuse of previous designs.

Reduce the number of design iterations needed for successful design. Design iterations are inevitable during design, analysis and refinement. However, if functional analyses/evaluations are performed earlier in the design process, the number of iteration cycles and design time can be reduced. Moreover, the SME can reduce the number of design iterations by using previous functional analyses/evaluations for similar designs. Extensive analyses and simulations at the design verification stage can drastically reduce—but probably never fully eliminate—the need for physical prototyping and testing.

Maximize reuse of designs and design elements. Significant reductions in development time can be achieved by the reuse of previous designs or design elements. Reuse has always been practiced, but with designs stored in notebooks or file drawers and poorly archived, the time taken to retrieve a design was often more than the time taken to design it from scratch. With the database tools of AEEs, there is an opportunity to index, search, and retrieve previous designs according to a wide range of criteria, thereby significantly reducing development time.

Improve interdisciplinary communication and collaboration. Various collaboration tools in the design process can also reduce design time. The use of collaboration tools in the design process with various engineering disciplines will reduce design/manufacturing misunderstandings, thus reducing physical testing and design/prototyping iterations, process risks, and potential delays. Collaboration tools are particularly valuable when problems are encountered at the manufacturing or assembly stages, and rapid re-designs/re-analyses are needed to rectify the situation.

The tight integration of engineering processes, including CAD, CAE, and CAM, will contribute to shortening the product development cycle. The software integration technologies and smooth standards-based data interchanges that are adopted in many of the CAD/CAM/CAE tools eliminate unnecessary rework and potential sources of error in data preparation for sequences of engineering processes.

3.1.2 Product Quality

The use of an AEE linking analysis and simulation tools not only reduces the product development cycle by eliminating prototypes and extensive physical tests, but also greatly enhances the quality of the products developed via the following methods:

Enhanced Depth of Performance Analysis. The low cost of simulations and quick design/simulation iteration cycles provided by AEEs allow design teams to thoroughly investigate the functional quality of a product before it is manufactured. It has often been observed that this capability of quickly evaluating whether the designer’s intent is satisfied is most critical in the earliest stages of conceptual design, where the designer attempts to synthesize a form to satisfy the most critical functional requirements. An AEE CAD component that can accept a coarse, almost sketch-like form description and an embedded CAE analyzer that can simulate the behavior of the product at this level of detail can be of great value in properly initiating the design process.

Optimization of Final Design. For subsequent, detailed stages of design, multiple levels of simulation tools are available for various requirements. The most basic and popular are general-purpose finite element analysis (FEA) tools. Specialized FEA tools are also available in the areas of non-linear analysis, mold flow analysis, metal forming, casting analysis, fluid dynamics analysis, etc. System analysis tools also contribute to the enhancement of product quality. Multi-disciplinary analysis and optimization tools are another category of tools for quality enhancement. Some optimization tools automate iterative analysis with numerical optimization, exploratory search, and expert system approaches.

Improved Collaboration in Early Design Stages. AEEs also provide important means for effective collaboration at the earliest design stages between designers, analysts, and manufacturing engineers. This allows the design team to reflect all aspects of the product development process in the design so that later design changes are minimized. Last-minute design changes greatly affect the cost and quality of products. A number of collaboration tools are available from commercial sources.

Expanded Reuse of Proven Designs. Design reuse, mentioned above, can also increase product quality, in at least two ways. First, by extending the database of previous designs with information about each product's performance and success in the marketplace, searches and retrievals of previous designs for use in new situations can be restricted to successful products only. Second, by exercising design reuse within one product, the number of different kinds of product components such as bolts or switches can be greatly reduced, increasing the product's maintainability.

Enhanced Methods of Quality Evaluation. Increased product reliability can be achieved through quality engineering tools, reliability-based design and optimization, and tools for robust design.

3.1.3 Cost in Product Development and Manufacturing

Cost reduction is one of the most important issues to maximize the profit in a manufacturing enterprise. Cost reduction can be achieved in many ways; however, this report deals only with issues related to the engineering aspects supported by AEEs. Ways in which AEEs can produce cost reductions include the following:

Design Optimization. The most immediate and direct cost reduction in a product can be achieved by design optimization. In most cases, the target functions for the optimization are related to cost. Combinations of various analysis and optimization tools can be used for specific optimization targets. Manufacturability and cost analysis tools also can be utilized at the early stages to save on product costs. Design reuse, as discussed above, can also reduce product cost by minimizing the number of different kinds of product components.

Risk Reduction through Design Experiments. Design experiments at early stages of the design process reduce product development cost. Analyses, functional simulations, assembly and manufacturing simulations all contribute to the early detection of potential design problems. Nearly 80% of the product cost is committed in the conceptual and preliminary design stages, while most of the actual cost is incurred in the production stage. Also, the ease of making design changes is dramatically reduced once the design is in the detail design stages. Therefore the early detection of potential design problems is crucial to reducing lead time and cost.

Manufacturing Optimization through Simulation. Factory/manufacturing simulation tools can save substantial amounts of funds invested in production facilities. Manufacturing system simulation tools are used for determining the optimal equipment configuration and layout; troubleshooting existing systems, including identifying bottlenecks in the operation; and testing equipment controls prior to installation. These simulations lead to direct savings in capital investment and enhanced productivity.

3.2 Benefits External to SME

AEEs provide benefits to the SME that are visible to external customers and suppliers. These benefits help the SME in a strategic sense in that the external customers and suppliers perceive a higher level of capability or responsiveness from the SME, as described below.

Coping with Global Enterprises and Markets. AEEs permit SMEs to provide quick response to the competitive global market in every aspect, including RFQ response, quickly changing market demands, and shortened product life. Flexibility can be accomplished by carefully implementing AEEs to provide detailed and timely information that is suitable for the SME's individual needs.

For example, consider an SME that competes in a small market by specializing in high performance systems in an aerospace domain. The SME may create an AEE that enables timely and technically detailed information to be placed into proposals. In this case, the AEE is providing the SME with the capability to cost-effectively communicate confidence in a proposed design to customers who are most concerned with technical performance.

Communication with Customers and Suppliers. Effective communication with customers and suppliers can be achieved with various collaboration tools and catalog facilities within an AEE. Efficient technical communication between customers and suppliers not only reduces the development time, but also enhances the quality of the product. Therefore, enabling close and efficient technical collaboration upstream with suppliers and downstream with customers improves competitiveness.

For example, an SME that adopts a 3D CAD tool that supports a common data standard can use this information to support supply chain communication. If a part must be manufactured at another location (outsourced), the 3D CAD tool can generate a data file that can be sent to the supplier to automatically generate a CAM file to manufacture the part. Additionally, the SME can send the final 3D CAD file to the customer to ensure the product integrates into a larger assembly.

3.3 Summary

Some of the benefits an AEE can offer to an SME include:

- **Reduction in product development time.** AEEs encourage and support design reuse and parametric design processes, eliminate redundant efforts during the design process, encourage functional analysis earlier in the design cycle, and encourage collaboration among designers, engineers, manufacturers, suppliers, and customers;
- **Reduction in production time.** AEEs enable design optimization by eliminating overly conservative assumptions. They minimize component inventories by encouraging and supporting design reuse. They also enable process designers to simulate and optimize manufacturing processes during the product design stage
- **Improvement in product quality,** AEEs encourage and support functional analysis and simulation prior to manufacturing. They enable design optimization by evaluating the impacts of design trade-offs. They validate design performance prior to manufacturing. They encourage and support multi-disciplinary collaboration among designers, engineers, manufacturers, suppliers, and customers. They encourage and support reuse of existing successful designs. They enable the use of advanced simulation techniques such as Monte Carlo and Taguchi methods
- **Reduction in product cost.** AEEs enable design optimization, eliminating costly, overly-conservative assumptions. They encourage and support design reuse, minimizing the required component inventory. They enable process designers to simulate and optimize manufacturing processes during the product design stage
- **Reduction in product development cost.** AEEs create reductions in the product development schedule (see above). They detect functional problems earlier in the design process, when they are less costly to fix. They encourage and support design experiments early in the design process
- **Improved market agility.** AEEs enable the SME to cope with rapidly changing global market demands and competitive environments
- **Improved communications.** AEEs provide a means of improving communications with both customers and suppliers, strengthening the supply chain.

4 Technical Considerations for AEE Adoption

4.1 Issues To Be Addressed

The following is a brief outline of the technical issues that an SME needs to consider before adopting or implementing an AEE. Primary emphasis is placed on the engineering process within the enterprise, and to the design activities within that process. Similar issues may arise from the marketing, manufacturing, and service processes. Depending on the scope anticipated for the AEE, such issues may have to be combined with the purely engineering- and design-oriented issues.

Evaluation of current state. The first consideration is the creation of an up-to-date and accurate evaluation of the firm's current state. Key aspects of such an evaluation are:

- *the current mix of products*, particularly their similarities, differences, and potential for creating product families;
- *the degree of integration* and level of communication with marketing, manufacturing, service, etc., as well as with customers and suppliers: paper and telephone; electronic transfer and e-mail, PDM, PLM, etc.;
- *the current level of computer use*, e.g., none, isolated design/analysis/manufacturing applications, basic AEE, or intermediate AEE;
- *the current skill and knowledge level* of in-house designers, engineers, and analysts, as well as external consultants available to the SME; and
- *perceived problems* for which AEE adoption or enhancement is a potential solution, e.g., time delays, cost overruns, communication bottlenecks, product quality and variability.

Definition of goal state. The next consideration is to attempt to define, as clearly as possible at this stage, the expectations of the changed conditions and modes of operation that the adoption or upgrading of an AEE may bring to the organization. Such a definition must be driven by clear business objectives, and is best organized along the five axes used for describing the current state used above, as follows:

- *intended mix of products*, whether to retain present mix, expand or contract it based on technical considerations, or create a hierarchy of product families;

- *intended degree of integration and communication*, which may range from further retrenchment to increased levels of both data and process integration within the organization (e.g., cross-train designers, analysts, and engineers or integrate/disperse design functions), and beyond (e.g., various forms of partnering with suppliers and customers);
- *intended level of computer use* according to the scale given above (specifics of the AEE to be adopted will not be known at this stage, but a preliminary target level may be defined for the different roles involved);
- *skill and knowledge need inventory and training needs*, to correspond to target levels of professional activities; and
- *strategies to address and overcome perceived problems* uncovered.

With the current and goal states identified and documented, the strategic plan to move from the former to the latter can be initiated. The succeeding sections discuss briefly the technical considerations that enter into the strategic plan.

4.2 Choice of AEE Level and Scope

Levels. As discussed in Chapter 2, AEEs may be categorized into three levels based on their capabilities as basic, intermediate, or comprehensive AEEs.

Full-fledged comprehensive AEEs do not exist at the present time. The NRC defines them as goals [**NRC 99**], while the NIST architecture is intended to identify interfaces for potential standardization. [**Sriram 01**] Although not yet complete, the engineering environments presently in place at some of the largest aerospace, automobile, and shipbuilding enterprises are reasonable approximations of the NRC AEE concept.

Intermediate-level AEEs constructed of COTS software components are routinely used by the majority of mid- to large-scale manufacturing enterprises. These environments are by no means standardized, and exhibit a large range of variation in at least three respects:

- *breadth* in terms of the number and kind of design subdisciplines supported;
- *depth* in terms of levels of the design process (e.g., conceptual, preliminary, detailed) or divisions of the organization supported (e.g., marketing, manufacturing, service); and
- *degree of data integration* among the environment components, ranging from fully integrated databases supporting all components to totally disjunct components communicating through files or messages.

Breadth and depth will collectively be referred to as the *scope* of the AEE.

Local engineering environments, routinely found in even the smallest manufacturing enterprises, typically consist of a CAD tool that also serves as the data repository and a discipline-specific CAE tool or, at most, a few such tools. In the mechanical manufacturing area, the CAE tool is, almost without exception, a finite element analysis tool for evaluating mechanical behavior in terms of stresses and displacements.

Direction of evolution. The choice of an appropriate AEE to effectively and efficiently support an SME's goal state will generally be some combination of:

- expanding the scope of the current environment;
- moving up a level in the AEE hierarchy; and
- increasing the degree of data integration.

Moves of more than one level in the AEE hierarchy, e.g., moving from a manual environment to an intermediate AEE level, are not encouraged, as there are too many conceptual and practical steps involved that are only learned by extended practice and exposure to the next higher level.

The most common move direction is expansion of scope. Additional CAE analyses beyond those incorporated in the environment, as well as additional linkages to other phases of the product development process, frequently co-exist within an organization for considerable amounts of time before they are integrated into the environment. At other times, developments external to the engineering group necessitate expansion of the environment in breadth or depth or both. Finally, changes in the marketplace, such as the introduction of new products and services, may warrant expansion of scope by the addition of new tools.

Explicit moves up the hierarchy may be warranted by either internal or external factors. The prime internal factor is the desire or need to move from an unstructured collection of tools to an integrated suite and eventually to full interoperability among the tools. A major component of this migration, the need for increasing the degree of data integration, is discussed separately below. External (to the engineering function) factors driving the move to a higher-level environment may be internal to the organization (e.g., increased scope of engineering design activities, closer linkage to other corporate activities), or external (e.g., tighter linkages along the supply chain, increased dependence on application service providers (ASPs)). In general, a move to a higher-level environment is warranted whenever there is increased need for the full set of tools to "speak as a single voice" with the external world.

The means of communication among the tools comprising an engineering environment vary enormously, from manual transcription of the output of one program to the input of another one—presumably a rarity today—through file transfers with or without standard formats and/or translations, to preprogrammed application program interfaces (APIs) on to full interoperability. A common form of upgrading or migrating an engineering environment is by increasing the degree of data integration among the applications. One way of accomplishing this is through the introduction of shared databases. Databases have the further advantage of providing integrity and versioning controls, and can eventually evolve into searchable repositories of the organization's past successful designs.

4.3 Understanding the AEE COTS Market

After an SME determines the desired level of AEE capability, the SME must examine available AEE components within the AEE market, select specific AEE COTS components and execute an AEE technology adoption plan. This section provides general concepts concerning the AEE COTS market. The next section provides a partial set of references to available resources for evaluating and selecting AEE COTS components. Chapter 5 presents the range of AEE COTS components in greater detail in order to increase awareness and focus attention on critical interoperability issues.

4.3.1 AEE COTS Solution

The significant consolidation within the AEE COTS market has resulted in many AEE vendors partnering with other vendors to provide a complete COTS solution for a manufacturer. This leads SMEs to decide between pursuing an AEE COTS solution from one vendor or combining a suite of AEE COTS components from multiple vendors. Each path has benefits and weaknesses.

If an SME adopts an AEE COTS solution from one vendor, this approach minimizes some of the COTS component interoperability issues. In addition, the SME only contracts support from one vendor and simplifies employee training, because the vendors' AEE tools often use common interfaces. However, this approach is typically a larger initial investment and increases the SME dependency on the COTS vendor. Specifically, the SME must follow the updates and product changes from that one vendor. In addition, if the SME determines that an AEE component is not suitable and considers a component from another vendor, the interoperability with AEE tools outside the COTS solution may be very limited.

The SME can also choose to combine several AEE components from multiple vendors into a custom AEE, but this approach also raises issues. The interoperability across AEE components is not ensured by any one vendor, so this becomes the responsibility of the SME. The SME must also deal with multiple vendors and plan training to support multiple products, which may have different user interfaces. One key benefit of this approach is that the SME can start small and grow incrementally by choosing the specific AEE components that are the best fit for its needs.

The technical considerations in configuring an AEE are largely component- or design function-specific. It is taken for granted that in the engineering organization of any manufacturing concern, a CAD tool will be the primary AEE component generating, visualizing, communicating, and modifying the physical form and the assembly of designs, as well as one of the primary linkages, with PDM or PLM, to manufacturing and CAM. CAD systems are categorized into entry, “light,” and “full strength” levels, with substantial, if not complete, compatibility between the last two.

A further consideration in choosing a COTS tool is often interoperability with customers. SMEs frequently serve as subcontractors to larger prime contractors. In an effort to maximize interoperability and data sharing, some prime contractors mandate the use of specific COTS tools. This can be a significant difficulty for a small manufacturer, forcing him to adopt a new tool that may not be the best fit for its operation. This is further complicated when dealing with multiple prime contractors, each with its own preferred tool set. Fortunately, this occurrence is rare. AEE tool vendor implementation of data interchange standards such as STEP is improving data sharing capabilities among different tools, but this is an evolutionary change that requires buyers to thoroughly test AEE tool interoperability before committing to a specific tool.

4.3.2 Targeted Users

AEE tool vendors tend to have a variety of products that target a range of users. For SMEs, it is important to understand the targeted users of an AEE COTS tool and the level of training required to use the tool.

For example, some CAE tools are complex and provide a wide range of functionality because they are targeted at analysts or lead engineers. However, many CAE tool vendors also sell lower cost tools that have been simplified to target engineers or designers. A common practice by vendors is that in addition to a full-fledged CAE tool, they provide a simplified version embedded in and compatible with various CAD systems. These embedded tools have limited capabilities, but are easier to learn and use. They are appropriate for use by designers and engineers in the conceptual and preliminary stages of the design process, even if the full-fledged version needs to be used by analysts later for detailed design and product verification.

As other analysis technologies mature and become available to the designers (e.g., computational fluid mechanics, multiphysics, mathematical optimization), it can be expected that they will be either added to current tools or become available as separate AEE components.

Increasingly, PDM will become an essential AEE component, in either embedded or integrated form, both for the control of the design process itself and for the integration of the engineering function into the total product delivery system. It is to be expected that PLM will in short order also become an important AEE component, even for the smallest environments.

Chapter 5 presents COTS examples of potential AEE components.

4.4 Choosing COTS Products for AEE Components

There is a substantial body of literature on the topics of the evaluation of COTS products and of constructing systems comprised of COTS components [**Carney 98**]. Although much discussion of COTS evaluation is general in nature, a relevant example in the manufacturing domain is [**Brownsword 00**]. This literature can be used for choosing AEE COTS products as well, with a few important provisos:

- There is typically less customization of the COTS products in this area than in other application domains, such as commerce or management;
- Documentation is important, as always, but in addition to traditional forms of documentation, it is particularly important to have clear and credible documentation of the theoretical basis of the product, elaborated through numerous examples;
- The degree of support and training from the vendor and the availability of local expertise on the product are very important selection factors; and
- Similarly, the popularity of the tool and the upgrade plans of the vendor are important factors.

The last two factors imply a degree of conservatism of the AEE users. Such conservatism is amply warranted by the ethical and professional responsibilities of engineers and designers for the products they design. This responsibility cannot be relegated to the tools they utilize.

In addition to the general COTS evaluation criteria mentioned above, the evaluation must include technical criteria relevant to AEE. For example, a common CAE component is FEA. The technical considerations in choosing the appropriate FEA tool are many:

- Will non-linear analyses be needed? If so, what kinds (material and/or geometric nonlinearities)?
- Will dynamic analyses be needed? If so, what kinds (modal, harmonic, time-domain, frequency-domain)?
- Will specialized finite elements and processing capabilities be needed (e.g., thick-walled cylinders, sheet metal)?
- Will special types of pre- and post-processing be needed?

These technical issues are sometimes difficult for SMEs to identify, but Chapter 5 provides a summary of common criteria.

4.5 Summary

Technical factors to be considered when adopting an AEE include:

- evaluation of the current state of the SME to determine the current mix of products, degree of internal integration, current level of computer use, current skill and knowledge levels, and perceived problems;
- definition of a goal state, including the desired future state of the SME, and the strategies to overcome the perceived problems;
- definition of the scope and level of the AEE to be adopted, based on the foregoing evaluations;
- specification of the requirements for the components of the AEE; and
- selection of the COTS AEE components satisfying the requirements.

5 COTS Elements of AEEs

5.1 Classification of COTS AEE Architectural Elements

The NRC identifies AEE components and their characteristics in three categories, as shown in Table 1 [**NRC 99**]. The check-marked entries are considered to be relevant to this report and are listed with references to the sections in which they are discussed.

Table 1: NRC AEE Elements

√	1. Computation, Modeling, and Software	
√	A. Multidisciplinary analysis and optimization	Section 5.3
√	B. Interoperability of tools, data, and models	Section 5.4
√	C. System analysis and synthesis	Section 5.5
√	D. Collaborative, distributed systems	Section 5.6
	E. Software structures that can be easily reconfigured	
	2. Human-Centered Computing	
	A. Human-adaptive interfaces	
√	B. Virtual environments	Section 5.7
√	C. Immersive systems	
	D. Telepresence	
	E. Intelligence augmentation	
	3. Hardware and Networks	
	A. Ultrafast computing systems	
	B. Large high-speed storage devices	
	C. High-speed and intelligent networks	

Chapter 2 defines three levels of AEEs and their respective components. The correspondence between the NRC AEE components and those previously identified is shown in Table 2.

While all the components listed in the NRC report need to be exploited for full-scale AEE systems for large manufacturing organizations such as Boeing or General Motors, SMEs need only a portion of the components identified. When it comes to the urgent and short-term implementation needs of SMEs, currently available AEE components are very limited. The goal of this report is to identify candidate COTS products for each AEE software component relevant to SMEs, with increased specificity and breadth at the intermediate and comprehensive levels.

The presentation is generally organized according to the classification of the NRC report.

Table 2: Classification of AEE Components

Engineering Function	**SOURCE**			
	NRC AEE	**Comprehensive AEE level**	**Intermediate AEE level**	**Basic AEE level**
Form Capture	• Not specifically addressed	• Traditional CAD	• Traditional CAD	• Traditional CAD
Functional Analysis	• Multidisciplinary analysis, optimization • System analysis and synthesis	• Knowledge-based CAD • CAE Tools • Immersive CAD	• CAE tools	• Embedded analyzers • Compatible analyzers
Process Management	• Not specifically addressed	• Work flow manager	• PDM linkage	• Not specifically addressed
Data Storage	• Large high-speed storage devices • Interoperability of tools, data, and models	• Design evolution database • Design repository	• Design database • Design repository • Catalog access facility	• CAD database
Human Interface	• Virtual environ. • Immersive systems	• Immersive CAD	• CAD interface • CAE interface	• CAD interface • CAE interface
Communications	• Collaborative, distributed systems • Interoperability of tools, data, and models	• Design net • Process planning net • Production net • Client net	• Local area network (LAN) • Internet	• LAN • Internet

5.2 CAD Tools

Geometric CAD tools, not specifically discussed in the NRC report, are among the most important and widely used COTS components. Most current geometric CAD tools support feature-based parametric modeling, with some small variations in the capabilities among them. The choice of the right CAD tool depends on a number of different concerns, including current design practices, budget, the software environment, the main product line of the SME, available add-on modules, other existing tools within the company for interoperability and integration, etc. Specific modeling capabilities, such as surface modeling or assembly modeling, may have to be checked for the company's particular needs. Historically, CAD tools began to be available on mainframe computers and workstations, and these tools eventually evolved into CAD/CAM/CAE tools with a variety of add-on modules.

Representative "full-featured" mechanical CAD tools include Pro/Engineer (http://www.ptc.com/), CATIA (http://www.catia.com/), IDEAS (http://www.plmsol-eds.com/) and Unigraphics NX (http://www.plmsolutions-eds.com/). As personal computers (PCs) become more powerful, PC-based low-cost CAD tools with more limited capabilities appeared in the market. In fact, today the border between the full-strength CAD tools and the PC-based "light-duty" CAD tools becomes obscure, in that PC-based CAD tools have gradually been providing increasingly more sophisticated capabilities and add-ons. "Light-duty" CAD tools include SolidWorks (http://www.solidworks.com/), Solid Edge (http://www.plmsolutions-eds.com/), Autocad Inventor (http://www.autodesk.com/), IronCAD (http://www.ironcad.com), think3 (http://www.think3.com), Cadkey (http://www.cadkey.com), Microstation (http://www.bentley.com), and Visual CAD (http://www.visualcad.com). A comprehensive evaluation of the above CAD tools, along with several others, can be found in the CAD Rating Guide by B. Holtz and available from http://www.cyonresearch.com. Other useful sites for discussion and evaluation of CAD tools are http://www.eareport.com, http://www.upfrontezine.com, and http://www.tenlinks.com.

5.3 Multidisciplinary Analysis and Optimization

Engineering analysis and optimization techniques are evolving from single or uncoupled problem solving in single domains to multi-disciplinary or coupled problem solving. In this section, examples of commercial analysis tools that can model and solve single-domain and coupled multiphysics problems are reviewed. A structural optimization tool as an example of optimization software and two multidisciplinary engineering optimization environments are also introduced.

5.3.1 Engineering Analysis and Simulation Tools

The most popular and frequently used CAE analysis tools are FEA tools for structural, thermal, and fluid flow analysis. The major CAE software vendors provide FEA modules with convenient user interfaces to CAD models. Frequently, the core analysis modules are licensed from vendors specializing in analysis software and interfaced with CAD systems. Two popular general purpose FEA tools are Ansys (http://www.ansys.com/) and Nastran (http://www.mscsoftware.com/).

Some of the more specific analysis needs and representative corresponding specialized analysis tools are non-linear analysis (Marc, http://www.mark.com/, LS-DYNA, http://www.ls-dyna.com/); mold flow analysis (Moldflow, http://www.moldflow.com/); metal forming analysis (DEFORM, http://www.deform.com/); casting analysis (MAGMA, http://www.magmasoft.com/); and fluid dynamics analysis (FLUENT, http://www.fluent.com/).

Dynamic mechanical system simulation and analysis tools are also commercially available with varying degrees of specialization. ADAMS (http://www.mscsoftware.com/products/products_detail.cfm?PI=413), Pro/ENGINEER Mechanism Dynamics (http://www.ptc.com/), and DADS (http://www.lmsintl.com/) are representative examples of such products.

In order to bridge the gap between CAD and CAE activities in the product development process, CAE tools for preliminary and simplified analysis embedded in CAD systems have recently emerged. Examples in this category are DesignSpace (http://www.ansys.com/), VisualNastran (http://www.mscsoftware.com/), CATIA Generative Part Stress Analysis (http://www.catia.com/) and Unigraphics Strength Wizard (http://www.eds.com/products/plm/). The goal of these products is to provide the capability of early assessment of the behavior of the design, before going into elaborate detailed design. Since these tools are to be used by designers, not analysis specialists, the user interfaces are designed to be simple and easy to use. After the preliminary analyses are completed, the models generated for analysis may be further used in detailed CAD operations.

5.3.2 Multiphysics Modeling and Analysis

Multiphysics modeling is important, since real-world mechanical behavior is often the result of not one, but several, physical factors acting simultaneously. A chemical reaction, for instance, cannot take place without mass and heat transfer also occurring. FEMLAB (http://www.femlab.com/), based on MATLAB (http://www.mathworks.com/), is a simulation tool that can arbitrarily couple any number of nonlinear physical processes into a single model and solve them simultaneously. This analysis tool solves a system of partial differential equations simultaneously, rather than sequentially, to improve convergence. This implies that analysts can model and simulate their applications as close to reality as possible and necessary for the problem at hand. Similarly, Professional Multiphysics (http://www.algor.com/) and ANSYS/Multiphysics (http://www.ansys.com/) enable engineers from multiple disciplines to couple the effects of different types of physical behavior and study their impact on a design, thus performing more realistic simulations.

5.3.3 Optimization

Every effort in product development in a manufacturing enterprise is targeted, informally at least, towards optimizing some design feature or manufacturing process. More formal optimization approaches are available to enhance the efficiency and effectiveness of the optimization process. A broad range of tools is available focused on different aspects of optimization, including shape, geometry, and topology optimization of a machine part or structure, mechanical system optimization, and distributed multidisciplinary optimization.

Altair OptiStruct (http://www.altair.com/) is one of the finite element based structural analysis and optimization tools for conceptual design and design refinement. Its capabilities for topology, shape, and size optimization can be used to design and optimize structures to reduce weight and tune performance.

ADAMS (http://www.adams.com/) provides suites of mechanical system simulation tools for specialized application domains, including the automotive, aerospace, machinery, and railcar industries. The capabilities include modeling of mechanical systems, mathematical and visual simulation, and optimization for user-defined optimization criteria.

NuEngineer (http://www.numan.com/) allows engineers to design, analyze and optimize designs with artificial intelligence techniques, across engineering applications with different tools. The software provides integration tools for CAD and analysis tools. The software enables engineers to automatically search through many new designs across different engineering applications and platforms with intelligent search criteria.

iSIGHT (http://www.engineous.com/engineous.html) is an optimization tool that integrates analysis tools and enables design explorations. It automates iterative analysis with numerical optimization, exploratory search, and expert system approaches. It also provides quality engineering tools such as Monte Carlo analysis, reliability-based design and optimization, and the Taguchi method for robust design.

A summary of the COTS tools presented in Sections 5.2 through 5.3.3 is shown in Table 3.

Table 3: Sample of COTS CAD and CAE Tools

Tool	Supplier	Function
Pro/Engineer	PTC	High-end CAD
CATIA	Dassault Systemes	High-end CAD
IDEAS	Electronic Data Systems	High-end CAD
Unigraphics	Electronic Data Systems	High-end CAD
SolidWorks	SolidWorks Corp.	Midrange CAD
Solid Edge	Electronic Data Systems	Midrange CAD
Autocad Inventor	AutoDesk Inc.	Midrange CAD
Ansys	ANSYS, Inc.	Full-featured FEA
Nastran	MSC Software Corp.	Full-featured FEA
Marc	MSC Software Corp.	Nonlinear FEA
LS-DYNA	Livermore Software Technology Corporation	Nonlinear FEA
Moldflow	Moldflow Corp.	FEA for injection molding
DEFORM	Scientific Forming Technologies Corp.	FEA for metal forming

MAGMA	MAGMA Foundry Technologies, Inc.	FEA for casting

FLUENT	Fluent Inc.	FEA for fluid dynamics
ADAMS	MSC Software Corp.	Dynamic mechanical simulation and analysis
Pro/ENGINEER Mechanism Dynamics	PTC	Dynamic mechanical simulation and analysis
DADS	LMS International	Dynamic mechanical simulation and analysis
DesignSpace	ANSYS, Inc.	Entry-level FEA
VisualNastran	MSC Software Corp.	Entry-level FEA
CATIA Generative Part Stress Analysis	Dassault Systemes	Entry-level FEA
Unigraphics Strength Wizard	Electronic Data Systems	Entry-level FEA
FEMLAB	COMSOL, Inc.	Multiphysics FEA
MATLAB	The MathWorks	Environment for data analysis, visualization, and application development
Professional Multiphysics	Algor, Inc.	Multiphysics FEA
ANSYS/ Multiphysics	ANSYS, Inc.	Multiphysics FEA
OptiStruct	Altair Engineering, Inc.	Structural FEA and optimization
NuEngineer	Numan Intelligence, Inc	Integrating/optimizing environment for CAD and CAE tools
iSIGHT	Engineous Software, Inc	Integrating/optimizing environment for CAD and CAE tools

5.4 Interoperability of Tools, Data, and Models

Interoperability of tools, data, and models becomes increasingly important for the close integration of engineering processes in an extended enterprise. CAD must communicate with CAE to facilitate the engineering analysis needed in the design process. CAD must communicate with CAM to provide the smooth transition from design to manufacturing. CAM must communicate with numerically controlled (NC) machine tools to execute the manufacturing activities. CAD must communicate with PDM to ensure proper product configuration control. Communication protocols such as IGES (Initial Graphics Exchange Specification) (www.nist.gov/iges/), STEP (STandard for the Exchange of Product model data) [ISO **94]**, and various OMG (Object Management Group) standards have been created to facilitate this inter-tool communication. In this section, current solutions and near-future plans to address interoperability issues in engineering environments are discussed. Various data interchange paths, depicted in Figure 10, are addressed below in detail, with examples of available commercial tools and protocols.

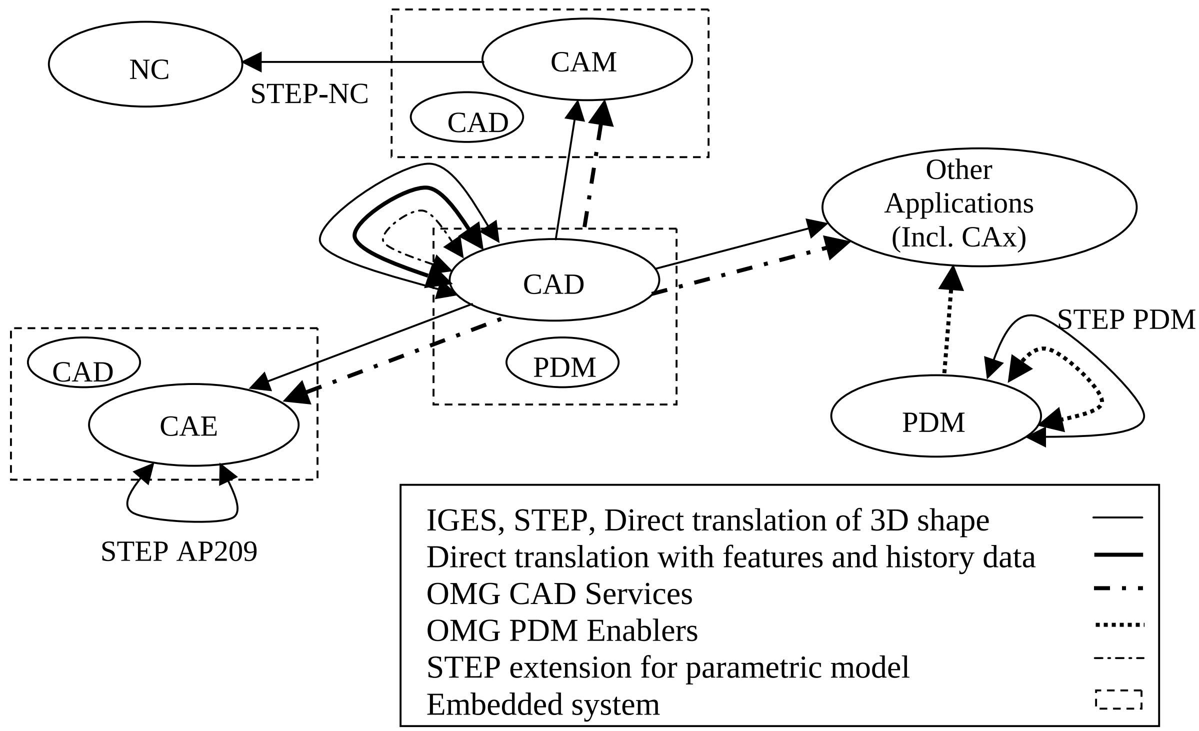

Figure 10: Data Interchange Map Between Application Areas

5.4.1 CAD-CAD Interoperability

Computer technology began to penetrate into product development and manufacturing processes with the emergence of CAM technology in the 1950s. However, it was only after the 1970s that computer use became popular in product design under the name of CAD. CAD technology had been supporting the development of the product's shape description with two-dimensional drafting and three-dimensional modeling capabilities until feature-based parametric design technology emerged in the mid 1980s. The major motivations for using CAD were digital archiving, ease of reuse, and potential linkage to CAM. Tighter integration of CAD with downstream applications, such as CAM and CAE, came later. Even before the advent of three-dimensional parametric design technology, there existed several different commercial CAD products and in-house software developed by manufacturing enterprises. Users of CAD products began to realize that the data created with one system was not interchangeable with other systems and their internally developed databases. An effort to create a standard for the exchange of CAD data began in 1979; this standard later became IGES. The fundamental idea of IGES was to transfer two-dimensional drawing data, later including three-dimensional shape data, in fixed file format, with an electronic form.

Although IGES served its purpose of exchanging CAD data between different CAD systems, limitations of the standard were observed. The major deficiencies were large file sizes, long processing times, lack of upward compatibility due to the fixed file format and, most importantly, the restriction of information exchange only to shape data rather than covering complete product data. Despite these limitations, IGES is being supported by most CAD products and is still widely used for CAD data exchange.

In the meantime, the idea of utilizing a geometric modeling kernel for developing CAD products emerged in 1987. The first commercial modeling kernel, ACIS, appeared in 1990. Later, similar kernels, such as Parasolid, Designbase, and Open CASCADE, became available as products. It was contemplated that the interoperability problem of exchanging three-dimensional shape data might be solved if one of the kernels were widely adopted for CAD product development. However, this never happened, for several obvious reasons. Major CAD vendors did not want to give up their own proprietary modeling kernels due to both technical reasons and company policies. Even if one modeling kernel had been widely adopted at the time, the interoperability problem would have not been solved because of the new modeling paradigm, with feature-based, parametric, and history-based modeling, which began to appear in the mid 1980s. However, three-dimensional solid shape data exchange with a kernel-based data format, such as the '.sat' files from ACIS, is also currently supported and used between CAD products that utilize the same modeling kernel.

After the shortcomings of the IGES had been observed, a new standardization effort for the representation of product model data began in 1984. This new standard was based on existing standards and was targeted to provide a mechanism for the exchange of lifecycle product model data in computer interpretable electronic form. The resulting international standard, ISO 10303, was informally named STEP **[ISO 94]**. One of the significant departures from existing standards was that a formal information modeling technology was adopted to represent data in the standard, instead of using fixed file formats. Another ambitious goal was the idea of sharing product data between various departments and organizations beyond simple data exchange. In 1994, the first STEP standard at the application level, AP 203 *Configuration Controlled 3D Designs of Mechanical Parts and Assemblies,* was approved by ISO **[ISO 94]**. Fourteen application protocols (APs) have been approved as international standards at the time of writing this report. Among these, AP 203 is still the most widely supported standard in commercial products and is used extensively. PDES Inc., an international industry/government consortium devoted to accelerating the development and implementation of STEP, examines commercial products for STEP translation capabilities and reports the results periodically (http://pdesinc.aticorp.org/vendor.html). Also, US PRO**,** a nonprofit membership organization established by industry, began STEP certification in 1998 (http://www.uspro.org/). STEP-certified products are those that have successfully completed a syntacticevaluation of the product's adherence to the STEP standard in accordance with the testing procedures and guidelines that form a part of the standard.

Although STEP AP 203 is widely supported in commercial products, it exhibits serious deficiencies in handling feature-based parametric product model data. The new modeling paradigm, namely feature-based parametric modeling, came into the market in the mid 1980s, and the technology has been adopted by most major CAD/CAM vendors since then. However, STEP AP 203 was designed toward the conventional static three-dimensional shape representation with configuration data. Currently there is no agreed-upon standard to represent feature-based parametric product data, except STEP AP 214 **[ISO 214:01]** and AP 224 **[ISO 224:01]**, in which there are limited feature-based representation schemes for machining purposes. However, several research activities are in progress to address the interoperability of CAD models with parametric capability [**Pratt 01**].

In response to the urgent need of solving parametric CAD data interchange problems, companies have recently begun to provide translators for exchanging product data, including feature, history, and constraint information, with their own proprietary technology. Proficiency (http://www.proficiency.com/) and TTI (http://www.translationtech.com/) provide similar functionalities for exchanging native feature and history data between four major CAD products: CATIA, Unigraphics, Pro/Engineer, and SDRC IDEAS. However, their business models differ. Proficiency markets its translating software as an enterprise solution, while TTI provides pay-per-use translation service as an ASP, as discussed below. Theorem Solutions (http://www.theorem-usa.com/) and ITI (http://www.DEXCenter.com/) also provide software and pay-per-use services for direct translation between major CAD tools and standard-based translation. InterOp (http://www.spatial.com/) is a standalone translator with the same translation capability.

5.4.2 Accommodation of Legacy CAD Data

3D CAD-translated data from other systems or static solid model data in legacy databases are hard to edit and utilize further within modern parametric feature-based systems. Some CAD tools offer feature recognizer modules for building their own native parametric feature-based data automatically from static 3D data. The data generated this way may not represent exactly the designer's intention or modeling process, but it will at least allow easier modification of the model later. SolidWorks (http://www.solidworks.com/index.html) and Solid Edge (http://www.solid-edge.com/) provide feature recognition modules for this purpose.

5.4.3 CAE-CAE Interoperability

Data interchange problems between CAE systems have not been seriously addressed until recently. Various analysis systems had their own proprietary interfaces and internal representations for preparing analysis models and representing analysis results. Occasionally, input data formats of the more popular analysis software have been supported by other systems for interoperability. However, design and collaboration on a product model in an extended enterprise of many companies necessitated a standard for describing the analysis data (http://pdesinc.aticorp.org/pilots/engineering.html). STEP AP 209 provides a neutral data format representation of analysis models needed to conduct engineering analyses within an iterative design-analysis environment using heterogeneous analysis tools [**ISO 209:01**]. STEP AP 209 enables version control of design and analysis information linked to a product structure; it is thus a powerful CAD/CAE interoperability aid as well. STEP AP 209 was approved as an international standard in 2001, and it is expected to be widely supported by analysis systems.

5.4.4 PDM-PDM Interoperability

Collaboration on product data in an extended enterprise of many companies also necessitated a standard for describing product data within PDM systems. Although the work is still in progress, the ISO 10303 STEP PDM Schema provides a reference information model for the exchange of a central, common subset of the data being managed within PDM systems. It represents the intersection of requirements and data structures from a range of STEP application protocols, all generally within the domains of design and development of discrete electro/mechanical parts and assemblies. Although the STEP PDM Schema is still under development, several PDM systems currently support it.

In an alternative approach, the OMG PDM Enablers is intended to provide access to the services of product data management systems from various application software systems in a manufacturing enterprise (ftp://ftp.omg.org/pub/docs/mfg/99-10-04.pdf). Activities supported by such "client" applications encompass product conception and planning, product design, manufacturing engineering, production, delivery, and maintenance. The emphasis is on providing interfaces for the management of product data.

5.4.5 CAD-CAE Interoperability

Some system analysis tools, such as kinematic and dynamic analysis software, have their own modeling interfaces, not compatible with other systems. However, most FEA analysis tools offer capabilities for importing 3D shape data from CAD systems. Major vendors of CAD systems offer FEA modules "integrated" with CAD tools, even though the integration means only a convenient user interface and the smooth transfer of 3D shape data from the CAD module to the FEA module. Most of the independent FEA tools compatible with CAD systems provide data interface modules for major native CAD data formats and for standard formats such as IGES and STEP. STEP AP 209, discussed above, provides explicit linkages between the shape data in the design (i.e., CAD) and analysis models.

However, successful data import from a CAD module to an FEA module does not guarantee a successful analysis. There are two categories of practical problems that impede the smooth integration of CAD and analysis tools. The first category is related to improper geometry data that is not suitable for processing in the analysis, mainly due to erroneous practices of

CAD operators and to problems resulting from data translation. This kind of problem can be solved by properly training CAD operators and by using geometry healing tools such as GeometryQA (http://www.cadfem.de/knowledge_engineering/pqa/geometryqa_download.pdf), CAD/IQ and CADfix (http://www.transcendata.com/products_cadfix.htm).

The second category is related to the fact that the models needed for analysis are usually different from the detailed 3D design model. Very often, a significant amount of time is consumed in idealization or remodeling for analysis after the detailed 3D design is finished. This effort can be reduced by the feature suppression capabilities of some CAD tools and/or supplementary modeling tools such as mid-plane extraction tools for mold flow analysis. The feature suppression capability may be very efficient when the CAD operator or designer has some knowledge of the needs of the downstream analysis activities, since successful feature suppression operations heavily depend on how the model is created. On the other hand, technologies for automatic or even semi-automatic idealization from detailed 3D shapes to analysis models, which may involve multiple levels of abstraction for various domain-specific analyses, are not yet commercially available, except for mid-plane generation from thin 3D solid models for mold flow analysis.

5.4.6 CAD-CAM Interoperability

Data interchange between CAD and CAM tools has not been a serious issue in the past, because CAM tools operate only on the final detailed geometry. Most of the problems encountered during numerical control code generation are related to geometry details such as surface discontinuities due to different tolerances between CAD and CAM tools, and cracks, sliver surfaces, duplicate surfaces, reversed surfaces, etc., due to CAD operators' poor practices. These problems can be solved by properly training CAD operators and by using geometry analysis or fix/healing tools. Current CAM tools provide data interface for IGES, STEP and major native CAD formats and generate ISO 6983 G-code for NC controllers. A new initiative, STEP-NC [STEPNCRef], is being carried out in the STEP community to develop a standard for more streamlined and intelligent interfaces between CAD and CAM, which will eventually make ISO 6983 obsolete. With the new standard, future NC controllers will operate on 3D shape data and high-level machining operations instead of direct commands for motion control in machine tools (http://www.steptools.com/library/stepnc/index.html).

5.4.7 CAD-PDM Interoperability

It is not necessary for the typical SME to implement a full-scale PDM system for product data management. Implementation of full-scale data management solutions requires a substantial investment in time and money for planning, setup, and deployment. However, some PC-based CAD tool vendors have begun to include essential components of PDM capabilities in their CAD tools (http://www.solid-edge.com/insight/default.htm, http://www.think3.com/products/). Capabilities of these tools include data vaulting, revision management, engineering change order processing and bill of materials (BOM) management so as to help companies capture, share, and reuse the collective knowledge of their design engineering organizations. Although this built-in PDM capability may not fit perfectly every company's needs and may not be easily customized, it is worth investigating during any CAD tool selection process.

The interoperability protocols discussed in Sections 5.4.1 through 5.4.7 are summarized in Table 4.

Table 4: Interoperability of AEE Tools

	CAD	CAE	CAM	PDM
CAD	STEP AP203	STEP AP209	STEP NC	
CAE	STEP AP209	STEP AP209		
CAM	STEP NC			
PDM				STEP PDM

5.5 System Analysis and Synthesis

5.5.1 Design Methodology Tools

Traditionally, the design process has been considered an iterative process of applying art, experience, and science by designers. Although this is largely true, more systematic design approaches can be applied in order to reduce iterations and to generate better designs from design concepts. These methods are particularly useful in the integrated design-analysis, function-driven design, and multifunctional design-analysis usage scenarios of Section 2.5, which feature early analysis-driven design iterations.

Axiomatic design is one such design methodology. Axiomatic design theory is based on the notion that axioms, or universally accepted principles, can be used as the foundation for good design. Acclaro (http://www.axiomaticdesign.com/) helps designers make better design decisions, based on a fundamental set of principles that determine good design practices. The fact that the axiomatic design methodology is based on a fundamental set of design principles that operate in multiple domains differentiates its applicability from that of knowledge-based design support systems that are closely tied to their application domain.

TRIZ (Theory of Inventive Problem Solving) is based on information extracted from patents, and provides analytical and knowledge-based tools that serve as a systematic path to innovation. Innovation WorkBench and its companion tools (http://www.ideationtriz.com/) based on TRIZ can be used to solve innovative problems in design and engineering.

Quality Function Deployment (QFD) is a systematic process for motivating a business to focus on its customers. It is used by cross-functional teams to identify and resolve issues involved in developing products for customer satisfaction. Tools based on the QFD approach, such as QFD/CAPTURE (http://qfdcapture.com/), can be used in product design to provide a customer-oriented point of view.

Design of Experiments (DOE), using the Taguchi approach, attempts to improve product quality, defined as consistency of performance. The prime motivation behind the Taguchi experiment design technique is to achieve reduced variation, hence producing robust designs. Qualitek-4 (http://www.rkroy.com/wp-q4w.html) and iSIGHT (http://www.engineous.com/engineous.html) are examples of tools that support robust design processes with the Taguchi approach.

5.5.2 Knowledge-Based Design Support Systems

CAD systems are basically shape defining tools, while important design decisions are made by designers reasoning about function, using their expertise, experience, and supporting tools, such as analysis tools, in their particular domain. The concept of knowledge-based design is to capture domain-specific design rules in design support systems, whether these rules are represented in mathematical form or in rule-based form, and to help non-expert designers to make better design decisions. This technology is supported in the commercial market in two ways. One is the so-called "knowledgeware" that provides easily customizable tools to represent or supply links to a knowledge base of experts and such information as product rules, performance data, and legislative and safety codes, and to provide interfaces to CAD models. ICAD from Knowledge Technologies International (http://www.ktiworld.com/our_products/icad.shtml), and AML (http://www.technosoft.com/) belong to this category of products. More general design environments, not restricted to specific application areas, can be built using Catia Generative Knowledge 2 (http://www.catia.com/) and Unigraphics NX (http://www.eds.com/products/plm/unigraphics_nx/).

Another approach is the "design wizard" available as a design support tool tightly linked to a specific CAD system. In this case, the design support system is already implemented towards a specific application domain such as mold design, sheet metal part design, or piping design. SolidWorks Piping (http://www.solidworks.com/), CATIA Sheetmetal Design (http://www.catia.com/), Unigraphics Mold Wizard (http://www.eds.com/products/plm/), and I-DEAS Harness Design (http://www.plmsol-eds.com/) are examples of such products.

5.5.3 Tools for System Analysis

Matlab (http://www.mathworks.com/) is a tool for technical computation, modeling, analysis, and visualization. It can be customized for specific engineering applications such as automotive and aerospace engineering. It allows quick system analysis of specific problems for which an off-the-shelf tool is not readily available. Many third party application tools built on top of Matlab are available in various application areas. Another tool which offers capabilities for general scientific computing is Mathematics (http://www.wolfram.com/).

5.6 Collaborative, Distributed Systems

With the development of software integration technologies over the network, many engineering systems are finding their way into collaborative distributed systems for efficiency and improved productivity. PDM systems, product design systems, CAD systems, and analysis systems are among systems that exploit the advantages of collaborative and distributed systems concepts. Although many software products claim that they support collaborative engineering, the most practical, affordable, and widely accepted products for collaboration for now are 3D data viewers over the network, described below.

5.6.1 Support for Visual Collaboration

CAD data viewers are used for visual collaboration on product data between manufacturing enterprises and their supply chains. With these viewers, people around the world can work together on the same visual data, simultaneously and in real time, across organizational and technological boundaries. This software is also useful when multiple CAD systems are used throughout the organizations, because viewers support multiple CAD formats for visualization. Viewers allow every authorized member in the organization to deal with heterogeneity, visualizing designs from a variety of formats without running CAD software. Viewers enable design review meetings over the Internet by allowing project members to view and analyze a model concurrently while shifting control between members. Common functionalities other than visualization over the network include markup, geometric measurement, extraction of inertial properties, and generation of cut views. Popular products in this category include e-VIS (http://www.e-vis.com/), 3DView (http://www.actify.com/), Cimatron QuickConcept (http://www.cimatron.com/), and AutoVue (http://www.cimmetry.com/).

5.6.2 Support for Collaborative Product Definition

Collaboration for product development in a distributed environment goes beyond just visual collaboration in design meetings between remote parties. Engineers must be linked up with their colleagues over the Internet and develop products together. In this way design challenges can be identified and solved without delays and misunderstandings.

One of the products with such an idea is OneSpace (http://www.cocreate.com/). OneSpace products, with a built-in CAD tool at the core, enable design teams to capture real-time input from an extended design team. The user interface allows engineers to discuss and collaboratively improve the design together with manufacturers, external development partners, and colleagues in other disciplines. OneSpace products also enable designers to further develop and enhance the parts and assemblies created by others by treating imported designs like native designs. This capability is useful because designers often need to share ideas and expertise, even when they are working with separate models on different CAD systems. For efficient collaboration, OneSpace provides modules to manage access rights, data, and projects in a way that encourages close collaboration while protecting each company's intellectual property.

Alibre Design (http://www.alibre.com/) takes a different approach to accomplish collaboration in product design and real-time team modeling. It provides CAD modeling and data repository capabilities through the Web-based server. Engineers need only minimal client interface software to access interactive and collaborative 3D design service and data management service at the server. The Web-based service bureau mechanism allows members of the extended enterprise and all tiers of the supply chain to share data and collaborate in real time. The low-cost standard hardware requirements and the ease of deployment of this approach could be beneficial to SMEs. However, data security is one of the major concerns.

Recently, several vendors have focused on Product Lifecycle Management (PLM) frameworks, which support collaborative design activities throughout the product lifecycle. The PLM market is currently dominated by EDS' Teamcenter (http://www.eds.com/products/plm/teamcenter/), PTC's Windchill (http://www.ptc.com), MatrixOne's Matrix10 (http://www.matrixone.com/), and IBM/Dassoult's Smarteam/Enovia (http://www-1.ibm.com/solutions/plm/), with other players such as Alventive (http://www.alventive.com) providing support for real time 3D collaboration, project data space, and project tracking. In addition, companies such as Toyota Motor Corporation are commercializing software developed for addressing in-house needs (see http://www.xxen.net/e-home/). An analysis of these and other PLM frameworks can be found in reports from Gartner (http://www.gartner.com), DH Brown Associates Inc. (http://www.dhbrown.com), Daratech (http://www.daratech.com) and CIMdata (http://www.cimdata.com).

5.6.3 OMG CAD Services

While most of the standard activities related to product design are focused on the representation of product data, the OMG has initiated a standard called *CAD Services for high-level functional and operational interfaces for mechanical CAD systems* (http://www.omg.org/homepages/mfg/mfgppe.htm). The aim of this standard is to provide users of design and engineering systems the ability to seamlessly integrate best-in-class software across a wide variety of CAD/CAM/CAE tools through Common Object Request Broker Architecture (CORBA) interfaces. These standard interfaces make possible a distributed product design environment that includes a variety of CAD systems. The intent is to expose the existing CAD functionality through high-level functional and operational interfaces. These interfaces are to complement existing standards such as STEP. This activity is currently under progress and is supported by 12 organizations including software vendors such as Dassault Systems, Spatial Technologies, and Theorem Solutions.

5.7 Virtual Environments, Immersive CAD, and Simulation Systems

The immersive environment is an extension of virtual reality. In this environment, the user is an active participant in the virtual scene. A display unit mounted in the user's headset projects a virtual view that moves as the user's head is moved. The user wears an instrumented glove, the image of which moves in the virtual view as the user's hand is moved. In some immersive systems the glove provides pressure feedback to the user as she/he "grabs" an object in the virtual view.

There are numerous engineering design applications of immersive environments. Automobile, truck, and other equipment operators are doing extensive ergonometric studies to design and analyze their equipment for human comfort and efficiency. Similarly, simulations of manufacturing operations, such as manual part assembly, are performed in immersive environments. Increasingly, immersive environments are beginning to augment, if not replace, physical simulators such as flight and driving simulators.

An "inverted" immersive environment arises when the projected computer output is superimposed on the user's view of the real world through the use of a wearable computer with a head-mounted display. Practical engineering applications of wearable computers abound, particularly in the maintenance and inspection of complex systems that are difficult or dangerous to reach. The maintenance worker or inspector has both hands free, and with simple commands can call up relevant parts of the design model, operating or maintenance instructions, or previous inspection reports she/he needs to perform the work required.

One application area of graphical virtual reality (VR) technology, combined with discrete simulation technology, has been for simulating and optimizing manufacturing systems in the early stages of factory design. Manufacturing system simulation tools are used for determining the optimal equipment configuration and layout, troubleshooting an existing system, including identifying bottlenecks in the operation, and testing equipment controls prior to installation. The simulation can also predict problems related to material flow and working conditions of human operators in the workplace.

Usually, factory layout and design modules provide a user-definable component library of shop floor and assembly equipment, as well as related information such as dimensions and possibly cost. The planner designs a layout by browsing through the library, selecting desired equipment and positioning it in the 3D-workplace layout. Some simulation tools allow the planner to analyze line throughput while taking into account different product mixes, variants, and production volumes. Human models are also provided to allow the planner to design a manual workplace that is optimized for assembly time, reachability, fields of view, and detailed hand motions for assembly.

Representative tools for virtual factory simulation include the AutoMod suite of simulation software (http://www.autosim.com/), a suite of simulation products for factory simulation, robotics, and machining from Delmia (http://www.delmia.com/), products including eM-Workplace from Technomatix Technologies Ltd. (http://www.tecnomatix.com/), and factory modeling and layout analysis products from EDS (http://www.eds.com/products/plm/).

5.8 Engineering ASP on the Web

An environment component not considered by the NRC report but of considerable potential interest to SMEs is the concept of application service providers (ASPs). ASP is a new type of business model that provides various application services on a pay-per-use basis on the Internet. ASP for engineering tasks came later than in other application domains such as business transactions. The complex nature of engineering data and activities, including the handing of complex structures of product data and 3D shape data, is a challenge to the ASP concept in the engineering domain. However, in some engineering areas related to product development processes, the ASP concept is well accepted and several service providers are active in the market. Several of these are discussed below.

5.8.1 CAD Data Translation

This is probably the most widely accepted ASP application related to product development processes. There are two reasons that justify wide acceptance of CAD data translation through ASPs. One reason is that CAD data translation is not an everyday engineering activity. Furthermore, there are many combinations of source and destination pairs for translation, of which a few pairs are occasionally used. Therefore, with ASPs there is no need to purchase expensive software and maintain the software to catch up the version changes of data formats of commercial tools and standards. The second reason is that, unlike other interactive engineering activities, input data for translation requests is simple and the output is a single file. As described previously, translation services are available between and across standard formats, kernel-based formats, and native CAD system formats with optional feature-based parametric data.

STEP Tools, Inc. (http://www.steptools.com/) offers free STEP translation service and markets standalone STEP translators for Parasolid and ACIS solid models. ITI (http://www.DEXCenter.com/) offers CAD translation service for IGES, STEP, and STL formats and four major commercial CAD formats, along with CAD data repair and "healing" service. TTI (http://www.translationtech.com/) provides pay-per-use translation services for feature-based parametric data between four major CAD systems. Theorem Solutions (http://www.theorem-usa.com/) also provides direct translation services between major CAD tools and standard-based translation services.

5.8.2 Engineering Analysis

FEA is another area of engineering application potentially well suited for the ASP model. It is computation intensive and requires little interaction during the actual computation, if the analysis model is well formulated in advance. Analysis with ASP is not appropriate for simple preliminary analyses that require rapid response time during frequent design modification and analysis iterations; in this case the computations are not likely to be intensive. However, ASP analysis will be cost-efficient for the occasional detailed analyses with complex models that require considerable computational resources. By using ASP analysis services, SMEs with occasional demands for computation-intensive analyses can avoid the costly investment for software and high performance hardware and maintenance costs for upgrades.

The e-compute service from Altair (http://www.altair.com/) requires its pre-processing module to be installed on the client computer. The server is connected through the client pre-processing module, and the analysis job is sent to the server. Then the server carries out the computations and generates analysis reports. The simulation center by MSC software (http://simulate.engineering-e.com/) does not require any client code installed on the local computer. Several analysis tools, including a CAD tool, are available through a graphical interface that looks like the standalone analysis tool to the user. The e-CAE from ANSYS (http://www.ansys.com/ecae/) provides similar service by receiving analysis models through the Internet. Web4Engineers' (http://www.web4engineers.com/) site provides various engineering tools including CAD, CAE, and CAD viewers through the Web.

5.8.3 CAD and Data Repository

As mentioned above, some companies offer usage of CAD tools through the Web interface. Alibre Design (http://www.alibre.com/) offers CAD modeling and data repository capabilities through the server. Engineers need only minimal client interface software to access interactive and collaborative 3D design and data management services at the server. Web4Engineers (http://www.web4engineers.com/) offers 2D CAD tools through the Web. The simulation center at MSC Software (http://www.mscsoftware.com/) offers IronCAD through a Web interface.

5.8.4 Parts Catalog Services

The availability of electronic 3D part catalogs can reduce the total time required for product design. This technology can also be used for quick configuration of design variations with detailed geometries. For the supplier, supplying a standard parts catalog with 3D data means tighter engineering integration with the customers. With this technology, suppliers can interact with their customers at the early stages of product design with engineering details. The PartLib Web site (http://www.partlib.com/) offers a free repository for CAD parts, libraries, and catalogs. PARTsolutions (http://www.part-solutions.com/) offers both a part catalog server and tools for viewing, publishing, and catalog searching.

5.9 Summary

Technology trends and representative product examples of common COTS elements for AEE components for SMEs have been presented in this report. The AEE components and characteristics from the NRC AEE Phase 1 report have been expanded into more detailed levels so as to be able to relate AEE elements to their corresponding commercial products. It is to be emphasized again that the lists of COTS products presented are intended to be illustrative rather than exhaustive, and that the range of COTS elements is expected to continue to grow in the future. Another trend discernible from the descriptions is the increasingly tighter integration or “bundling” of vendors’ products and services, to the point where specialized “mini-AEEs” may soon become available as COTS.

The components described in this report cover a wide range of characteristics necessary to implement AEEs. A single SME does not need to implement all of these components, but needs to carefully identify the components necessary for its specific needs, the planned interactions between them, and the range of COTS products implementing the needed components. A carefully prepared plan will lead to successful expansion of the AEE with additional components in the future.

References

[Brownsword 00] Brownsword, L. & Place, P. *Lessons Learned Applying Commercial Off-the-Shelf Products: Manufacturing Resource Planning II Program* (CMU/SEI-99-TN-015, ADA379746). Pittsburgh, PA: Software Engineering Institute, Carnegie Mellon University, June 2000.

[Carney 98] Carney, David J. *Quotations from Chairman David - A Little Red Book of Truths to Enlighten and Guide on the Long March Toward the COTS Revolution*. Pittsburgh, PA: Software Engineering Institute, Carnegie Mellon University, 1998.

[Fenves 90] Fenves, S. J.; Flemming, U.; Hendrickson, C.; Maher, M. L.; & Schmitt, G. “Integrated Software Environment for Building Design and Construction.” *Computer-Aided Design 22*, 1 (1990): 27-36.

[Fenves 01] Fenves, S. J. *A Core Product Model For Representing Design Information* (NISTIR 6736). Gaithersburg, MD: National Institute for Standards and Technology, 2001.

[Fenves 03] Fenves, S. J., Y. Choi, B. Gurumoorthy, G. Mocko and R. D. Sriram, *Master Product Model for the Support of Tighter Integration of Spatial and Functional Design* (NISTIR 7004). Gaithersburg, MD: National Institute of Standards and Technology, 2003.

[Fisher 89] Fisher, G.; McCall, R.; & Morch, A. *Design Environments for Constructive and Argumentative Design*, in *Human Factors in Computing Systems*, K. Brice and C. Lewis (editors). Special Issue of SIGCHI Bulletin, 269-275. New York, NY: ACM, 1989.

[ISO 94] ISO 10303-203:1994, *Industrial automation systems and integration -- Product data representation and exchange -- Part 203: Application protocol: Configuration controlled design.*

[ISO 209:01] ISO 10303-209:2001, *Product data representation and exchange: Application protocol: Composite and metallic structural analysis and related design.*

[ISO 214:01] ISO 10303-214:2001, *Industrial automation systems and integration -- Product data representation and exchange -- Part 214: Application protocol: Core data for automotive mechanical design processes*

[ISO 224:01] ISO 10303-224:2001, *Industrial automation systems and integration -- Product data representation and exchange -- Part 224: Application protocol: Mechanical product definition for process planning using machining features*

[NRC 99] National Research Council. *Advanced Engineering Environments, Phase 1*. Washington, DC: National Academy Press, 1999.

[NRC 00] National Research Council. *Design in the New Millennium, Advanced Engineering Environments, Phase 2*. Washington, DC: National Academy Press, 2000.

[PDES 99] PDES Inc. *Recommended Practices for AP209*. <http://pdesinc.aticorp.org/rec_prac.html> (1999).

[Pratt 01] Pratt, M. J. & Anderson, B. D. "A Shape Modeling Applications Programming Interface for STEP standard." *Computer-Aided Design 33*, 7 (2001):531-543.

[SPIRC 03] Mitchell, P. & Trichtinger, J. *SPIRC-SEI/TIDE Project*. Pittsburgh, PA: Southwestern Pennsylvania Industrial Resource Center (now Catalyst Connection), 2003.

[Sriram 01] Sriram, R. D. "Standards for Collaborative Product Development." *Proceedings of the 8th ISPE International Conference on Concurrent Engineering: Research and Applications*. Tustin, CA, July 29-Aug. 1, 2001. ISBN:0-9710461-0-7, 2001.

[Sutton 98] Sutton, P. R. & Director, S. W. "Framework Encapsulations: A New

Approach to CAD Tool Interoperability," 134-139. *Proceedings of the 35th Design Automation Conference*, San Francisco, CA, June 15-19, 1998. New York, NY: ACM Press, 1998 (ISBN 0-89791-964-5).

[Woodbury 97] Woodbury, R.; Flemming, U.; Coyne, R.; Fenves, S. J.; & Garrett, J. H. Jr. "The SEED Project: A Software Environment to Support the Early Phases in Building Design," 781-786. *Proceedings of IEA/AIE '95*. Melbourne, Australia, June 6-8, 1995. New York, NY: ACM Press, 1995.

Glossary

2D	two-dimensional
3D	three-dimensional
AEE	advanced engineering environment
ANSI	American National Standards Institute
AP	application protocol
API	application program interface
ASP	application service provider
CAD	computer-aided design
CAE	computer-aided engineering
CAM	computer-aided manufacturing
CORBA	Common Object Request Broker Architecture
CMU	Carnegie Mellon University
COTS	commercial off-the-shelf
DOE	Design of Experiments
DPG	Design and Process Group (of NIST)
FEA	finite element analysis
IGES	Interim Graphics Exchange Standard
ISO	International Standards Organization
LAN	local area network
NASA	National Aeronautics and Space Administration
NC	numerical control
NIST	National Institute of Standards and Technology
NRC	National Research Council
OMG	Object Management Group
PC	personal computer
PDES	Product Data Exchange using STEP

PDM	product data management
PLM	product lifecycle management
PRP	product realization process
QFD	Quality Function Deployment
RFQ	request for quotation
SEI	Software Engineering Institute
SME	small manufacturing enterprise
STEP	STandard for the Exchange of Product model data
TIDE	Technology Insertion, Demonstration, and Evaluation
URL	Uniform Resource Locator

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13. ABSTRACT (MAXIMUM 200 WORDS)

Advanced engineering environments (AEEs) are computational and communications systems that can create virtual and/or distributed environments linking researchers, technologists, designers, manufacturers, suppliers, and customers, providing for the orderly integration of tools used and data developed during the design phase of a product. AEEs consist of design tools (e.g., computer-aided design (CAD), computer-aided engineering,), data repositories (e.g., design database, evolution database,), and the networks linking these components and other enterprise processes.

Although AEEs can improve the productivity of a small manufacturing enterprise (SME), a key barrier to SME adoption is a lack of awareness of AEEs. This report provides an overview of AEE technologies for SMEs, starting with a description of the levels of AEE capability and a summary of the benefits of AEE technology.

AEEs for SMEs are most often constructed through the integration of commercial off-the-shelf (COTS) information technology (IT) tools, but successful adoption of these tools requires planning and commitment. This report provides SMEs with an overview of technical considerations for AEE adoption to enable such planning. Interoperability of these tools and efficient communication between the users of these tools is also discussed

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