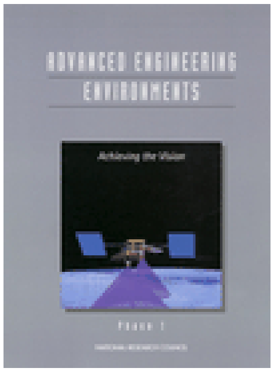

Advanced Engineering Environments: Achieving the Vision, Phase 1

Committee on Advanced Engineering Environments, National Research Council

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THE NATIONAL ACADEMIES
Advisers to the Nation on Science, Engineering, and Medicine

ADVANCED ENGINEERING ENVIRONMENTS

Achieving the Vision

Phase 1

Committee on Advanced Engineering Environments
Aeronautics and Space Engineering Board
Commission on Engineering and Technical Systems
National Research Council

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Preface

Economic pressures in the global economy are forcing aerospace and other high-technology industries to improve engineering performance in order to remain competitive. These improvements include faster insertion of new technologies, lower design and development costs, and shorter development times for new products. One way to help realize improvements in project design and management on a global scale is through the development and application of advanced engineering environments (AEEs). AEEs would incorporate advanced computational, communications, and networking facilities and tools to create integrated virtual and distributed computer-based environments linking researchers, technologists, designers, manufacturers, suppliers, and customers.

Significant progress has been made during the last 15 years in the application of computer-aided design, engineering, and manufacturing systems. Building on that success, government, industry, and academia now have a historic opportunity to develop and deploy AEE technologies and systems. For example, the National Aeronautics and Space Administration (NASA) has initiated both near-term and far-term projects related to AEEs. As part of these efforts, NASA's Chief Engineer and Chief Technologist requested that the National Research Council and the National Academy of Engineering conduct a two-phase study to assess the current and future national context within which NASA's plans must fit (see Appendix A). The Advanced Engineering Environments Committee was appointed to carry out this task (see Appendix B). The results of Phase 1, which focused on the near term (the next 5 years), are documented in this report. The results of Phase 2, which will focus on the far term (5 to 15 years), will be documented in the Phase 2 report.

As described herein, the committee validated that AEEs could contribute to important objectives related to the development of complex new systems, products, and missions. However, advancing the state of the art enough to realize these objectives requires a long-term effort and must overcome a number of significant technical and cultural barriers. Much remains to be done in the near term, as well, both to lay the foundation for long-term success and to achieve near-term improvements in areas where technology has matured enough to improve the effectiveness of current practices.

This report has been reviewed by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the authors and the National Research Council in making the published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The content of the review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their participation in the review of this report:

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George Hazelrigg, National Science Foundation
Larry Howell, General Motors Research and Development Center
Robert Naka, CERA, Inc.
Henry Pohl, National Aeronautics and Space Administration (retired)
Bruce Webster, Simmetrix, Inc.

While the individuals listed above have provided many constructive comments and suggestions, responsibility for the final content of this report rests solely with the authoring committee and the National Research Council.

The committee also wishes to thank everyone else who supported this study, especially those who took the time to participate in committee meetings (see Appendix C).

Robert E. Deemer, Chairman
Advanced Engineering
Environments Committee

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Executive Summary

INTRODUCTION

Advances in the capabilities of technologies applicable to distributed networking, telecommunications, multi-user computer applications, and interactive virtual reality are creating opportunities for users in the same or separate locations to engage in interdependent, cooperative activities using a common computer-based environment. These capabilities have given rise to relatively new interdisciplinary efforts to unite the interests of mission-oriented communities with those of the computer and social science communities to create integrated, tool-oriented computation and communication systems. These systems can enable teams in widespread locations to collaborate using the newest instruments and computing resources. The benefits are many. For example, a new paradigm for intimate collaboration between scientists and engineers is emerging. This collaboration has the potential to accelerate the development and dissemination of knowledge and optimize the use of instruments and facilities, while minimizing the time between the discovery and application of new technologies.

This report describes the benefits and feasibility of ongoing efforts to develop and apply advanced engineering environments (AEEs), which are defined in this report as particular implementations of computational and communications systems that create integrated virtual and/or distributed environments linking researchers, technologists, designers, manufacturers, suppliers, and customers. Table ES-1 lists AEE system components and their characteristics, as defined by the authoring committee.

This study was sponsored by the National Aeronautics and Space Administration (NASA) and was conducted by a committee appointed by the National Research Council and National Academy of Engineering. The Statement of Task directed the committee to pay particular attention to NASA and the aerospace industry. In most cases, however, the committee determined that issues relevant to NASA and the aerospace industry were also relevant to other organizations involved in the development and/or use of AEE technologies or systems. Therefore, the report is written with a broad audience in mind. Most of the findings and recommendations, although they apply to NASA, are not limited to NASA, and so are applicable to all organizations involved in the development or use of AEE technologies or systems.

A HISTORIC OPPORTUNITY

The committee believes that a historic opportunity exists for maturating AEE technologies and integrating them into comprehensive, robust AEE systems. As the capabilities of computational systems and the sophistication of engineering models and simulations advance, AEE technologies will become more common in both the private and public sectors. However, it remains to be seen how quickly AEE systems will be developed and what capabilities they will

TABLE ES-1 AEE System Components and Characteristics

Computation, Modeling, and Software
- multidisciplinary analysis and optimization
- interoperability of tools, data, and models
- system analysis and synthesis
- collaborative, distributed systems
- software structures that can be easily reconfigured
- deterministic and nondeterministic simulation methods

Human-Centered Computing
- human-adaptive interfaces
- virtual environments
- immersive systems
- telepresence
- intelligence augmentation

Hardware and Networks
- ultrafast computing systems
- large high-speed storage devices
- high-speed and intelligent networks

demonstrate, particularly in the critical area of interoperability. Within the federal government, the Department of Defense, NASA, the Department of Energy, the National Science Foundation, and the National Institute of Standards and Technology have much at stake in terms of their ability to accomplish complex, technically challenging missions and/or to maximize the return on their investments in the development of AEE technologies and systems for use by other organizations.

In the 1960s, the Advanced Research Projects Agency (ARPA, the predecessor of the Defense Advanced Research Projects Agency) began work on a decentralized computer network. That effort produced the ARPANET, which served both as a test bed for networking technologies and as the precursor to the Internet. ARPA took advantage of a historic opportunity created by new technological capabilities to initiate a revolution in communications. A similar opportunity exists today. The technological challenges with AEEs, however, are more complex than those involved in developing the ARPANET and the Internet. In addition, the barriers to successful deployment are more varied and substantial. As a result, the current opportunity is too big for any one organization to achieve. To take full advantage of the opportunity represented by AEEs, a government-industry-academia partnership should be formed to foster the development of AEE technologies and systems in the following ways:

- Develop open architectures and functional allocations for AEEs to guide the development of broadly applicable, interoperable tools.
- Create specific plans for transitioning the results of government research and development to the commercial software industry and/or software users (e.g., the aerospace or automotive industries), as appropriate.
- Develop an approach for resolving information management issues.

AEEs can reach their full potential only if many organizations are willing to use them. Involving a broad partnership in the development of AEE technologies and systems would create equally broad benefits. For example, cooperation from other government agencies and industry is essential for NASA to achieve the objectives of its AEE-related research and development. However, it is not necessary for individual agencies such as NASA to await the formation of a broad partnership before involving outside organizations. In fact, NASA's actions could stimulate broad interest and demonstrate the mutual benefits of forming partnerships. The committee recommends that NASA draft a plan for creating a broad government-industry-academia partnership. In addition, to demonstrate the utility of partnerships on a small scale, NASA should charter a joint industry-academia-government advisory panel that focuses on interactions between NASA and outside organizations.

VISION

An ideal AEE would encompass concept definition, design, manufacturing, production, and analyses of reliability and cost over the entire life cycle of a product or mission in a seamless blend of disciplinary functions and activities. The ideal AEE would ease the implementation of innovative concepts and solutions while effortlessly drawing on legacy data, tools, and capabilities. Interoperability between data sets and tools would be routine and would not require burdensome development of new software to provide customized interfaces. The AEE would accommodate a diverse user group and facilitate their collaboration in a manner that would obviate cultural barriers among different organizations, disciplines, and geographic regions. It would be marked by functional flexibility so its capabilities could be reoriented and reorganized rapidly at little or no cost. The AEE would include a high-speed communications network for the rapid evaluation of concepts and approaches across engineering, manufacturing, production, reliability, and cost parameters with high fidelity. It would be amenable to hardware and software enhancements in a transparent way.

The committee summarized the ideal AEE in the following vision: AEEs should create an environment that allows organizations to introduce innovation and manage complexity with unprecedented effectiveness in terms of time, cost, and labor throughout the life cycle of products and missions. A road map for realizing this vision appears in Figure ES-1 and is discussed below.

CURRENT SITUATION

After contacting representatives of many government, industry, and academic organizations involved in the development and use of AEE technologies, the committee noted that many of these organizations face the same top-level challenges in terms of competitive pressure to reduce costs, increasing complexity in tools and systems, and the other items listed in the top box of Table ES-1. Although government agencies do not face the same competitive market forces as industry, technology-intensive agencies, such as the Department of Defense, the Department of Energy, the Federal Aviation Administration, and NASA are all charged with developing new systems to maximize organizational effectiveness and accomplish ambitious agency missions.

In response to these challenges, the affordability of products and processes is being given much higher priority by government agencies and industrial organizations. Industry and government have already made significant progress in using computer-aided tools to improve processes for design, analysis, and manufacturing. This is especially true in the electronics industry where rule-based design and automated manufacturing are now commonplace. In the mechanical design area, progress has been made in the solid geometry portion of the process, but no equivalent capability has been

Current Situation

- Fifteen years of experience with CAD, CAE, and CAM systems[a]
- Competitive pressures to reduce costs
- Increasing complexity in tools and systems
- Proliferation of tools and data
- Need for integration and sharing of information among tools and organizations
- Individual AEE technologies being developed and, in some cases, implemented by government and industry
- AEE systems are not yet available
- Focus on integrated product development
- Large gap between the state of the art and the long-term vision for AEEs

↓

Objectives/Benefits

- Develop AEE systems that would
  - — enable complex new systems, products, and missions
  - — greatly reduce product development cycle time and costs
- Define an AEE implementation process that would
  - — lower technical, cultural, and educational barriers
  - — apply AEEs broadly across U.S. government, industry, and academia

↓

Barriers

- Integration of tools, systems, and data
  - — lack of tool interoperability
  - — proliferation of tools
  - — existing investment in legacy systems
- Information management
  - — proliferation of all types of information
  - — configuration-management issues
- Cultural, management, and economic issues
  - — difficulty of justifying a strong corporate commitment to implementing AEE technologies or systems
  - — lack of practical metrics for determining the effectiveness of AEEs
  - — unknowns concerning implementation costs
- Education and training
  - — training of current workforce
  - — education of future workforce

↓

Actions

- Achieve consensus on AEE requirements
- Overcome barriers
- Achieve consensus on appropriate organizational roles, and plan future activities accordingly

↓

AEE Vision

[a] CAD = computer-aided design. CAE = computer-aided engineering. CAM = computer-aided manufacturing.

Figure ES-1 Road map for achieving the AEE vision.

developed for modeling, analyzing, and integrating the performance parameters of systems, subsystems, and components. The committee does not believe this capability can be achieved by simply updating existing tools. For many organizations, a fundamental change in the engineering culture will be necessary to take advantage of breakthroughs in advanced computing, human-machine interactions, virtual reality, computational intelligence, and knowledge-based engineering as advances move from the laboratory to the factory and other operational settings. Making this change in a timely fashion and supporting the widespread use of AEE technologies and systems by government and industry will only be possible if AEE research and development are integrated into a coherent vision and supported by concerted efforts in both the near term (the next 5 years) and the far term (5 to 15 years).

OBJECTIVES AND BENEFITS

To achieve the AEE vision, the committee defined a set of key objectives to guide AEE research, development, and implementation. The top-level benefits that AEEs can provide and the top-level requirements AEEs should satisfy are closely linked to and inherent in these key objectives, which are listed in the second box of Figure ES-1 and discussed below.

Enable Complex New Systems, Products, and Missions

Using traditional processes to design, develop, procure, and operate the systems needed to satisfy the complex missions of industry and government is becoming increasingly impractical in terms of cost, schedule, and personnel. The complexity of products and processes has rapidly increased, and the amount of data required to define, manufacture, and maintain these products has grown dramatically in size and heterogeneity. Design, manufacture, and maintenance often occur internationally, so this large mass of data must be accessible and movable over long distances and at high speed. AEEs offer the potential to improve the accuracy and efficiency of engineering processes throughout the life cycle. For example, AEE systems would enable industry to develop advanced systems more quickly with fewer personnel and at lower cost. AEEs would enable government agencies and industry to accomplish missions and develop products that are not feasible using current processes.

Greatly Reduce Product Development Cycle Time and Costs

Using traditional methods for development of complex new systems or products, the bulk of a program's life-cycle costs are set by decisions made very early in the development cycle (the definition phase). Errors made during this phase can result in costly and time-consuming design changes later in the process. These changes may ripple throughout a number of subsystems and require extensive rework. Even if the individual changes are small, the net effect can be substantial.

In the commercial world, a reduction in product development cycle time helps manufacturers increase market share by enabling them to create new and better products more quickly than their competition. In the government sector, reducing product development time helps agencies complete projects sooner, thereby reducing costs and improving services or achieving mission objectives more quickly and freeing personnel and other resources to move on to the next task.

One way to reduce product development cycle time and costs is to develop AEEs that enable designers to determine quickly and accurately how proposed designs will affect the performance of new systems and subsystems and how the change in performance will affect the prospects for mission success. High-fidelity models and simulations that integrate tools from all aspects of the mission life cycle would enable mission planners and system designers to perform trade-off study sensitivity analyses early in the design process that encompass the total life cycle. High-fidelity simulations would also reduce the need for physical test models of new designs.

Lower Technical, Cultural, and Educational Barriers

To realize the potential benefits of AEEs, the development of AEE technologies and systems must be coordinated with the development of a comprehensive, multifaceted implementation process tailored to the varying characteristics and issues associated with different AEE technologies and system components. A key objective of the implementation process should be lowering the barriers to change and innovation that keep old systems and processes in place long after more effective alternatives are available. As discussed in more detail below, these barriers may involve technical, cultural, economic, and/or educational factors.

Apply AEEs Broadly across U.S. Government, Industry, and Academia

AEE development should also be consistent with the broader objective of applying AEEs throughout government, industry, and academia. The widespread use of AEEs is also important to maximizing their value to a particular organization. Complex products and missions typically are implemented by partnerships comprised of many different organizations, and the AEEs adopted by one organization will have the greatest utility if its partners use compatible AEEs. This implies that developers must avoid approaches that would restrict the applicability of AEEs to a small number of settings.

BARRIERS

History is littered with plans, both strategic and tactical, that were conceptually and technically brilliant but failed because the barriers to success were not carefully considered. AEEs that can realize the vision and meet the objectives are not presently feasible, and there are many barriers to success. Common problems observed in the industry and government organizations surveyed by the committee are listed below:

- The challenge of tool and system integration is ubiquitous.
- The proliferation and management of information, which is intrinsic to AEE technologies, introduces difficulties in both the near and far term.
- Cultural, management, and economic issues often impede the implementation of AEE technologies.
- Education and training are significant factors in terms of the time and cost required to realize the benefits of AEE technologies.

A detailed list of barriers identified by the committee appears in Table ES-2. Although overcoming many barriers will be difficult, barriers can often be transformed into opportunities if creative minds are brought to bear on the problem. For example, current engineering systems have shortcomings in the interoperability of tools and data sets that hinder the effective, widespread use of AEE technologies. Resolving interoperability issues will require cooperation among the developers and users of AEE technologies and systems, and the mutual understanding that results from such cooperative efforts could have benefits that extend far beyond the development of AEEs.

ACTION

The committee is firmly convinced that practical AEE systems that have most of the capabilities of the ideal system can be developed. Some AEE technologies are already available and are being deployed, even as efforts to develop comprehensive, broadly applicable AEE systems continue.

Define Requirements

AEE research and development should be consistent with the system objectives, components, and characteristics described in Figure ES-1 and Table ES-1.

Overcome Barriers

It is essential to develop a practical approach for improving the interoperability of new product and process models, tools, and systems and linking them with legacy tools, systems, and data. Because a universal solution is not likely to be found in the near term, efforts to overcome interoperability issues will remain a significant “cost of doing business.” These issues should be prioritized and met head on to reduce this cost as quickly as possible. To help achieve long-term success, government agencies and other organizations with a large stake in the successful development of AEEs should interact more effectively with standards groups to facilitate the development of interoperable product and process models, tools, and systems, along with open system architectures. Specific, high-priority interoperating capabilities should be defined along with action plans and schedules

TABLE ES-2 Barriers to Achieving the AEE Vision

Integration of Tools, Systems, and Data

1. Lack of tool interoperability
2. Continued proliferation of tools, which aggravates interoperability issues
3. Existing investments in legacy systems and the difficulty of integrating legacy systems with advanced tools that support AEE capabilities
4. Little effort by most software vendors to address interoperability or data-exchange issues outside of their own suite of tools
5. Multiple hardware platform issues—computers, hardware, databases, and operating systems
6. Lack of formal or informal standards for interfaces, files, and data terminology
7. Increasing complexity of the tools that would support AEE capabilities
8. Difficulty of inserting emerging and advanced technologies, tools, and processes into current product and service environments
9. Supplier integration issues
10. Difficulty of integrating AEE technologies and systems with other industry-wide initiatives, such as product data management, enterprise resource management, design for manufacturability/assembly, and supply-chain management

Information Management

1. Proliferation of all types of information, which makes it difficult to identify and separate important information from the flood of available information
2. Difficulty of maintaining configuration management for product designs, processes, and resources
3. Need to provide system “agility” so that different types of users can easily input, extract, understand, move, change, and store data using familiar formats and terminology
4. Difficulty of upgrading internal infrastructures to support large bandwidths associated with sharing of data and information
5. Need to provide system security and to protect proprietary data without degrading system efficiency

Culture, Management, and Economics

1. Difficulty of justifying a strong corporate commitment to implementing AEE technologies or systems because of their complexity and uncertainties regarding costs, metrics, and benefits
2. Lack of practical metrics for determining the effectiveness of AEE technologies that have been implemented
3. Unknowns concerning the total costs of implementing AEE technologies and systems and the return on investment
4. Difficulty of securing funding to cover the often high initial and maintenance costs of new AEE technologies and systems in a cost-constrained environment
5. Risk—and someone to assume the risk (management, system providers, or customers)
6. Planning and timing issues—when to bring in the new and retire the old
7. Difficulty of managing constant change as vendors continually upgrade AEE tools and other technologies
8. Diversity of cultures among different units of the same company

Education and Training

1. Need to upgrade labor force skills along with technology and tools to support an AEE capability
2. Difficulty of incorporating AEE technologies into university design curricula

for establishing appropriate standards and achieving specified levels of interoperability.

Product and process descriptions frequently differ within user organizations, across user organizations, and between users and suppliers. This lack of commonality often requires that users customize commercially available tools before they can be used, which greatly reduces the cost effectiveness of using AEE tools. Corporate and government leaders should seize the opportunity to develop robust and flexible AEE tools for creating, managing, and assessing computer-generated data; presenting relevant data to operators clearly and efficiently; maintaining configuration management records for products, processes, and resources; and storing appropriate data on a long-term basis.

Historically, industry, government, and academia involved in the development of AEE-type technologies have not paid enough attention to the organizational, cultural, psychological, and social aspects of the user environment. To correct this oversight, organizations that decide to make a major investment in developing or implementing AEE technologies or systems should designate a “champion” with the responsibility, authority, and resources to achieve approved AEE objectives. The champion should be supported by a team of senior managers, technical experts, and other critical stakeholders (e.g., suppliers, subcontractors, and customers typically involved in major projects). For example, the committee was concerned about apparently inadequate coordination among AEE-related activities at NASA’s operational and research Centers. The NASA-wide teams being used to direct the Intelligent Synthesis Environment functional initiative should be consolidated and strengthened to improve their ability to perform the following functions:

- Define distinct AEE requirements and goals for NASA operational and research Centers.
- Ensure that NASA’s AEE activities take full advantage of commercially available tools and systems to avoid duplication of effort.
- Overcome cultural barriers in NASA so that new AEE technologies and systems will be accepted and used.
- Disseminate AEE plans, information, and tools at all levels within NASA.
- Provide centralized oversight of AEE research and development conducted by NASA.

Government agencies involved in the acquisition of advanced aerospace products and other complex engineering systems could also support the spread of AEE technologies and systems by providing incentives for contractors to implement appropriate AEE technologies and systems and document lessons learned. These incentives should target both technical and nontechnical (i.e., cultural, psychological, and social) aspects of AEE development and implementation.

In the area of education and training, universities should work with government and industry to identify and incorporate basic AEE principles into the undergraduate design experience. An advisory panel with representatives from industry, universities, the National Science Foundation, NASA Centers, and other government agencies and laboratories should be convened by NASA or some other federal agency involved in AEE research and development. The panel should define approaches for accelerating the incorporation of AEE technologies into the engineering curriculum, the basic elements of a suitable AEE experience for students, and specific resource needs.

Define Organizational Roles and Plan Future Activities Accordingly

In general, the development of application-specific tools should be left to industry. Government agencies should not develop customized tools that duplicate the capabilities of commercially available tools. Instead, government agencies should support the development of broadly applicable AEE technologies, systems, and practices in the following ways:

- Improve generic methodologies and automated tools for the more effective integration of existing tools and tools that will be developed in the future.
- Develop better models of specific physical processes that more accurately portray what happens in the real world and quantify uncertainties in model outputs.
- Identify gaps in the capabilities of currently available tools and support the development of tools that address those gaps, preferably by providing incentives for commercial software vendors to develop broadly applicable tools.
- Develop test beds that simulate user environments with high fidelity for validating the applicability and utility of new tools and systems.
- Develop methods to predict the future performance of AEE technologies and systems in specific applications and, once implemented, to measure their success in reaching specified goals.
- Explore the utility of engineering design theory as a tool for guiding the development of AEE technologies and systems.
- Use contracting requirements to encourage contractors to adopt available AEE technologies and systems, as appropriate.
- Address issues related to the organizational, cultural, psychological, and social aspects of the user environment.
- Provide incentives for the creation of government-industry-academia partnerships to foster the development of AEE technologies and systems.

To demonstrate the utility of and build support for the formation of a broad partnership, a single government agency could initially charter a standing, joint industry-academia-government advisory panel to focus on interactions between that agency and outside organizations. For example, a NASA advisory panel could be established as a means of periodically identifying areas of overlap between high-payoff requirements of external users and NASA's research and development capabilities. This advisory panel could also identify areas of commonality between the capabilities of external organizations and NASA's own requirements. This would facilitate technology transfer and allow NASA to focus its AEE research and development on the areas of greatest need.

1

Introduction

Advances in the capabilities of technologies applicable to distributed networking, telecommunications, multi-user computer applications, and interactive virtual reality are creating opportunities for users in the same or separate locations to engage in interdependent, cooperative activities using a common computer-based environment. These capabilities have given rise to relatively new interdisciplinary efforts to unite the interests of mission-oriented communities with those of the computer and social science communities to create integrated, tool-oriented computation and communication systems. Whether they are called "collaboratories," "computer-supported cooperative work" (CSCW) technologies, "coordination technologies," "groupware," and "advanced engineering environments" (AEEs), all of these technologies and systems facilitate the sharing of data, software, instruments, and communication devices with remote colleagues. They attempt to create an environment in which all resources are virtually local regardless of the user's physical location. Thus, research and development (R&D) on these technologies must pay explicit attention to the participants' organizational and social contexts by taking into account situations, roles, social interactions, and task interdependencies among participants, as well as functional requirements in system design, development, implementation, and evaluation.

For most engineering tasks, collaborations currently rely heavily on face-to-face interactions, group meetings, individual actions, and hands-on experimentation—with groups ranging from gatherings of a few people to several hundred members of large project teams. Through a shared electronic infrastructure, computer and telecommunication systems enable teams in widespread locations to collaborate using the newest instruments and computing resources. The benefits of such collaborations and systems are many. For example, a new paradigm for intimate collaboration between scientists and engineers is emerging that could accelerate the development and dissemination of knowledge and optimize the use of instruments and facilities, while minimizing the time between the discovery and application of knowledge.

DEFINING AN ADVANCED ENGINEERING ENVIRONMENT

Discussions about AEEs often focus on their potential for eliminating barriers to innovation; for providing seamless design, engineering, and manufacturing capabilities; and for assessing product reliability, life-cycle costs, and supportability quickly and accurately. To understand the long-term potential of AEEs, they must first be defined. As treated in this report, AEEs (i.e., AEE systems) are defined as particular implementations of computational and communications systems that create integrated virtual and/or distributed environments[1] linking researchers, technologists, designers, manufacturers, suppliers, and customers involved in mission-oriented, leading-edge engineering teams in industry, government, and academia. AEE systems will incorporate a variety of software tools and other technologies for modeling, simulation, analysis, and communications. Some of the tools and other technologies needed to create AEE systems are already being used in operational engineering environments and processes. The current challenge is to develop new and improved technologies and to integrate them effectively with currently available technologies to create comprehensive, interoperable AEE systems, as described in the vision that appears below.

The committee's definition of an AEE is discussed in the following sections, which describe the committee's long-term vision for AEEs; a vignette of an ideal AEE; and the objectives, components, and characteristics of AEEs. These

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[1] Virtual environments are defined as "an appropriately programmed computer that generates or synthesizes virtual worlds with which the operator can interact" (NRC, 1995). "Distributed environments" refer to nonvirtual, collaborative computing systems.

topics are discussed in more detail in the remainder of the report.

Vision

The committee collected information about the current state and future utility of AEEs from governmental, industrial, and academic organizations involved in AEEs either as developers, providers, or users of technologies or services (see Appendix C). Based on that information, the committee defined the following vision: AEEs should create an environment that allows organizations to introduce innovation and manage complexity with unprecedented effectiveness in terms of time, cost, and labor throughout the life cycle of products and missions.

Vignette: The Ideal AEE

One way to explain the ultimate goals and benefits of developing AEEs is through a top-level description of an ideal AEE, which would encompass concept definition, design, manufacturing, production, and analyses of reliability, performance, and cost over the entire life cycle in a seamless blend of disciplinary functions and activities. The ideal AEE would ease the implementation of innovative concepts and solutions while readily drawing on legacy data, tools, and capabilities. Interoperability between data sets and tools would be routine and would not require burdensome software development. The ideal AEE would accommodate diverse user groups and facilitate their collaboration in a manner that eliminates cultural barriers. It would be marked by functional flexibility that would allow rapid reorientation and reorganization of its capabilities at little or no cost. The AEE would include a high-speed communications network to enable rapid, high-fidelity evaluations of concepts and approaches across engineering, manufacturing, production, reliability, and cost parameters. It would be amenable to hardware and software enhancements in a transparent way.

Unfortunately, an ideal AEE is not presently achievable at the enterprise level. Integrating "all" of an enterprise's data and analysis capabilities is impossible because no widely accepted standards have been established. Other, more subtle issues, such as cultural resistance and the difficulty of credibly demonstrating benefits, must also be addressed. An ideal AEE would span all of an enterprise's operations, and in a traditional organization rarely is anyone with sufficient authority and responsibility designated to implement an AEE.

Despite these difficulties, the committee believes that useful elements of AEE systems can be developed in the near term to demonstrate some of the capabilities of the ideal system. This would require an organizational "center of gravity" empowered to identify analyses and data sets where interoperability is most important, designate specific tools as enterprise standards without having to achieve internal consensus, and support the ongoing process as needs and available technologies and software change. With this kind of leadership, a good deal of the promise of AEEs could be realized.

Objectives

To determine the requirements for realizing the vision, the committee defined two key objectives that AEEs should satisfy:

- Enable complex new systems, products, and missions.
- Greatly reduce product development cycle time and costs.

In addition, AEE technology and system developers should devise a comprehensive, multifaceted implementation process that meets the following objectives:

- Lower technical, cultural, and educational barriers.
- Apply AEEs broadly across U.S. government, industry, and academia.[2]

Components

After defining the AEE vision and objectives, the committee identified three key components of an AEE: computation, modeling, and software; human-centered computing; and hardware and networks. These elements will interact dynamically to reflect the current state of engineering practice, available technology, and cultural developments.

Effective AEEs must be oriented toward users who will have a wide range of needs and abilities. Therefore AEEs must be modular in nature, dynamic in an evolutionary sense, and open to users with broad cultural and social differences. A critical, yet sometimes under-appreciated, aspect of AEEs is the social and psychosocial dynamics of organizations.

Characteristics

The committee identified specific characteristics that represent users' needs for each component of an AEE that meets the objectives described above. The most important characteristics for each component are listed in Table 1-1.

The committee strongly believes that AEEs should fulfill both operational and research functions. Although these functions are often very different, most technology industries require high-fidelity tools for both types of activities, and addressing both functions concurrently will help reduce cycle time from research to development.

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[2] The objectives are discussed in more detail in Chapter 3.

TABLE 1-1 AEE System Components and Characteristics

Computation, Modeling, and Software
- multidisciplinary analysis and optimization
- interoperability of tools, data, and models
- system analysis and synthesis
- collaborative, distributed systems
- software structures that can be easily reconfigured
- deterministic and nondeterministic simulation methods

Human-Centered Computing
- human-adaptive interfaces
- virtual environments
- immersive systems
- telepresence
- intelligence augmentation

Hardware and Networks
- ultrafast computing systems
- large high-speed storage devices
- high-speed and intelligent networks

STUDY OVERVIEW

The Statement of Task for this study requires the committee to conduct a two-phase assessment of existing and planned methods, architectures, tools, and capabilities associated with the development of AEE technologies and systems and their transition into practice by the current and future workforce. This report documents the results of Phase 1.

Focusing on the near term (the next 5 years), Phase 1 examined potential applications of AEEs; explored the potential payoffs of AEEs on a national scale; evaluated how AEEs relate to the development of relevant technical standards and analyses of cost and risk; identified technical, cultural, and educational barriers to the implementation of AEEs, opportunities that could be created by AEEs, and needs for education and training; and recommended an approach for the National Aeronautics and Space Administration (NASA) to enhance the development of AEE technologies and systems with broad application in industry, government, and academia.

Expanding on the results of Phase 1, Phase 2 will focus on the potential and feasibility of developing AEE technologies and systems over the long term (the next 5 to 15 years). Specific tasks will include evaluating the potential for AEEs to contribute to NASA's long-term goal of revolutionizing the engineering culture; assessing potential long-term payoffs of AEEs on a national scale; examining broad issues, such as infrastructure changes, interdisciplinary communications, and technology transfer; describing approaches for achieving the AEE vision, including the potential roles of government, industry, academic, and professional organizations in resolving key issues; and identifying key elements of a long-term educational and training strategy to encourage the acceptance and application of AEEs by existing and future workforces. (The complete Statement of Task for this two-phase study appears in Appendix A.)

ORGANIZATION OF THE REPORT

Subsequent chapters illustrate the current state of the art in AEE technologies and systems (Chapter 2), describe AEE requirements and alternatives for meeting those requirements (Chapter 3), discuss barriers to the implementation of AEEs (Chapter 4), and summarize near-term actions that should be taken to pursue the AEE vision (Chapter 5).

In keeping with the Statement of Task, many sections of the report place special emphasis on aerospace engineering and NASA. However, many of the challenges associated with AEEs are shared by other organizations within the federal government, private industry, and academia. Therefore, many of the findings and recommendations are applicable to all organizations engaged in developing and applying AEE technologies.

REFERENCE

NRC (National Research Council). 1995. Virtual Reality: Scientific and Technical Challenges. Committee on Virtual Reality Research and Development. Washington, D.C.: National Academy Press.

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Current Practices

OVERVIEW

Modern information technologies had their beginnings at the dawn of the computer age with the application of computer technology to large problems. This process was driven, in part, by the need to solve large, complex engineering problems associated with the development of military systems. The fruits of this labor were subsequently applied to nonmilitary applications, resulting in computational techniques that are now used for modeling weather, aircraft aerodynamics, and many other types of engineering and scientific systems. One of the objectives of this study is to define how the current state of practice (i.e., operational engineering systems) might evolve as increasingly capable AEE technologies and systems are developed and deployed. The committee examined the current state of the art (i.e., AEE technologies as they exist in research and testing laboratories) for guidance in determining the future direction and capabilities of operational engineering environments.

An effective design process must balance many different factors, such as customer requirements, performance, cost, safety, system integration, manufacturability, operability, reliability, and maintainability. Software relevant to AEEs, however, has been developed as a collection of individual "tools" with little or no coupling among them. Tool integration is an area of active research in academia, industry, and government, but practical, broadly applicable solutions are not yet available for operational use. This lack of interoperability inhibits the use of traditional tools in AEEs, which by their nature require a high degree of integration. Improving the interoperability of software tools has been slow because of the cost of solving this complex problem, uncertainties about the return on investment, and the psychological and social dynamics of organizations.

With currently available engineering methods, many tests and analyses can be conducted using simulations instead of physical models. For example, Boeing successfully used a digital (computer-generated) mock-up of the 777 instead of building a full-scale mock-up prior to production. In addition, most certification requirements are satisfied using design analyses instead of physical tests. However, even more capable systems, such as AEEs, would improve both the accuracy of simulations, especially at the system level, and the confidence that senior managers place in those simulations. For example, Boeing uses wind-tunnel tests—not computational fluid dynamics—for final sizing of aircraft structural members. Boeing also uses physical testing as part of the certification process for the landing gear, even though the Federal Aviation Administration allows a purely analytical approach.

Current attempts to implement AEE technologies often do not adequately consider cultural and social aspects of organizations, even though doing so may be critical to success. A recent National Research Council workshop on the economic and social impacts of information technology noted that information technologies rarely have consistent effects on the performance of groups or organizations, largely because outcomes are highly conditioned by the social and behavioral characteristics of the environments in which they are implemented (NRC, 1998). For example, the R&D headquarters of a global pharmaceutical firm introduced a groupware tool to facilitate the sharing of early experimental results among researchers as part of a major effort to reduce R&D cycle time (Ciborra and Patriotta, 1996). The intent was to enable researchers to capitalize quickly on successful breakthroughs and to avoid repeating others' failed trials. "Get it right the first time" was the slogan. The groupware was rarely used, however, because researchers had no incentive to put new findings into a shared database where others might use them to "get it right" first, nor did they have any incentive to disclose their failures. To stimulate use of the groupware, management announced a policy of taking contributions to the shared knowledge base into account in performance reviews. The result was a sharp increase in usage, but for the most part the contributions were neither timely nor valuable.

Early work by Grudin (1988) demonstrated that even a straightforward distributed tool like group scheduling may not be successful if it benefits some individuals (e.g., managers with secretaries who keep their calendars) more than others (e.g., professionals who do not have personal secretarial support). In contrast, group decision-support technology introduced in the headquarters of an international financial organization seemed to yield significant performance improvements because it equalized roles in the decision-making process (Bikson, 1996).

Although not all attempts at implementation are successful, the clear trend is toward increased use of new information management and engineering design tools. In the United States, the federal government funds most R&D for computing technologies relevant to AEEs. This R&D addresses a wide spectrum of information technologies, but only up to the test bed level of implementation. Industrial R&D has focused on the evolution of existing engineering practices that are mature and low risk.

To illustrate the current state of practice, the following sections summarize key aspects of several ongoing efforts to develop and implement AEEs by Ford, Boeing Commercial Airplane Group, Deneb Electronics, NASA, the U.S. Department of Defense, the National Science Foundation, the U.S. Department of Energy, and interorganizational task groups.

FORD

A major design challenge faced by product development teams at companies like Ford is to avoid unintentionally establishing top-level program objectives that are incompatible with each other. For example, a new product development effort might accept the challenge of meeting specific goals related to vehicle performance, retooling costs, and reliability, only to discover later that the performance and reliability goals cannot be achieved without exceeding the allowable budget for retooling costs. Goals can be adjusted at that point, but a large number of engineering changes must be made that would not have been necessary if the original program objectives had been more realistic.

In the traditional vehicle design process, a top-level team meets weekly to discuss issues, disperses to conduct discipline-specific investigations of particular issues using support staff, and then reconvenes to discuss the results of the investigations. Ford's vision for the future is to have a small group meet continuously, using quick turnaround processes to investigate and resolve issues on a daily basis. This approach would greatly reduce the duration and cost of vehicle programs.

Ford makes extensive use of computer-aided design (CAD), computer-aided engineering (CAE), and computer-aided manufacturing (CAM) tools. To facilitate data management and enhance overall effectiveness, Ford decided in 1995 to limit the total number of CAD, CAM, and CAE tools and to buy commercial off-the-shelf tools whenever possible to reduce its reliance on internally developed tools. Ford also decided to standardize its design processes by using one CAD tool, I-DEAS.[1] The selection of I-DEAS was based as much on the capabilities of the vendor, Structural Dynamics Research Corporation, as on the particular qualities of I-DEAS as it then existed. Ford also hired Structural Dynamics as its tools integrator (to integrate I-DEAS with other tools created by Structural Dynamics and other vendors) and adopted Metaphase, another Structural Dynamics product, as its product information management tool.

Ford decided to migrate from an environment with many different CAD systems to a single CAD tool over a period of five years, which the company considered a very aggressive goal. Ford's engineering organization is product-centered, and the conversion to I-DEAS is taking place on a vehicle program-by-vehicle program basis. However, some vehicle systems, such as the power train, are common to many different vehicles. This created complications when some vehicle programs (including the power train) were converted to I-DEAS while other programs using the same power train were still using old tools.

Ford has partly centralized its management of engineering tools to facilitate the documentation and distribution of tools throughout the company and to eliminate marginal tools. Periodically, inventories are taken to identify new tools that have been developed in-house or purchased from outside sources. These tools are evaluated and, if not needed, they are purged. This is a difficult cultural process because people are often reluctant to give up familiar tools.

Ford is increasingly using a digital mock-up to guide its entire design, engineering, and manufacturing process. In some cases, Ford has been able to assess designs and release components and systems for production without having to fabricate and test prototypes. Ford is also moving toward the use of "digital factories" to assess manufacturing processes before factories are configured for the launch of new products.

CAD/CAM/CAE staff at Ford are collocated with other staff assigned to interdisciplinary product teams for design and development. Each team decides what the CAD/CAM/CAE staff will work on; central CAD/CAM/CAE management provides guidance on how tasks will be executed.

For various reasons, thousands of design changes are made during the product development cycle for a new vehicle. Analytically assessing how changes individually and collectively impact total vehicle performance is difficult, and performance problems that occur infrequently may not

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[1] The name I-DEAS originated as an acronym for Integrated Design Engineering Analysis Software. I-DEAS is a registered trademark of Structural Dynamics Research Corporation. The committee did not conduct a comparative analysis of the engineering practices or tools used by specific organizations. The National Research Council does not endorse the use of any particular software tools or vendors.

show up in the relatively limited number of production-representative prototypes that can be tested. These problems eventually surface as warranty claims, which adds to the total cost of the program.

BOEING COMMERCIAL AIRPLANE GROUP

Boeing implemented many new processes for the 777 airplane, with the goal of improving quality and reducing development cost and time. New processes included design-build teams, digital product definition of parts and tools, digital preassembly, concurrent product definition, and the use of a single CAD tool (CATIA).[2] However, Boeing has not yet fully implemented concurrent product definition because subsystems with long manufacturing lead times must be designed much sooner than other subsystems. Designers of subsystems with short lead times are reluctant to finalize their designs sooner than necessary just to be compatible with the schedule of long-lead time subsystems.

In a large organization like Boeing, coordinating engineering methods and practices is very difficult. In addition, because Boeing products are dispersed worldwide, Boeing encounters many cultural barriers. The 777 design process involved 4,500 engineers, about 200 design-build teams, six design partners, 3 million parts, two versions of CATIA, more than 350 Boeing-developed application programs, and more than 150,000 CATIA models. Because of the huge investment required to implement the new engineering processes used with the 777, the new processes did not reduce development costs compared to traditional methods. The 777 has demonstrated improved reliability and availability compared to previous new aircraft, but those improvements resulted from a number of factors, and it is impossible to isolate the effect of improved engineering processes. The difficulty of unambiguously identifying the economic savings and product improvements resulting from the implementation of AEE technologies is not unique to Boeing.

The 737-X started out as a relatively minor design upgrade but ended up with about 90 percent new design. The 737-X design process was a modified version of the 777 process; changes were made based on lessons learned from the 777 program. For example, the digital design process used for the 777 was focused on the early steps of the product development cycle, such as requirements analysis. Because most of Boeing's costs are associated with manufacturing, the 737-X process focused more on digital manufacturing, interference management, and other activities that could improve the manufacturing process.

To reduce the cycle time for new airplane development and improve its overall competitiveness, Boeing continues to work with its software vendors to improve engineering processes. Areas of current interest include the development and application of knowledge bases and virtual product and process models. Because Boeing is such a large user of CATIA, it has been able to influence the evolution of CATIA and associated tools. For example, Dassault Systèmes purchased Deneb Robotics, a software company that specializes in digital manufacturing, to improve CATIA's ability to address Boeing's manufacturing concerns.

DENEB ROBOTICS

Deneb Robotics, Inc., a subsidiary of Dassault Systèmes, has distinguished itself as a provider of digital manufacturing software. Deneb products are designed for integration with major CAD programs, such as I-DEAS, CATIA, Unigraphics,[3] and Pro/ENGINEER.[4] A customized set of interfaces is needed for each CAD program. Creating the interface capability can be a labor-intensive job for Deneb product developers, and using the interface capability, which requires data reduction in preparation for simulation, has been a labor-intensive job for users. As products are updated, however, the interfaces are becoming more automated, and the increasing speed of computers is reducing the degree of required data reduction.

Deneb offers a suite of tools that can be used to design factory layouts for maximum throughput. These tools can also be used to include manufacturing and maintenance considerations throughout the product and process development cycle. This allows system designers to avoid problems in the manufacture, assembly, and maintenance that traditional methods often do not identify until a physical prototype has been fabricated and tested. For example, one tool emulates machine tools, enabling controllers to visualize, analyze, and validate that new control programs developed to manufacture specific parts will operate as expected. Parts can be machined in a virtual environment and then evaluated to determine if they meet the accuracy specifications required by the part design. Another tool provides a three-dimensional, interactive simulation environment for visualizing and analyzing human motions required in the workplace to determine the effects of reaching, lifting, posture, cycle time, visibility, and motion for a range of body types. The resulting data can then be factored into the design of products, processes, and maintenance procedures.

In addition to internally funded product development, Deneb also participates with manufacturing companies in several government-sponsored R&D projects. For example, the Defense Advanced Research Projects Agency (DARPA) is funding Deneb and Raytheon Electronic Systems to develop tools that can use models of products and manufacturing facilities to generate and execute manufacturing

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[2] The name CATIA originated as an acronym for Computer-Aided Three-Dimensional Interactive Application. CATIA is a registered trademark of Dassault Systèmes.

[3] Unigraphics is a registered trademark of Unigraphics Solutions, Inc.

[4] Pro/ENGINEER is a registered trademark of the Parametric Technology Corporation.

simulations automatically. DARPA also funded a portion of Deneb's development of technologies associated with virtual prototyping, virtual reality, ergonomic analysis, high-level architectures,[5] and web browsers through multiple programs with the Electric Boat Division of General Dynamics. In addition, the Air Force funded development of Deneb's common-object request broker architecture (CORBA)[6] capabilities through the Simulation, Assessment, and Validation Environment (SAVE) project with Lockheed Martin, which is now being implemented as a pilot project with both the Boeing and Lockheed Martin teams involved in the Joint Strike Fighter Program.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Like many other large research and technology organizations, the most common forms of communications used by NASA rely on viewgraphs, paper, telephones, and email. Video-conference facilities enable real-time personal interactions, and desktop computer networks enable the electronic transfer of information between compatible systems and tools. But a broad spectrum of engineering analysis tools can neither communicate electronically nor interact effectively with each other.

The NASA administrator has stated that NASA must do more than update its engineering tools to keep pace with advanced scientific and engineering knowledge—it must fundamentally change its engineering culture. Accordingly, NASA is instituting the Intelligent Synthesis Environment (ISE) functional initiative to develop AEE technologies and systems. The ISE initiative is focused on integrating widely distributed science, technology, and engineering teams and enabling them to create innovative, affordable products rapidly. The ISE initiative, which is targeted at both science and engineering applications, has five elements:

- Rapid Synthesis and Simulation Tools
- Cost and Risk Management Technology
- Life-Cycle Integration and Validation
- Collaborative Engineering Environment
- Revolutionize Cultural Change, Training, and Education

In the near term, NASA's Collaborative Engineering Environment element is trying to implement a state-of-the-art, multidisciplinary, integrated design and analysis capability to enable teaming of NASA personnel located at geographically dispersed sites. This program includes building collaborative engineering centers at each NASA Center[7] and uses commercial off-the-shelf technology as much as possible. The current design for the collaborative engineering centers provides audio, video, and data conferencing using video projectors, smart-boards, video scan converters, remote control systems, scanners, and document cameras. Additional capabilities are being installed in some collaborative engineering centers. For example, specialized graphics hardware is being integrated with existing video projectors to provide an immersive environment and virtual-reality conferencing.

In some cases, the utility of the collaborative engineering centers has prompted individual Centers to procure additional facilities at their own expense. For example, Kennedy Space Center is installing six collaborative engineering centers. Standardized, simplified, pre-engineered procurement has proven to be an important factor in the proliferation of these facilities because it makes it much easier for Centers to acquire additional facilities (compared to the effort it would take to design and install such facilities as separate procurements). Even so, the incorporation of AEE technologies into the daily work of NASA personnel has not yet spread broadly across Center organizations and programs. In some cases, AEE technologies seem to be spreading primarily through informal, personal contacts by midlevel managers rather than as a result of implementation plans approved by high-level Center managers.

The Collaborative Engineering Environment element of the ISE functional initiative is using an evolutionary approach to deploy AEE technology and improve NASA's near-term capabilities. Plans for all five elements of the ISE initiative include R&D focused on long-term, revolutionary improvements. The five-year objectives and associated metrics proposed for each element are listed in Table 2-1.

After the objectives in Table 2-1 were established, the resources allocated to the ISE functional initiative in federal budget guidelines were reduced by about one-third. ISE program managers intend to revise the ISE objectives to align them with these guidelines. The objectives will probably remain the same, but the metrics will change. In addition, ISE managers are negotiating partnerships with personnel from other NASA offices with the hope that the original objectives might still be achieved.

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[5] High-level architecture, which is commonly referred to by the acronym HLA, is an emerging technology for linking geographically dispersed simulations of various types to create realistic, virtual environments for highly interactive simulations.

[6] CORBA is an architecture and specification for creating, distributing, and managing distributed program objects in a network. It allows programs developed by different vendors and operating at different locations to communicate in a network through an "interface broker." Object-oriented programming focuses on objects that must be manipulated rather than the logic required to manipulate them. Examples of objects include human beings (who can be identified by name and address) and structures (which can be defined in terms of properties and characteristics).

[7] In this report, *Center* (with a capital *C*) refers to a NASA field Center, such as Johnson Space Center or Langley Research Center; *center* (with a lower case *c*) refers to other types of centers, such as collaborative engineering centers or NASA centers of excellence.

TABLE 2-1 Five-Year Objectives and Associated Metrics for Each Element of NASA's ISE Functional Initiative

Rapid Synthesis and Simulation Tools

- Objective: Develop advanced design and analysis tools.
- Metrics
  - — Reduce design and mission development time by 50 percent.
  - — Reduce design cycle testing by 75 percent.
  - — Reduce costs related to redesign and rework by 75 percent.

Cost and Risk Management Technology

- Objective: Improve cost and risk management capability.
- Metrics
  - — Develop capability to predict mission life-cycle cost to within 10 percent.
  - — Develop capability to predict quantified mission life-cycle risks with 95 percent confidence.

Life-Cycle Integration and Validation

- Objective: Streamline mission life-cycle integration.
- Metrics
  - — Increase science return per mission dollar by an order of magnitude.
  - — Develop approaches to reduce mission risks by two orders of magnitude.
  - — Reduce mission development costs by an order of magnitude while retaining appropriate levels of science return.
  - — Develop design processes that use trade-off analyses involving mission life-cycle cost, risk, and performance to identify and achieve realistic goals in each of these areas.

Collaborative Engineering Environment

- Objective: Revolutionize engineering and science practice in NASA enterprises.
- Metrics
  - — Demonstrate, in practice, reduction of mission development time to 18 months.
  - — Reduce technology insertion time, risk, and costs by an order of magnitude.
  - — Reduce by 80 percent the workforce required to support mission operations.

Revolutionize Cultural Change, Training, and Education

- Objective: Revolutionize the engineering and science culture to enhance the creative process.
- Metrics
  - — Enhance and augment practical experience of new engineering graduates by 50 percent.
  - — Eliminate technical obsolescence of the workforce through education and training.
  - — Remove cultural management barriers.

Source: Malone, 1998.

In addition to the ISE functional initiative, NASA is sponsoring the Intelligent Systems Program as a separate, though complementary, effort to develop information technologies with application to AEEs. The Intelligent Systems Program has four elements:

- Automated Reasoning
- Human-Centered Computing
- Intelligent Systems for Data Understanding
- Revolutionary Computing

AEE technologies are multidisciplinary in nature, can be used in a wide variety of applications, and are relatively new. As a result, large organizations often have a difficult time keeping track of and coordinating efforts to develop or apply AEE technologies and processes. In fact, the top-level requirements for the ISE functional initiative include execution of a national program that involves partnerships between NASA and other government agencies, industry, and academia. However, in addition to the ISE initiative and the Intelligent Systems Program, many other NASA programs sponsor research and application projects involving AEE tools and systems. In some cases, these projects seem to have been initiated in response to local problems or opportunities and do not appear to be coordinated with, or to take advantage of, AEE development efforts by other NASA programs, other government agencies (see below), or industry.

Kennedy Space Center is building a virtual shuttle operations model as a ground processing aid to support space station missions. Ground processing aids such as this enable first-time work to be conducted in a virtual environment instead of the real environment. This reduces the need for mock-ups and allows real work to be done by real facilities and planning work to be done by virtual facilities. Aids like the shuttle operations model can also be used to brief personnel prior to operations in the real environment. Kennedy chose to develop its shuttle operations model as an in-house program instead of using commercially available software. The model is currently being used to conduct real-time "what-if" assessments of how to move and manipulate equipment within the Space Station Processing Facility, to develop and validate procedures, and to support the development of government-supplied equipment for the shuttle and space station. Kennedy intends to enhance the system by adding capabilities for human-factors assessments, thermal management (to predict temperature changes), calculation of equipment center of gravity (to track the effect of changes in mass), calculation of distances between any two points, enhanced proximity and collision avoidance (to validate that planned operations will avoid equipment collisions), and dual-user capability (to allow simultaneous, interactive manipulation of the virtual environment by two users). Many of these capabilities already exist in similar, commercially available software.

U.S. DEPARTMENT OF DEFENSE

DARPA has funded a number of R&D projects related to AEE technologies and processes. For example, the Simulation Based Design Initiative is developing open, scalable systems to support distributed concurrent engineering using virtual prototypes, virtual environments, and shared product models.

Department of Defense laboratories and contractors are also investigating simulation-based acquisition to provide government and industry personnel with collaborative simulation technology integrated across the entire acquisition process. Specific goals are listed below:

- Substantially reduce the time, resources, and risk associated with acquisition.
- Increase the quality, military worth, and supportability of fielded systems while reducing life-cycle costs.
- Enable integrated product and process development (IPPD) across the entire acquisition life cycle.

The Joint Simulation Based Acquisition Task Force used quality function deployment (QFD)[8] to create a prioritized list of 34 actions for advancing simulation-based acquisition. The 10 highest priority items are listed below (MSOSA, 1998):

1. Implement appropriate collaborative environments.
2. Define, adopt, and develop relevant standard data interchange formats for the simulation-based acquisition architecture.
3. Establish a concept of operations for using distributed product descriptions throughout the acquisition life cycle.
4. Establish a process for populating and managing an on-line repository for use by the Department of Defense and industry.
5. Define and develop "reference" systems and a technical architecture for implementing a collaborative environment.
6. Implement technical mechanisms to protect proprietary and classified information.
7. Identify and provide core funding support for simulation-based acquisition.
8. Establish consistent multilevel modeling and simulation frameworks.
9. Establish a process for verification, validation, accreditation, and certification for determining authorities for models, simulations, and data.
10. Establish service/agency ownership authority for models, simulations, tools, and data in the simulation-based acquisition systems architecture.

Simulation-based acquisition is being developed and prototyped by facilities such as the Navy's Acquisition Center of Excellence. Also on behalf of the Navy, the Electric Boat Division of General Dynamics has assembled a team of hardware, software, and modeling companies to develop a system that includes virtual environments and anthropomorphic simulations for the design of new submarines. Similarly, the Air Force is exploring the use of AEE technologies for the Joint Strike Fighter Program being conducted by Lockheed Martin and Boeing. The Fast Track Virtual Manufacturing System and the SAVE project are being used to evaluate cost, schedule, and risk factors of alternative approaches to manufacturing specific items. These projects include feature-based design, integrated analysis, feature-based machining, assembly simulation, and process-flow simulation. The Joint Strike Fighter Program projects that these tools and processes could reduce total life-cycle costs for the joint strike fighter by 2 to 3 percent, which could result in savings on the order of $3 billion. Both the Navy and Air Force programs use commercial software packages.

NATIONAL SCIENCE FOUNDATION

The National Science Foundation (NSF) has funded a great deal of U.S. computer science research related to AEEs. Since 1990, NSF has funded half a dozen projects to explore collaboratory technology. A National Research Council study in 1993 coined the term "collaboratory" by merging the words "collaboration" and "laboratory." That study defined a collaboratory as a

> ". . . center without walls," in which the nation's researchers can perform their research without regard to geographical location—interacting with colleagues, accessing instrumentation, sharing data and computational resources, and accessing information in digital libraries (NRC, 1993).

The same report suggested that

> . . . the fusion of computers and electronic communications has the potential to dramatically enhance the output and productivity of U.S. researchers. A major step toward realizing that potential can come from combining the interests of the scientific community at large with those of the computer science and engineering community to create integrated, tool-oriented computing and communications systems to support scientific collaboration (NRC, 1993).

NSF is currently sponsoring cross-disciplinary research as part of its knowledge and distributed intelligence initiative. This is an ambitious effort that

> . . . aims to achieve, across the scientific and engineering communities, the next generation of human capability to generate, model, and represent complex and cross-disciplinary scientific data . . . ; to transform this information into knowledge by combining and analyzing it in new ways; to deepen the understanding of learning and intelligence in natural and artificial systems; to explore the cognitive, ethical, educational, legal, and social implications of new types of learning, knowledge, and interactivity; and to collaborate in sharing knowledge and working together interactively (NSF, 1999).

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[8] QFD is a formal process of mapping system components and characteristics against program goals.

TABLE 2-2 Implementations of Collaborative Environments for Various Scientific and Engineering Purposes

Project	**Field**	**Internet Address (as of January 1999)**
Remote Experiment Environment	fusion	www.FusionScience.ORG/collab/REE/
DCEE[a]	physics	www-itg.lbl.gov/DCEEpage/DCEE_Overview.html
DOE2000 Projects	physics	www-unix.mcs.anl.gov/DOE2000/
ACSI[b]	physics	www.llnl.gov/asci/
SPARC[c]	space physics	www.crew.umich.edu/UARC/
BioMOO[d]	biology	bioinfo.weizmann.ac.il:8888/
Microscopic Digital Anatomy	biology	www-ncmir.ucsd.edu/CMDA/
InterMed	medicine	smi-web.stanford.edu/projects/intermed-web/
Diesel Collaboratory	combustion	www-collab.ca.sandia.gov/Diesel/ui.new/
EMSL Collaboratory[e]	environment	www.emsl.pnl.gov:2080/docs/collab/

[a] DCEE = Distributed, Collaboratory Experiment Environments
[b] ACSI = Accelerated Strategic Computing Initiative
[c] SPARC = Space Physics and Aeronomy Research Collaboratory
[d] MOO = MUD, object oriented, where MUD = multiple user dimension
[e] EMSL = Environmental Molecular Science Laboratory (of the Pacific Northwest Laboratory)

The anticipated payoffs of research into knowledge and distributed intelligence include higher scientific productivity; improved abilities to analyze complex problems; enhancements in science and engineering education through the development of improved learning tools, technologies, and environments; and a better understanding of the legal, ethical, and societal implications of increased capabilities to gather and access information.

U.S. DEPARTMENT OF ENERGY

The U.S. Department of Energy has made a major commitment to developing the technology needed to create a virtual laboratory system encompassing the scientific resources of U.S. national laboratories. Virtual laboratories would enable greater participation by scientists around the world in achieving the science and technology objectives of the Department of Energy.

A major step in this effort was the Distributed, Collaboratory Experiment Environments Program, which included several research projects related to AEEs. For example, Lawrence Livermore National Laboratory, Oak Ridge National Laboratory, the Princeton Plasma Physics Laboratory, and General Atomics have developed a computer environment that allows scientists at remote locations to conduct research using the D-IIID tokamak fusion facility. R&D on fusion energy is an archetype of research that must be carried out at a few large central facilities, and systems that facilitate the involvement of remote users increase the efficient use of these facilities. In a separate effort, the University of Wisconsin-Milwaukee demonstrated remote operation of a synchrotron radiation beam-line at the Advanced Light Source located at Lawrence Berkeley National Laboratory. In addition, Pacific Northwest National Laboratory developed a test bed for research in environmental and molecular sciences that allows remote operation of unique instruments. The DOE2000 program, which replaced and expanded the Distributed, Collaboratory Experiment Environments Program, is focused on industrial collaboration.

The most recent Department of Energy initiative, which is being conducted in collaboration with NSF, is the Scientific Simulation Initiative. The initiative is applying the high-performance computing capability developed under the Accelerated Strategic Computing Initiative to nondefense purposes.[9] The Scientific Simulation Initiative will include R&D on human-centered computing technology to improve interactions associated with problem definition and visualization of results.

Additional information on collaborative efforts, including some of those mentioned above, is available via the Internet as indicated in Table 2-2.

INTERORGANIZATIONAL STUDIES

Industry and government have sponsored a number of studies related to AEE technologies and systems. For example, the interim report of the President's Information Technology Advisory Committee (formed in 1997 to conduct an independent assessment of information technology

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[9] The Accelerated Strategic Computing Initiative is part of the Department of Energy's Science-Based Stockpile Stewardship Program (see www.llnl.gov/asci/).The purpose of the Accelerated Strategic Computing Initiative is to create leading-edge computational modeling and simulation capabilities to facilitate a shift from nuclear test-based methods to computational-based methods for maintaining the safety, reliability, and performance of the U.S. nuclear weapons stockpile.

in the United States) identified four high-priority research areas for information technology: software, scalable information infrastructure, high-end computing, and socioeconomic and workforce impacts (PITAC, 1998). The report states that special emphasis should be placed on component-based software design and production techniques and on techniques for designing and testing reliable, fault-tolerant systems. The advisory committee also determined that significant research will be necessary to understand the behavior of flexible, scalable systems serving diverse customers, especially in complex applications that involve large numbers of users, users demanding high reliability and low latency,[10] or mobile users requiring rapid reconfiguration of networks. Extremely fast computing systems, with both rapid calculation and rapid data movement, are essential for many applications, such as improved weather and climate forecasting, advanced manufacturing design, and the development of new pharmaceuticals.

The President's Information Technology Advisory Committee also concluded that the government was under-investing in long-term research on information technologies. In response, the President's fiscal year 2000 budget proposes to increase research on information technology by 28 percent ($366 million). The increase would fund the Information Technology for the Twenty-First Century (IT^2) initiative, which would build on existing federal research programs such as the Next-Generation Internet Program and the Accelerated Strategic Computing Initiative. Agencies to be involved in the IT^2 initiative include NSF, the Department of Defense (including DARPA), the Department of Energy, NASA, the National Institutes of Health, and the National Oceanic and Atmospheric Administration. As currently planned, about 60 percent of the funding will be used to support university-based research. IT^2 research will develop advanced software, networks, supercomputers, and communications technology. In addition, the IT^2 initiative will examine economic, social, training, and educational issues associated with the development and use of advanced information technologies (NCO, 1999).

The Next-Generation Manufacturing Project, which was sponsored by the Department of Energy, the Department of Defense, the National Institute of Standards and Technology, and NSF, involved representatives of more than 100 organizations from industry, government, and academia. The project issued a report in 1997 that recommended how manufacturers, working individually and in partnership with government, industry, and the academic community, can improve their competitiveness. Table 2-3 lists the imperatives for success described in the report (NGM, 1997).

TABLE 2-3 Imperatives from the Next-Generation Manufacturing Project

Workforce/workplace flexibility, which is provided by a new set of practices, policies, processes, and culture that enables the employee to feel a sense of security and ownership, while enabling a company to capitalize on the creativity, commitment, and discretionary effort of its employees and, at the same time, maintain the flexibility to continually adjust the size and skills of the workforce

Knowledge supply chains, which radically improve the supply and dissemination of knowledge throughout manufacturing organizations by applying concepts of supply-chain management to the relationships between industry, universities, schools, and associations

Rapid product and process realization, which enables all stakeholders to participate concurrently in the design, development, and manufacturing process

Management of innovation, which includes both initial creativity and the successful implementation of new concepts

Management of change, which applies deliberate change to the current state of an organization to achieve a more competitive future state

Next-generation manufacturing processes and equipment, which are facilitated by a growing knowledge base of the science of manufacturing and used to rapidly adapt to specific production needs

Pervasive modeling and simulation, which enable virtual production and allow production decisions to be made on the basis of modeling and simulation methods rather than on build-and-test methods

Adaptive, responsive information systems, which can be reshaped dynamically into new systems by adding new elements, replacing others, and changing how modules are connected to redirect data flows through the total system

Collaboration among extended enterprises, which are formed by the seamless integration of a group of companies, suppliers, educational organizations, and government agencies to create a timely and cost-effective service or product

Integration of enterprises to connect and combine people, processes, systems, and technologies and ensure that the right information is available at the right location, with the right resources, at the right time

Source: NGM, 1997

OBSERVATIONS ON THE CURRENT STATE OF THE ART

Based on its selective review of current AEE activities, the committee made the following general observations:

- The challenge of tool and system integration is ubiquitous.
- Proliferation of information and information management problems are intrinsic to AEEs and will create difficulties both in the near and far term.
- Cultural, management, and economic issues often impede AEE implementation.

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[10] Latency refers to the time delays that occur in real-time interactions between remote locations. Low latency (i.e., small time delays) helps increase the fidelity of simulations.

- Education and training are significant factors in terms of the time and cost required to realize the benefits of AEEs.

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3

Requirements and Alternatives

INTRODUCTION

As industries and governments around the world attempt to become more competitive in the world marketplace, *affordability*, defined as the ratio of system effectiveness to the cost of achieving this effectiveness, has become a vital criterion or figure of merit for determining success. Organizations are also trying to better understand the performance of new systems early in the design process, before a substantial fraction of program costs has been committed to a particular product design or mission concept. Rather than simply updating existing tools, the committee believes that many organizations must fundamentally change their engineering culture to take advantage of breakthroughs in advanced computing, human-machine interactions, virtual reality, computational intelligence, and knowledge-based engineering. The committee believes that achieving this goal and applying AEE technologies and systems across a wide range of government and industry activities will only be possible if AEE R&D is integrated into a coherent vision of future science and engineering. The remainder of this chapter discusses top-level AEE objectives, benefits, and requirements; components-level requirements; and alternative approaches for achieving the objectives.

TOP-LEVEL OBJECTIVES, BENEFITS, AND REQUIREMENTS

The committee identified the following top-level objectives that AEEs should satisfy:

- Enable complex new systems, products, and missions.
- Greatly reduce product development cycle time and costs.

In addition, AEE technology and system developers should devise a comprehensive, multifaceted implementation process that meets the following objectives:

- Lower technical, cultural, and educational barriers.
- Apply AEEs broadly across U.S. government, industry, and academia.

As described in the following sections, the top-level benefits and requirements of AEEs are closely linked to these key objectives.

System Objectives

Enable Complex New Systems, Products, and Missions

To remain competitive in the marketplace, manufacturing industries must continually develop products that offer new capabilities, improved quality, and/or lower costs. Although government agencies do not face the same competitive market forces as industry, technology-intensive agencies, such as the Department of Defense, the Department of Energy, the Federal Aviation Administration, and NASA face a similar challenge of developing new systems to maximize organizational effectiveness and accomplish agency missions.

Traditional processes for designing, developing, manufacturing, and operating the systems needed to satisfy the complex missions of industry and government are becoming increasingly unsupportable because of cost, schedule, and personnel requirements. The complexity of products and processes has rapidly increased, and the amount and heterogeneity of data required to define, manufacture, and maintain these products have increased dramatically. Global design, manufacture, and maintenance means that this large mass of data must be accessible and movable over long distances and at high speed. The risk of error, of course, increases with more complex systems, and the cost and time implications of mistakes are magnified by the speed and scope of product deployment. AEEs have the potential to improve accuracy and efficiency of engineering processes throughout the life cycle of products and missions. For example, AEEs would enable industry to develop advanced systems more quickly with fewer personnel and at lower cost. Similarly, AEEs should enable government agencies and industry to accomplish missions and develop products that are not feasible using current processes.

Greatly Reduce Product Development Cycle Time and Costs

When complex new systems or products are developed using traditional methods, the bulk of a program's life-cycle costs are set by decisions made very early in the development cycle (the definition phase). Correcting errors made during this phase often involves costly and time-consuming design changes later in the process. For example, the initial product design may specify the basic system structure and a functional allocation for individual subsystems that commit the program to a particular direction. Later on, after subsystems are built and tested or, in the worst case, after the product is integrated, developers may realize that a particular subsystem or the integrated product cannot meet performance specifications. Corrective action may ripple throughout a number of subsystems, requiring extensive rework. Even if the individual changes are small, the net effect can be substantial.

In the commercial world, reducing product development cycle time helps manufacturers increase their market share by enabling them to create new and better products faster than the competition. In the government sector, reduced product development cycle time helps agencies complete projects sooner, thereby reducing costs and improving services or achieving mission objectives more quickly and freeing personnel and fiscal resources to move on to the next task.

One way to reduce product development cycle time and costs is to develop AEEs that allow designers to determine quickly and accurately how proposed designs will affect the performance of new systems and subsystems and how the changes in performance will affect the prospects for mission success. Integrating tools from all aspects of the mission life cycle would allow mission planners and system designers to do the following:

- Seamlessly integrate diverse, discipline-specific design and simulation tools that model and analyze components, subsystems, systems, and related processes from concept development to end-of-life disposal.
- Perform trade-off study sensitivity analyses early in the design process.
- Perform trade-off studies to assess appropriate parameters for each phase of the total life cycle.
- Reduce operational costs by ensuring that operational requirements are addressed early in the design process and in all trade-off studies.
- Lower manufacturing costs by
  - —making design for manufacturability an inherent part of the concept development and design process
  - —reducing the need to build physical test models of new designs
  - —reducing the need for design changes late in the cycle

The sophistication of simulations should be adjusted based on several factors, such as individual product or mission value and the size of the product run or number of missions planned. If the product is expensive enough to justify the cost, comprehensive simulations will be a worthwhile investment, even for small product runs. Launch vehicles and nuclear submarines, for example, certainly justify the cost of extensive simulations, even though they are not produced in large numbers.

Objectives of the Implementation Process

To realize the benefits of AEEs, the development of AEE technologies and systems must be coordinated with the development of a comprehensive, multifaceted implementation process. This process will have to include distinct elements tailored to the characteristics and issues associated with different AEE technologies and system components. The following two sections describe the top-level objectives of the implementation process.

Lower Cultural, Technical, and Educational Barriers

Because of barriers to change and innovation, old systems and processes are often retained long after more effective alternatives become available. These barriers may involve technical, cultural, educational, and/or economic factors. Technical barriers often involve the incompatibility of new systems with legacy systems, especially if an organization has a large investment in existing systems and infrastructure. For example, most of Boeing's existing in-house applications have been encoded using IBM's operating system (AIX), and it would be prohibitively expensive to make them compatible with other operating systems. This severely limits Boeing's ability to use computer hardware from other vendors.

To take advantage of changes in business practices and technology, organizations should develop systematic methods of encouraging innovation. Lowering barriers is an essential precursor to achieving the other benefits offered by AEEs. (See Chapter 4 for a discussion of specific barriers.)

Apply AEEs Broadly across U.S. Government, Industry, and Academia

Just as the development of AEEs should include an implementation process to maximize the benefits of AEEs for a particular organization, development efforts should also be consistent with the broader objective of applying AEEs throughout U.S. government, industry, and academia. In other words, approaches to AEEs should not restrict their applicability to a small number of settings.

Consider the significant differences between the automotive and aerospace industries. An automobile manufacturer may produce several hundred thousand automobiles of a popular model, and each vehicle may have a value of $20,000 to $50,000. An aerospace company, on the other hand, may produce just a few satellites, a few dozen launch vehicles, or a few hundred airplanes of a given model, and the value of each vehicle may be well in excess of $100 million. AEE technologies and systems must be flexible so they can be tailored to improve product quality and reduce costs throughout both industries.

The widespread use of AEEs will also maximize their value to individual organizations. Complex products and missions typically are implemented by partnerships of many different organizations, and the AEEs adopted by one organization will be more useful if its partners use compatible AEEs.

To achieve widespread use of AEEs, industry and academia must establish appropriate training and educational programs for current and future workers. In fact, AEEs themselves can be used as effective training tools. For example, the astronaut training methods traditionally used by NASA include neutral-buoyancy training, part-task training, and full-scale simulators; make limited use of virtual environment technology; and are very expensive. Neutral-buoyancy trainers, which require safety divers and equipment operators, may have a staff-to-student ratio as high as 40:1. Also, as NASA has learned the hard way, differences in the physics of vacuum and water reduces training fidelity, and methods practiced in buoyancy tanks sometimes don't work in space. Furthermore, the committee believes that a stressful training environment is an important element of training for stressful real-world situations. The space station raises additional training issues because the number of planned operations is so extensive that traditional training methods will be impractical.

AEEs that provide shared virtual environments can address these issues. In addition, AEEs would enable team training even when all members of the team are not at the same location (i.e., reducing the need to station astronauts at Johnson Space Center for months or years of on-site training prior to each mission). For this application, the fidelity with which remote participants are depicted will be especially important, although the required level of fidelity is lower for participants who know each other. Virtual environments can include "avatars," virtual participants whose actions and reactions are controlled by the training system in response to actions by the human participants.

TABLE 3-1 AEE System Components and Characteristics

Computation, Modeling, and Software
- multidisciplinary analysis and optimization
- interoperability of tools, data, and models
- system analysis and synthesis
- collaborative, distributed systems
- software structures that can be easily reconfigured
- deterministic and nondeterministic simulation methods

Human-Centered Computing
- human-adaptive interfaces
- virtual environments
- immersive systems
- telepresence
- intelligence augmentation

Hardware and Networks
- ultrafast computing systems
- large high-speed storage devices
- high-speed and intelligent networks

COMPONENT-LEVEL REQUIREMENTS

The AEE components and characteristics identified by the committee are listed in Table 3-1 and discussed in the sections that follow.

Computation, Modeling, and Software

The products and processes designed using AEEs will typically be large and complex, so AEEs must be capable of rapidly synthesizing and analyzing the performance of large combined hardware and software systems. Multidisciplinary tools will be required for analyzing attributes and subsystems, such as aerodynamics, thermal management, mission design, life-cycle costs, manufacturing, maintenance, and risk management. Traditionally, trade-offs among these attributes for shared resources (e.g., power or weight) have been made iteratively; to support rapid analysis and achieve "best" designs, AEEs will require a multifunctional optimization capability.

The models and simulations incorporated into AEE systems must effectively address the uncertainty and risk associated with the development of new systems. One way to reduce uncertainty is to validate simulations and models. Validation generally involves physical tests to verify that the performance of simulations and models is consistent with reality. In some situations, however, it is difficult to create high-fidelity models, and physical testing cannot remove all uncertainty and risk. Thus, AEEs must include methods for assessing the impact of residual uncertainty and risk. Deterministic simulation methods must be augmented or, perhaps, replaced by nondeterministic methods to account explicitly for uncertainties. For example, Monte Carlo techniques might be appropriate for analyzing models that are very computationally intense. Accounting for uncertainties will be particularly important in analyzing multiyear missions.

Computation, modeling, and software systems will also have to facilitate interactions among multiple decision makers with different values. For example, the merit of proposed new products and/or missions may be perceived very differently by researchers, technologists, designers, manufacturers, suppliers, and customers. Multidisciplinary analysis and optimization tools should include flexible input and output capabilities to accept inputs and display results in terms that make sense to each of these constituencies.

From an operational standpoint, AEEs must provide an infrastructure for distributed collaboration in which the geographical location of team members is completely transparent to the design process. The organizational location must also be transparent, which implies a high degree of interoperability among analysis tools, data, and models. The system should be fully associative, so that data are entered only once and are then accessible everywhere their use is authorized.

Because of the evolving nature of AEE capabilities, software structures must be reconfigurable quickly and economically. Ongoing maintenance needs and future system changes should be anticipated in the design of the original system and in the design of hardware and software upgrades.

Human-Centered Computing

The purpose of human-centered computing is to increase the communications bandwidth among users and between each user and the AEE system. Virtual reality and/or immersive systems provide users with visual, audio, and, in some cases, haptic feedback,[1] all of which increase the sense of *presence* or perceived reality of a simulation. With sufficient computing power, users can collaborate on redesigning in real time and experience the physical and performance results of their work through virtual interfaces. A less well known but equally powerful approach uses human-adaptive interfaces, which are adjusted by the system to suit the needs, skills, or mental state of the user.

Human-centered computing also includes intelligence augmentation, which uses software and hardware agents, decision-support software, knowledge-based systems, and autonomous learning systems to provide real-time design guidance. For example, AEEs should support decision methodologies compatible with multiple users who have different values and decision criteria.

Hardware and Networks

Ultrafast computing systems will be needed to support the real-time analyses and interfaces described above. These systems will probably involve massively parallel processors and, ultimately, a distributed heterogeneous computing capability to maximize computing power economically. Because of the size and complexity of the products and processes likely to be designed with AEEs, large data sets will have to be retrieved, modified, transported, analyzed, displayed, and stored. This will require large high-speed storage devices and high communications bandwidths.

Component-Level Requirements

To investigate component-level requirements, the committee conducted a survey of personnel associated with the following companies and projects: Caterpillar (construction equipment), Ford Motor Company (automobiles), Simmetrix (analysis software), the X-38 Program at NASA Johnson Space Center (prototype spacecraft), Boeing Electromagnetics (analysis of electromagnetic interference for large systems), Boeing CAD Research (tools for managing design geometries of large systems), Boeing Applied Research and Technology (aerospace vehicle design), and Shell Exploration and Production (energy). Personnel at these organizations were asked to identify typical engineering processes that would benefit from the capabilities of an AEE, shortfalls of current processes, desired improvements, and the implications of process improvements with regard to specific functional attributes of AEE system components. Survey responses received by the committee are summarized in Tables 3-2 and 3-3.

As Table 3-2 shows, most requirements involve computation, modeling, and software. Relatively few requirements are related to human-centered computing or hardware and networks, perhaps because users are more familiar with requirements related to computation, modeling, and software than with requirements related to the other three areas. Also, the survey did not specifically ask for inputs related to human-centered computing.

R&D focused on the common themes listed in Table 3-3 would have the greatest impact on the highest priority processes identified by the respondents. Based on these common themes, the committee identified 11 specific opportunities for NASA to conduct broadly applicable R&D through the creation of partnerships with industry and academia (see Box 3-1).

ALTERNATE APPROACHES

The committee identified three basic approaches for improving engineering processes. The first approach is an aggressive effort to maximize overall effectiveness by completely re-engineering existing processes and facilities using

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[1] Haptic simulations involve instrumented gloves or other devices worn or manipulated by users that provide tactile and force feedback to the user(s) to simulate the forces that would be experienced during a real event.

TABLE 3-2 Survey of AEE Requirements

Organization	Engineering Process	Improvements Desired	Computation, Modeling, and Software	Human-Centered Computing	Hardware and Networks
Caterpillar	preliminary and detailed design of whole vehicle system	• 30x reduction in design-cycle time • standards for concurrent product and process development • collaboration among companies	• 10 gigabyte CAD file • parametric design • system model with flexible body dynamics and all nonlinearities • distributed computing environment • probabilistic analysis • manufacturing and assembly simulation • eliminate CAD translation • standardized approach to systems engineering, component representation, assembly representation, test/analysis information, material properties, and boundary conditions	• advanced visualization for engineering workstations	• T-3 circuits (at 45 megabits/sec) between plants • Internet-based communication with suppliers
Ford	whole vehicle design	• 3x reduction in design-cycle time • improved quality • smaller number of prototypes	• 500,000 element mesh • parametric and stochastic models • CAE associative with CAD • sources of variability including material and dimensional stability • cost and manufacturability analysis • cross-attribute optimization • design for robustness • collaboration for global teams • standardized system engineering tools • standards for CAD and CAE	• advanced visualization (stereographic, holographic, and immersive) • full 3-D animation of total vehicle with real-time analysis updates	• 10x increase in speed for common product information systems • 10x to 30x speed increase for pre- and post-processing • 20x increase in speed for analyses
Simmetrix	simulation-based design of component and system	• CAE for design, not verification • faster analysis • better linkage of models	• generic parametric CAD model linked to attribute-specific CAD models • open CAD systems • geometry-based adaptive mesh		
NASA X-38	design of a space rescue vehicle	• faster analysis, more effective collaboration, and better configuration control • reduced testing	• single CAD package • linkage of CAD to in-house analysis packages • single analysis package • integration of structural analyses • integration of thermal, aerodynamic, and manufacturing analyses • collaboration for global teams • reliable CAM transmission to vendors		• low-cost video

TABLE 3-2 continued

Organization	Engineering Process	Improvements Desired	Computation, Modeling, and Software	Human-Centered Computing	Hardware and Networks
Boeing Electro-magnetics	analysis of electromagnetic radiation effects for large systems	• faster analysis • better 3-D representation • optimization capability for large models	• rapid model creation • 1,000,000+ element mesh • adaptive mesh refinement • integrated solvers • handle 10x larger problems • rapid design updates • optimization integrated with analysis • support for analytical “design of experiments” • binary standard for data transfer	• less involvement by users in managing analyses	• gigabit/sec data transmission • higher speed for analyses
Boeing CAD	management of geometry and configuration for very large systems, particularly at the concept stage	• shorter process • increased model size • better process management • faster, more capable trade-off studies	• elimination of data translation • product information management for configuration control • process modeler for management of dependent processes	• visualization of large data sets on low-end workstations • real-time collision detection for 15 to 20 gigabyte data sets • high-speed haptic interfaces for gigabyte data sets (e.g., for assembly sequence verification) • knowledge-based engineering tools	
Boeing Applied Research and Technology	whole aerospace vehicle design	• 2x to 10x reduction in cost and cycle time • control of product cost • improved distance collaboration	• rapid model updating • design reviews of 10,000+ part assemblies • design cost linked to CAD • nonlinear solvers • multifunction design optimization • cost trade-off studies • open environment for planning, design, and analysis • distributed decision making • generalized product data structures • standard approach to rapid modeling/generative design	• decision support capability • better visualization tools for exploring design space • haptic interfaces • natural language interfaces	• platform-independent environment for analyzing and viewing • Internet-based information delivery • virtual collocation
Shell Exploration and Production	evaluation of prospecting data from potential underground energy source	• 10x improvement in speed of evaluation • collaboration across remote sites	• 3-D graphics @ 3 million polygons/sec • 4 gigabyte data sets • 10x increase in analysis speed (one week turnaround)	• interactive visualization • photograph-quality maps (1,000 dpi) • real-time sectioning and texturing • 30 frames/sec animation	• interoperable platforms • satellite transmission from offshore prospects • collaboration across sites

TABLE 3-3 Common Themes

	Engineering Process	Improvements Desired	Computation, Modeling, and Software	Human-Centered Computing	Hardware and Networks
	broad-based design, development, and support of complex products	• reduced cycle time • reduced risk and higher quality • reduced total cost • improved collaboration	• gigabyte file size for pre- and post-processing of 10,000+ part assemblies • rapid modeling, model modification, and preparation for analysis • 1,000,000+ model (grid) size • parametric design • "open" CAD systems linked to CAE, CAM, product information management • accommodation of legacy data • support for manufacturing applications • integration of specific analyses • multiple-attribute analysis simultaneously from a single model (function, cost, support, and manufacturing) • incorporation of probabilistic analysis, nonlinearities, material and dimensional stability over time • support for analytical "design of experiments" techniques • multifunction optimization integrated with analysis • using standards to eliminate translation between different applications • imbedded intelligence • support for global teams and distributed decision making • open distributed environments supporting total product definition, configuration management, and lifetime support • standards for CAD; systems engineering; component and assembly representations; test and analysis data; and geometry, properties, boundary conditions, and results	• stereographic, holographic, immersive environments • desktop visualizations • less involvement by user in managing efficiency of analysis • high-speed haptic interfaces for gigabyte data sets • 100 megabit/sec communication • 10 to 30x speed increase for pre- and post-processing • 20x increase in speed for analyses • high-speed data transfer • Internet-based communication with suppliers	

AEE technologies and systems. Premature implementation of developmental technology in an operational setting, however, could be risky and expensive. If the new technology doesn't live up to expectations, the result could be ineffective and counterproductive. In fact, long-term damage could be done to the prospects for incorporating AEE technologies into operational settings because a bad experience with immature technology would make it more difficult to justify the use of advanced technologies in the future.

The second approach would adopt and integrate AEE technologies with existing systems and practices gradually, using staged implementation. Improvements made one at a time would be tested in practice and optimized before the next innovation is implemented.

The third, and most conservative, approach would defer the use of AEE technologies until a proven, comprehensive system has been developed. In the meantime, this approach

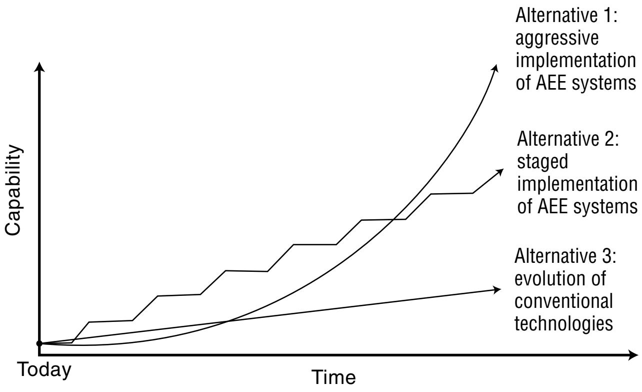

FIGURE 3-1 Approaches for improving engineering processes.

BOX 3-1
Opportunities for NASA-Industry-Academia Partnerships (based on a survey of seven private and public organizations)

Gigabyte file sizes and processing of assembly data sets with more than 10,000 parts. AEEs need the capability to display and modify large data sets. The space shuttle, the international space station, and many NASA payloads have more than one million parts.

Rapid modeling, model modification, and preparation for analysis. Desired reductions in engineering cycle time will require AEEs to generate models of new products and processes rapidly, to ensure that models of modified products and processes are consistent with models of the original products and processes (to facilitate comparative analyses), and to validate new models and capabilities before they are released for operational use.

Models with more than one million grids. To construct engineering models for current and future NASA projects, AEEs must have the ability to support models with large regular and irregular grids.

Accommodation of legacy data. Although AEEs will be used for the development of new products and processes, they will not operate in isolation from the current inventory of products, processes, and support services. Thus, specific attention must be given to the ability of AEEs to accept legacy data sets and interface with legacy systems for analysis and other engineering activities.

Support for manufacturing applications. NASA, like many large engineering organizations, conducts manufacturing operations using both in-house facilities and contractors. AEEs should have the ability to export data to and interface with manufacturing systems operated by other organizations.

Visualization. Collaborative (i.e., large-scale and/or distributed) visualization has demonstrated its ability to streamline the elements of the engineering enterprise that cross disciplinary and geographic boundaries. Thus, AEEs should provide immersive and nonimmersive three-dimensional displays and, potentially, nonvisual simulations (e.g., auditory, haptic, and vestibular simulations).[1]

Integration of individual analyses and simultaneous analysis of multiple attributes using a single model. Today, analyses of system functions, structural properties, thermal properties, cost, and/or manufacturability are usually conducted independently. AEEs should have the capability to do simultaneous analyses of specified sets of multiple attributes. This would be facilitated by the use of a single model from design to manufacture.

Multifunction optimization integrated with analysis. In addition to analyzing a product's performance against each attribute, AEEs should be able to define an optimal balance of performance when attributes compete for the same resource, such as power or weight. Traditional iterative methods are slow, costly, and inexact. Multifunction optimization provides a rigorous approach to finding the best balance. Although multifunction optimization is developing rapidly, it must be tailored to the specific attribute being analyzed. The needs of industry and government agencies, such as NASA, overlap in this area, so collaborative work could be fruitful.

High-speed haptic interfaces for gigabyte data sets. Haptic interfaces provide users with the opportunity for direct, feedback-enabled interactions with models. These interfaces can enhance the ability of design engineers to manipulate rapidly multicomponent objects of very large size.

Support for analytical "design of experiments." The use of a designed experiment (e.g., Taguchi methods) is a powerful statistical technique for simultaneously studying the effects of multiple variables on a system. For example, this technique is a powerful tool for establishing the robustness of a design or process in response to noise factors. To minimize the need to evaluate complex products and missions experimentally, AEEs should have the capability to rapidly create analytically designed experiments that operate seamlessly with the models and analyses used to evaluate attribute performance. This capability is especially important to the development of autonomous vehicles.

Open, distributed environment supporting total product definition, configuration management, and lifetime support. This is essentially the principal goal of AEE R&D conducted by NASA. It can be realized through the use of common object models in combination with hardware and software that demonstrate a high level of interoperability.

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[1] Vestibular simulations involve moving platforms to simulate the sensation of movement that would be experienced in a real event.

TABLE 3-4 Estimated Effectiveness of Alternative Approaches

	Alternative 1 Aggressive Implementation of AEE Systems	**Alternative 2** Staged Implementation of AEE Technologies	**Alternative 3** Evolution of Conventional Technologies
Risks			
Technology insertion	high	medium	low
Information complexity	high	medium	medium
Cultural impacts	high	medium	low
Total cost of implementation	high	medium	medium
Time required for implementation	3–5 years	1–3 years	< 1 year
Costs			
Software tool interoperability	high	medium	low
Legacy systems migration	high	medium	low
Commonality/standardization requirements	high	high	low
Training	high	medium	low
Information infrastructure requirements	high	medium	medium
Supplier interfaces requirements	high	medium	low
Maintaining systems effectiveness	high	high	medium
Potential Benefits			
Seamless interfaces	high	medium	low
Standardization	high	medium	low
Tools/information management	high	medium	low
Collaboration capabilities	high	medium	low
Real-time assessment	high	medium/high	low
Life-cycle management	high	medium	medium
Compatibility of product targets	high	medium	low

would rely on evolutionary improvements in conventional technology. This approach would unnecessarily postpone the benefits of implementing available AEE technologies.

Figure 3-1 is a conceptual comparison of the three alternatives. In the long-term, aggressive implementation of complete AEE systems has the largest potential payoff, but it also has the largest risks and highest costs. Staged implementation of AEE technologies is likely to outperform evolutionary improvements in conventional technology. Staged implementation is also likely to outperform the aggressive implementation of AEE systems, at least in the near-term and midterm, because it avoids the cost, time, and complexity of reinventing complete processes with unproven technologies. Table 3-4 characterizes the committee's estimates of the risks, costs, and benefits of these three alternatives. Before an organization selects an alternative, it should assess the subelements listed in Table 3-4 and their potential impact on the organization in question.

4

Barriers

INTRODUCTION

History is littered with plans, both strategic and tactical, that were conceptually and technically brilliant but failed because the barriers to success were not carefully considered. Many barriers must be overcome to develop and implement AEEs that achieve the vision and meet the objectives described in this report. Barriers, however, can often be transformed into opportunities if creative minds are brought to bear on the problem. For example, a lack of interoperability among tools and data sets currently hinders the effective use of AEE technologies. Efficient resolution of interoperability issues will require cooperation among developers and users of AEE technologies and systems, and the mutual understanding that results from such cooperative efforts could have benefits that extend far beyond the development of AEEs. This chapter summarizes the barriers associated with achieving the AEE vision and carrying out the recommendations in Chapter 5. The barriers are organized into four groups (see Table 4-1).

INTEGRATION OF TOOLS, SYSTEMS, AND DATA

The incompatibility of different software tools and hardware systems is viewed by some as inevitable. Commercial competition, which has fostered many incompatibility problems, has also resulted in many improvements that have benefited all users. Nevertheless, the committee does not believe current levels of incompatibility are either inevitable or beneficial.

A high level of integration, which is one of the defining characteristics of AEEs, is required to create an "environment" as opposed to a loosely bundled collection of tools and techniques. AEEs will be used to link researchers, technologists, designers, manufacturers, suppliers, customers, and other personnel who have a broad range of expertise and widely varying concerns. Effective AEEs must efficiently integrate tools and systems that address all areas of concern. Although efforts to develop AEE technologies and systems face many challenging problems, the integration of tools, systems, and data is the greatest barrier to achieving the AEE vision.

Integration problems are caused by many factors, and addressing them all will not be easy. To begin with, software tools are inherently incompatible unless interoperability was a specific goal of the software development process used to create them. For most tool developers, interoperability has had a relatively low priority. Commercial software vendors tend to operate in secrecy to protect proprietary information, especially as new software is being developed. Many tools, especially those generated by R&D organizations or manufacturers for in-house use, are tailored to address specific problems with maximum efficiency and cannot be easily integrated with more generic tools for application to a broad range of problems. With few exceptions, effective integration of software tools is currently possible only if all of the tools are provided by the same vendor. Accordingly, some organizations have selected a single vendor to provide an integrated suite of tools, based on the performance of the tool set as a whole.

A more common approach is for a company, project manager, or individual engineer to purchase the best tool for each application (or to create new tools when commercially available tools are not satisfactory). As a result, organizations sometimes cannot make their tools work together. In fact, the drive to improve the performance and efficiency of individual products and processes encourages the proliferation of new tools to take advantage of the latest advances in the state of the art. However, proliferation itself may become a significant barrier because it can dramatically complicate the interoperability problem, especially if an organization has been addressing this problem by creating individual links between different tools. The same integration problems apply to hardware systems. Systems provided by different vendors are sometimes incompatible, and software written

TABLE 4-1 Barriers to Achieving the AEE Vision

Integration of Tools, Systems, and Data

1. Lack of tool interoperability
2. Continued proliferation of tools, which aggravates interoperability issues
3. Existing investments in legacy systems and the difficulty of integrating legacy systems with advanced tools that support AEE capabilities
4. Little effort by most software vendors to address interoperability or data-exchange issues outside of their own suite of tools
5. Multiple hardware platform issues—computers, hardware, databases, and operating systems
6. Lack of formal or informal standards for interfaces, files, and data terminology
7. Increasing complexity of the tools that would support AEE capabilities
8. Difficulty of inserting emerging and advanced technologies, tools, and processes into current product and service environments
9. Supplier integration issues
10. Difficulty of integrating AEE technologies and systems with other industry-wide initiatives, such as product data management, enterprise resource management, design for manufacturability/assembly, and supply-chain management

Information Management

1. Proliferation of all types of information, which makes it difficult to identify and separate important information from the flood of available information
2. Difficulty of maintaining configuration management for product designs, processes, and resources
3. Need to provide system "agility" so that different types of users can easily input, extract, understand, move, change, and store data using familiar formats and terminology
4. Difficulty of upgrading internal infrastructures to support large bandwidths associated with sharing of data and information
5. Need to provide system security and to protect proprietary data without degrading system efficiency

Culture, Management, and Economics

1. Difficulty of justifying a strong corporate commitment to implementing AEE technologies or systems because of their complexity and uncertainties regarding costs, metrics, and benefits
2. Lack of practical metrics for determining the effectiveness of AEE technologies that have been implemented
3. Unknowns concerning the total costs of implementing AEE technologies and systems and the return on investment
4. Difficulty of securing funding to cover the often high initial and maintenance costs of new AEE technologies and systems in a cost-constrained environment
5. Risk—and someone to assume the risk (management, system providers, or customers)
6. Planning and timing issues—when to bring in the new and retire the old
7. Difficulty of managing constant change as vendors continually upgrade AEE tools and other technologies
8. Diversity of cultures among different units of the same company

Education and Training

1. Need to upgrade labor force skills along with technology and tools to support an AEE capability
2. Difficulty of incorporating AEE technologies into university design curricula

for hardware systems from one vendor may be incompatible with systems from other vendors.

Standards have been used in many fields to prevent or correct interoperability problems associated with, for example, tool interfaces, files, and data terminology and definitions. Some standards are formally approved for industry-wide applications. In other cases, informal standards serve as ad hoc guidelines for individual companies or small groups of companies working on joint projects. The committee reviewed engineering environments used by various government agencies and industries and found that in all cases users perceived the lack of general standards for engineering processes, work practices, and support systems as a major problem. Although many of the organizations had documented processes for their engineering enterprise, few actually adhered to them, and there was not enough continuity or commonality among the elements of individual organizations, especially between research and operational elements.

One way to create highly integrated AEEs is through the use of open architectures that allow the insertion of new elements using interfaces designed in accordance with predefined standards. Open architectures would extend the shelf life of AEE system architectures and reduce the cost of implementation and training by allowing system capabilities to change with minimal impact on user interfaces. A major impediment to establishing "official" industry-wide standards is that the coordination and approval process takes years, which is much longer than the life cycle of many technologies. Also, economic and business factors seem to provide little incentive for software companies to create standards-based solutions to compatibility problems. The user community—in individual industries and, in some cases, within individual companies—has not been able to reach consensus on appropriate standards, and, thus, it has been unable to motivate vendors to provide interoperable tools and systems. As a result, state-of-the-art technology and standards-based technology may be mutually exclusive, at least in the near term.

The committee believes it may be time to develop an alternative approach, such as a process for generating, rapidly approving, and frequently updating flexible, change-tolerant standards. Another solution would be to adopt tiered guidelines, with high-level information technology standards to govern communications in a particular industry and technology standards (e.g., SQL, OLE, or HTML) as local guidelines for individual organizations or major facilities in an organization. Individual projects could then use industry-wide and organizational standards to guide the development of new tools, and software vendors could produce tools compatible with industry standards for specific markets. In any case, standards should be developed with care because overly restrictive or poorly chosen standards would hinder, rather than foster, the development and application of advanced new tools and systems.

Even if *new* tools and systems are highly interoperable, AEEs will not become a practical reality unless they can be effectively integrated with legacy tools and systems. This is an immediate issue when assessing the practicality of inserting AEE technologies into an existing product environment. For example, the Electric Boat Division of General Dynamics created more than 6,000 programs (more than 4.5 million lines of code) to integrate its design, analysis, manufacturing, and program management tools with CATIA. This effort has generated important improvements in the design process, but seamlessly integrating the analysis process with the CAD process will require much additional work.

Another complicating factor is the increasing complexity of software tools and hardware systems. Companies must do more than simply integrate their processes internally. Increasingly, manufacturers are focusing their expertise on the assembly of products using systems, subsystems, and components provided by others. Currently, one-half to three-quarters of product costs may be associated with suppliers and subcontractors, and manufacturers' labor costs are reduced if suppliers provide subassemblies that are easily assembled. This requires closely involving first-tier suppliers in the design and manufacturing development process. Thus, external interfaces are becoming just as critical as internal interfaces, and engineering and design systems must be integrated across organizational boundaries. For example, DaimlerChrysler requires first-tier suppliers on some projects to use the same CAD/CAM software tools as DaimlerChrysler.

INFORMATION MANAGEMENT

One of the important advantages of AEEs will be the capability to construct, analyze, and test new designs and processes quickly in a simulated environment. Because this process will not involve building physical models, it will be possible to assess a much larger number of designs than with traditional methods. Also, because the collection of test data will not be constrained by physical instruments, the amount of data that can be collected will be limitless. With sophisticated new analysis methods, AEEs will generate tremendous volumes of data, even for relatively mundane products. This capability could become a critical barrier to the effective use of AEEs, however, if a flood of data hinders rather than facilitates an in-depth understanding of how new designs will perform.

Another serious challenge associated with the development and long-term use of virtual and distributed environments, such as AEEs, is configuration management (i.e., making sure that all engineering orders and other design changes are reflected in the simulations and models used to create and evaluate new designs and design changes). Configuration management has traditionally been used just for products, but it is being expanded to include processes and resources. This can be complicated. The same products may be manufactured in different plants, in different countries, with different tools, and by workers with very different skills. International sales often require that manufacturers provide economic offsets. As a result, advanced technology products may be produced in both the United States and foreign countries. In countries with very low labor costs, manufacturing processes tend to involve more manual labor and less automation than in a U.S. factory making the same products. The design process, simulations, and change-control system must be able to accommodate these differences.

Given projected rates of software obsolescence, the life spans of many products will vastly exceed the life span of the software used to develop them. For some products, design, analysis, and decision processes used today will have to be accessible in 20 or 30 years to facilitate reviews, redesigns, and upgrades that may occur late in the product life cycle. This will require long-term compatibility of current systems with future systems. For example, when Boeing upgrades its CAD software, legacy data are migrated upward into the upgraded software, but it is also retained in the original format. Retention of original data is required by the Federal Aviation Administration to enable reviews of the original product definition during accident investigations, certification of design modifications, and other purposes. However, problems associated with ensuring the usability of original, computer-generated data in native formats for decades have yet to be resolved.

Organizations reviewed by the committee have, in general, made good progress in making computer systems available to their workers, although some variability in performance is common. The principal infrastructure barrier cited by these organizations was network availability and bandwidth. A related concern was the lack of connectivity between organizational intranets and the Internet, which inhibits interorganizational sharing of data. In many cases, this lack of connectivity is intentional because of security considerations.

Although the utility of AEEs would generally be increased by technologies that facilitate the rapid exchange of information among system elements, AEE designers will also have to provide security to protect against the careless alteration or deletion of data, blatant vandalism (erasing files or data), and more subtle sabotage (altering data). Most data and software produced by government agencies are in the public domain, but it is essential that AEEs protect proprietary data in projects with industry participation. AEEs should prevent unauthorized users from gaining access to the system and allow organizations involved in cooperative enterprises to use proprietary data in some analyses without revealing that data to the other partners. Project participants must also resolve the issue of who will be liable if incorrect data caused by errors or vandalism in one organization's portion of an engineering effort are unknowingly passed along to other organizations.

CULTURE, MANAGEMENT, AND ECONOMICS

Even when new AEE technologies are ready for use, they will have to overcome cultural barriers that often prevent innovative technologies and methods from being used. Senior and middle managers must learn what is possible because without their support it is unlikely that AEE technologies or systems will be implemented and used to their full potential. For example, AEEs do not fit the traditional cost-time curve for new product development and acquisition. Additional resources will be needed early in the product development cycle to carry out the sophisticated analyses and simulations that are characteristic of AEE-based acquisitions. Senior managers will also have to ensure that personnel maintain proficiency with new AEE technologies and systems, even if this periodically causes short-term reductions in productivity.

AEE advocates argue that AEEs can reduce costs throughout the product life cycle. Implementing new AEE technologies, however, can be expensive. Two of the largest costs in moving to a new CAD tool, for instance, are the training of personnel and the translation of legacy data. AEE technologies and systems will also incur substantial ongoing costs to keep tools, systems, and staff training up to date. Additional expenses will be incurred when AEEs are applied to new design problems. AEE simulations can reduce the need to conduct physical tests of new designs, but only if the simulations have been validated.

Once an AEE technology has been implemented, it is difficult to prove that it is responsible for reduced costs or increased quality. AEE technologies generally reduce the size of the engineering staff required for a given project, and staff size is easy to measure. The overall effectiveness of a design process, however, can be very difficult to measure, especially because a cost estimating function—for the final product *and* for the design process itself—is not part of most design processes. In addition, many variables are usually at work while AEE technologies are being implemented, and isolating the effects of individual factors on costs or quality is usually not feasible.

Even if advanced design processes have the potential to improve product quality and increase profits in the long term, a company may be more concerned with near-term profits. A large investment in new infrastructure with an uncertain payoff may not be viewed favorably by business managers who must decide whether to accept the risk. Ideally, business decisions would be guided by metrics that predict the future performance of AEEs in specific applications and, once implemented, measure the success of AEEs in reaching specified goals. These metrics are not currently available.

Similar factors will also affect the implementation of AEE technologies and systems by government agencies. Managers of major acquisition programs with fixed budgets are generally reluctant to fund AEE activities unless they can be justified by a positive return on investment during the lifetime of that program. Unfortunately, the lifetime of many programs is too short to justify a large investment in new computer systems, software tools, and related infrastructure. Furthermore, program managers at agencies like NASA are often involved in complex first- or one-of-a-kind missions, such as the international space station or a planetary exploration mission. Using AEE simulations to replace physical tests on these missions would be especially risky without reliable methods for continuously validating the simulations. Models and simulations are generally based on past experience, but when they are applied to first-of-a-kind applications they must be extrapolated into new, untested territory. In these situations, program managers are faced with the challenge of assessing how well the applicable physics is known and how well it has been modeled. Overcoming this challenge often requires that program managers and technical experts work together to develop implementation plans that are consistent with organizational goals, existing processes, and available resources. Involving key vendors, subcontractors, and customers, as appropriate, can also help reduce risk.

In situations where conventional methods are particularly expensive and/or time consuming, it becomes easier to demonstrate the advantages of AEE alternatives in terms of cost and risk. For example, NASA's involvement in the development of improved training systems using AEE technologies is motivated by the high cost of traditional astronaut training methods. NASA's space shuttle training facilities were expensive to acquire (about $250 million for three shuttle simulators) and are expensive to operate (about $40,000 per hour for a shuttle simulator). The quality of current training systems is generally satisfactory, however, so NASA's primary motivation is reducing costs without degrading effectiveness. A substantial amount of money would be saved if NASA were able to shut down one or two shuttle simulators and replace them with comparable virtual reality training facilities.

EDUCATION AND TRAINING

One barrier to the use of state-of-the-art engineering and design tools is the steep learning curve. It currently takes an individual about three or four months to become proficient with some tools, and proficiency may be greatly degraded after six months of inactivity. Industry and government employers bear most of the training burden. Universities believe (and the committee agrees) that the university educational mission generally does not include the task of training students to become proficient with particular software packages.

AEEs should be designed to make use of the system as natural as possible to minimize the need for specialized training. Even so, education and training will be essential to teach people how to use AEE tools and how the results of their work will be used by others, so that output data produced in one phase or element of a project meets the informational requirements of other phases and elements. In addition, senior personnel, in what amounts to a technical mentoring role, should ensure that AEEs are used consistently within a given project or organization. Training must be consistent and continually available to refresh existing staff and to support new users. In some cases, investments in new training technologies may be warranted. For example, AEEs could themselves be used to facilitate training.

Training is also a concern because sometimes software changes faster than staff can be trained. Therefore, some companies may replace comprehensive training on new tools with a strategy that trains staff to perform specific software functions only as needed. This would reduce unnecessary training, shorten the time between training and practical application, and minimize the need for retraining.

5

A Historic Opportunity Findings and Recommendations

The committee believes that a historic opportunity exists today to foster the maturation of AEE technologies and to integrate them into comprehensive, robust AEE systems. As the capabilities of computational systems and the sophistication of engineering models and simulations advance, AEE technologies will become more common in both the private and public sectors. However, it remains to be seen how quickly AEE technologies and systems will be developed and what capabilities they will demonstrate, particularly in the critical area of interoperability. Within the federal government, the Department of Defense, NASA, Department of Energy, NSF, and National Institute of Standards and Technology have much at stake in terms of their ability to accomplish complex, technically challenging missions and/or to maximize the return on their investments in the development of AEE technologies and systems for use by outside organizations.

In the 1960s, the Advanced Research Projects Agency (ARPA, the predecessor to DARPA) started development of a decentralized computer network. That effort produced the ARPANET, which became both a test bed for networking technologies and a precursor to the Internet. ARPA took advantage of a historic opportunity created by new technological capabilities to initiate a revolution in communications. A similar opportunity exists today, but the technological challenges facing AEEs are more complex. The barriers to successful deployment are also more varied and substantial. As a result, the current opportunity is too big for any one organization. Success will require the cooperative efforts of a broad coalition of organizations.

Finding 1. A historic opportunity now exists to develop AEE technologies and systems that could revolutionize computer-based engineering processes, just as the Internet has revolutionized computer-based communications. This opportunity is too big for any one organization to realize on its own.

Recommendation 1. To take full advantage of the opportunity represented by AEEs, a government-industry-academia partnership should be formed. This partnership should foster the development of AEE technologies and systems in the following ways:

- Develop open architectures and functional specifications for AEEs to guide the development of broadly applicable, interoperable tools.
- Create specific plans for transitioning the results of research and development by government and academic organizations to the commercial software industry and/or software users (e.g., the aerospace or automotive industries), as appropriate.
- Develop an approach for resolving information management and organizational issues.

AEEs can reach their full potential only if many organizations are willing to use them, and the involvement of a broad partnership in the development of AEE technologies and systems would create equally broad benefits. For example, cooperation from other government agencies and industry is essential for NASA to achieve the objectives of the ISE functional initiative (see Table 2-1). However, it is not necessary for individual agencies, such as NASA, to await the formation of a broad partnership before moving in the direction suggested in Recommendation 1. In fact, NASA's actions could stimulate broad interest and demonstrate the mutual benefits of forming partnerships.

Recommendation 2. As part of its ongoing AEE research and development, NASA should draft a plan for creating a broad government-industry-academia partnership. In addition, to demonstrate the utility of partnerships on a small scale, NASA should charter a joint industry-academia-government advisory panel that focuses on interactions between NASA and outside organizations. This panel should periodically identify areas of overlap (1) between high-payoff requirements of external users and NASA's research and development capabilities, and (2) between the capabilities of external organizations and NASA's own requirements. This would facilitate technology transfer and allow NASA to focus its AEE research and development on the areas of greatest need.

Recommendation 2 is not intended to imply that NASA should necessarily take a leadership role in the national partnership described in Recommendation 1. However, NASA could get the process started by carrying out Recommendation 2. Once a national partnership is in place, individual agencies, corporations, and universities could take the lead in specialized areas consistent with their capabilities. In addition, subgroups could be formed to engage in mutual beneficial, collaborative efforts.

The findings and recommendations in the remainder of this chapter provide additional near-term guidance for achieving AEE requirements and benefits, overcoming the barriers to success, and assigning appropriate organizational roles. The Phase 2 report, which will be published separately, will address long-term actions.

The Statement of Task for this study directed the committee to pay particular attention to NASA and the aerospace industry. As a result, some findings and recommendations address issues specific to NASA and are meant primarily for NASA. In most cases, however, the committee determined that the issues relevant to NASA and the aerospace industry were also relevant to other organizations involved in the development and/or use of AEE technologies or systems, and most of the findings and recommendations are, therefore, directed to a broader audience.

REQUIREMENTS AND BENEFITS

The top-level AEE objectives identified by the committee encompass the primary requirements that AEEs should satisfy and the key benefits they will provide. These requirements are applicable to both industry and government, although the method of implementation will vary for different organizations and applications. Despite these variations, there are opportunities for organizations to benefit from joint solutions and from the lessons learned by others who have progressed farther with implementing AEE technologies.

Translating top-level objectives into specific, realistic program goals can be difficult, both for research organizations developing new AEE technologies and systems and for operational organizations planning to insert them into their design and manufacturing processes. One approach to AEE development is to identify areas where improved analytical capabilities are needed, to prioritize improvements in terms of their potential impact on key parameters (e.g., cost, schedule, or risk), to develop and integrate improved tools to achieve the highest priority objectives, and then to restructure organizational processes to take advantage of new capabilities, addressing cultural and procedural issues as they arise. A number of methods, such as QFD, can be used to facilitate the prioritization process.

Recommendation 3. Current AEE research and development is too diffuse and should be focused on the following top-level objectives:

- Enable complex new systems, products, and missions.
- Greatly reduce product development cycle time and costs.

In addition, AEE technology and system developers should devise a comprehensive, multifaceted implementation process that meets the following objectives:

- Lower technical, cultural, and educational barriers.
- Apply AEEs broadly across U.S. government, industry, and academia.

Finding 2. The top-level goals that NASA has established for the Intelligent Synthesis Environment functional initiative address important AEE requirements. However, given the resources that NASA plans to allocate to the initiative, the objectives of this initiative are overly ambitious. NASA plans to adjust the objectives accordingly.

Recommendation 4. NASA should establish an AEE "center of gravity" that is empowered to select the high-priority analyses and processes that will be developed, integrated, and deployed as a mission design system. To ensure success, the location, leadership, and staff of the center of gravity should be carefully selected to reflect the differing needs, capabilities, and perspectives of NASA's operational and research Centers. In addition, NASA should allocate resources for the ongoing maintenance of the mission design system and better coordinate related activities with outside organizations, in accordance with Recommendations 1 and 2.

BARRIERS

Finding 3. Efforts by industry and government to develop and deploy AEEs face significant barriers in the following areas:

- integration of tools, systems, and data
  - —lack of tool interoperability
  - —proliferation of tools
  - —existing investments in legacy systems
- information management
  - —proliferation of all types of information
  - —configuration-management issues
- cultural, management, and economic issues
  - —difficulty of justifying a strong corporate commitment to implementing AEE technologies or systems

  - lack of practical metrics for determining AEE effectiveness
  - unknowns concerning implementation costs
- education and training
  - training of the current workforce
  - education of the future workforce

The following sections contain specific recommendations related to these areas.

Integration of Tools, Systems, and Data

To be effective, AEEs must be constructed with a high degree of interoperability among all system components. However, despite steady evolution, state-of-the-art AEE tools are still mostly a collection of uncoupled or loosely coupled tools. Lack of interoperability is a major barrier to the efficient use of AEEs that warrants focused, concerted attention. However, a universal solution is not likely to be found in the near term, and interoperability issues are likely to remain a significant "cost of doing business." Interoperability issues should be prioritized and met head on to reduce this cost as quickly as possible. Long-term solutions will require continual pressure from user groups and the exploitation of new or enhanced information technologies, such as Internet-based tools.

The integration of advanced engineering and design tools has concentrated on and been successful in geometry, mechanical integration, and analysis. The use of computing to solve large, complex physical problems in areas such as weather, combustion, fluid dynamics, and aerodynamics has also been highly successful. Many complex products and missions, however, especially those related to aeronautics and space, are becoming increasingly dependent on synthesis and integration of software and other complex systems (e.g., avionics). To be effective in the largest number of applications, AEEs must include process-based models that are integrated with other AEE tools. These models should also integrate the capabilities and knowledge of the electronics and mechanical design communities to produce vehicles that effectively integrate electronics and mechanical systems.

Traditional methods of establishing software standards are not working because AEE technologies are advancing rapidly and involve many different organizations. In addition, not enough is being done to develop the most difficult analysis capabilities, such as predicting cost, risk, and manufacturability. Although goals such as CAD systems that are fully interoperable are worthwhile, they will be difficult to achieve, and AEE development should not be deferred because these ancillary goals have not been achieved. Instead, efforts should proceed in parallel in all key areas.

Recommendation 5. For AEEs to succeed, a practical approach must be developed for improving the interoperability of new product and process models, tools, and systems and linking them with legacy tools, systems, and data. Sponsors of AEE research and development should consider the integration of AEE product and process models, tools, data, and technologies related to software, avionics, manufacturing, operations, maintenance, economics, and other areas as a fundamental requirement.

Recommendation 6. Government agencies and other organizations with a large stake in the successful development of AEEs should interact more effectively with standards groups to facilitate the development of interoperable product and process models, tools, systems, and data, as well as open system architectures. Specific high-priority interoperating capabilities should be defined along with action plans, incentives, and schedules for establishing appropriate standards and achieving specified levels of interoperability.

Information Management

Most AEE R&D is focused on operational aspects, such as the development and integration of sophisticated tools and simulations. Supporting technologies, however, can be just as important. For example, automated tools and simulations will create a flood of data characterizing the results of simulated tests of new designs and design modifications. Automated data management systems will be necessary to maximize the amount of information that can be efficiently extracted from the data and minimize personnel requirements.

Finding 4. There is a lack of commonality in product and process descriptions within user organizations, among user organizations, and between users and suppliers. As a result, users must often customize commercially available tools before they can be used, which greatly reduces the cost effectiveness of new tools.

Recommendation 7. Corporate and government leaders should seize the opportunity to develop robust and flexible AEE tools for creating, managing, and assessing computer-generated data; presenting relevant data to operators clearly and efficiently; maintaining configuration-management records for products, processes, and resources; and storing appropriate data on a long-term basis.

Cultural, Management, and Economic Issues

Cultural, management, and economic issues often impede the implementation of new, technically advanced systems, such as AEEs. Issues include the diversity of cultures among different organizations and among different business units of the same company. In many cases, management is not committed to the implementation of AEE technologies because of uncertainties about costs, return on investment, when and how to insert AEE technologies into operational processes, the risk involved in deploying AEE technologies, and the availability of metrics for accurately predicting their effectiveness before implementation and measuring their effectiveness afterwards. Managing constant change, as vendors of AEE tools and technologies continually upgrade their products, is a daunting task. Resolving these and other issues will require a dedicated effort by organizations interested in developing or implementing AEE technologies or systems.

Many of the information technology tools currently used were designed without adequate regard for the cultural, psychological, and social aspects of the user environment. These tools have, therefore, not been as successful as traditional methods based on face-to-face interactions. Organizations may have to be restructured or flexible organizational structures created to foster a sense of purpose and belonging among geographically dispersed staff members.

Finding 5. Historically, not enough attention has been paid to the organizational, cultural, psychological, and social aspects of the user environment associated with AEE technologies.

Recommendation 8. AEEs should be integrated into the senior management culture of any organization that elects to make a major investment in developing or implementing AEE technologies or systems. Each organization should designate a "champion" with the responsibility, authority, and resources to achieve approved AEE objectives. The champion should be supported by a team of senior managers, technical experts (including human factors experts, social scientists, and psychologists), and other critical stakeholders (e.g., suppliers, subcontractors, and customers typically involved in major projects). Similar, subordinate teams should be assembled in major organizational elements or facilities involved in the AEE project. Guidance from these teams should be consistent with the organization's role in product development or mission operations and compatible with engineering practices already in place.

In the past, NASA has used its contracting authority to mandate the adoption of specific technologies. For example, NASTRAN[1] was created by a consortium of companies under contract to NASA in the early 1970s. NASA subsequently made copies of NASTRAN available to software developers, and several commercial versions were introduced. NASTRAN has been used extensively by automotive, aircraft, and spacecraft companies worldwide. The widespread adoption of NASTRAN was facilitated by the requirement that NASA contractors use NASTRAN in selected procurements.

Finding 6. Government agencies have frequently used contract provisions to influence the business practices of their contractors. This approach has also been used, on occasion, to influence engineering practices.

Recommendation 9. Government agencies involved in the acquisition of complex engineering systems should provide incentives for contractors to implement appropriate AEE technologies and systems and to document lessons learned. For example, AEE research and development funds could be used to provide contractual incentives for contractors to develop, test, demonstrate, implement, and/or validate AEE technologies and systems as part of major procurements. These incentives should target both technical and nontechnical (i.e., cultural, psychological, and social) aspects of AEE development and implementation.

The committee was concerned about apparently inadequate coordination among AEE-related activities at NASA's operational and research Centers. As an organization, NASA has yet to develop a shared vision or common motivation for AEEs. The committee also believes that NASA should develop a greater appreciation for organizational, behavioral, and other nontechnological barriers to fielding new AEE technologies successfully.

Recommendation 10. NASA should define an agency-wide plan for the development and implementation of comprehensive, improved engineering processes, practices, and technologies. The NASA-wide teams directing the Intelligent Synthesis Environment functional initiative should be consolidated and strengthened to improve their ability to perform the following functions:

- Define distinct AEE requirements and goals for NASA operational and research Centers.
- Ensure that NASA's AEE activities take advantage of commercially available tools and systems to avoid duplication of effort.
- Overcome cultural barriers within NASA so that new AEE technologies and systems will be accepted and used.
- Disseminate AEE plans, information, and tools at all levels of NASA.
- Provide centralized oversight of AEE research and development conducted by NASA.

Education and Training

AEEs will fulfill their potential only if users develop and maintain proficiency. For example, if universities graduate engineers who are not familiar with AEE technologies or the benefits they can provide, they will add to the barriers industry must overcome. On the other hand, if universities create a new cadre of AEE-knowledgeable engineers, they will

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[1] The name NASTRAN originated as an abbreviation for *NA*SA *str*uctural *an*alysis.

carry that knowledge with them and facilitate the adoption of AEE technologies by industry. This may be difficult for universities to do, however, because AEE technologies are advancing quickly, and tools are updated frequently. Current university curricula are mostly oriented towards a single discipline; interdisciplinary projects are rare—particularly in the capstone design projects that all engineering disciplines require of their undergraduates. AEEs are interdisciplinary by nature and, their greatest potential is for solving interdisciplinary problems.

Sophisticated AEE tools have a steep learning curve, which is a significant barrier to their implementation by industry or government. Training (e.g., helping students to become proficient with particular software packages) has not been, and should not be, the mission of undergraduate university curricula. However, AEE-related training might be a legitimate component of continuing education programs, distance education programs, five-year undergraduate engineering programs, or government programs, such as NASA's cooperative education program for engineering students. Training by specialized technical schools, as well as community colleges, could also reduce the training barrier.

Recommendation 11. An advisory panel with representatives from industry, universities, the National Science Foundation, NASA Centers, and other government agencies and laboratories should be convened by NASA or some other federal agency involved in AEE research and development. The panel should define incentives for accelerating the incorporation of AEE technologies into the engineering curriculum, define the basic elements that would comprise a suitable AEE experience for students, and specify resource needs.

ORGANIZATIONAL ROLES

Developing and implementing AEEs with broad applicability is a daunting challenge that will require the best efforts of industry, government, and academia. Although competitive concerns preclude complete openness in industry, a high degree of interorganizational cooperation and coordination is both desirable and feasible to avoid duplication of effort and to enable organizations to focus their energy on areas consistent with their missions and expertise.

Recommendation 12. AEEs should use commercially available tools as much as possible. In general, the development of application-specific tools should be left to industry. Government agencies should not develop customized tools that duplicate the capabilities of commercially available tools. If available tools are inadequate, government agencies should consider providing incentives for the development of improved, broadly applicable tools by commercial software vendors instead of developing specialized tools themselves. Government agencies should take the following actions to support the development of broadly applicable AEE technologies, systems, and practices:

- Improve generic methodologies and automated tools for integrating existing tools and tools that will be developed in the future.
- Develop better models of specific physical processes that more accurately portray what happens in the real world and quantify uncertainties in model outputs.
- Identify gaps in the capabilities of currently available tools and support the development of tools that address those gaps, preferably by providing incentives for commercial software vendors to develop broadly applicable tools.
- Develop test beds that simulate user environments with high fidelity for validating the applicability and utility of new tools and systems.
- Develop methods to predict the future performance of AEE technologies and systems in specific applications and, once implemented, to measure their success in reaching specified goals.
- Explore the utility of engineering design theory as a tool for guiding the development of AEE technologies and systems.
- Use contracting requirements to encourage contractors to adopt available AEE technologies and systems, as appropriate.
- Address issues related to the organizational, cultural, psychological, and social aspects of the user environment.
- Provide incentives for the creation of government-industry-academia partnerships to foster the development of AEE technologies and systems

AEEs are important to NASA because of their potential to enable the accomplishment of unique aeronautics and space missions. AEE R&D is also consistent with the National Aeronautics and Space Act of 1958. As currently amended, this statute includes the requirement that NASA "contribute materially to . . . the most effective utilization of the scientific and engineering resources of the United States."

Recommendation 13. NASA has many opportunities to achieve its objectives by leveraging the results of long-term AEE research and development by other organizations in government, industry, and academia. NASA also has opportunities to conduct AEE research and development that would be of value to other organizations. To maximize the effectiveness of both, NASA must improve its understanding of the capabilities and requirements of external organizations. NASA should convene a standing, joint industry-academia-government advisory panel (see Recommendation 2) to facilitate technology transfer and enable NASA to focus its AEE research and development on the areas of greatest need.

Appendices

Appendix A
Statement of Task

The National Research Council and the National Academy of Engineering will conduct a two-phase study of AEEs. The study will assess the current and future national context within which NASA's plans must fit. Phase 1 will focus on the near-term, especially the identification and assessment of needs, directions, and barriers during the next 5 years for the development and implementation of AEEs in a national framework. Phase 2 will focus on the far term and build on the results of Phase 1 to expand the assessment to the 5- to 15-year vision for incorporating AEE technologies and systems into both the current and future engineering workforces. Workshops may be used in both Phase 1 and Phase 2 to maximize participation by government, industry, and the academic community.

PHASE 1

The Phase 1 study will identify steps NASA can take in the near term to enhance the development of AEE technologies and systems with broad application in industry, government, and academia. Focusing on the near term, Phase 1 will complete the following specific tasks:

1. Develop an understanding of NASA's long-term vision of AEE, capabilities, and tools associated with the current state of the art in engineering environments, and near-term advances in engineering environments.
2. Conduct an independent assessment of requirements for, alternative approaches to, and applications of AEEs to aerospace engineering, considering both near- and far-term objectives.
3. At a high level, explore the potential payoffs of AEEs on a national scale, emphasizing the relationships between aerospace engineering and other elements of the national engineering scene and identifying the necessary conditions for achieving these payoffs.
4. Evaluate how AEE technologies relate to the development of relevant technical standards (e.g., collaborative, distributed computing and software systems interoperability) and engineering economic assessments (e.g., cost and risk assessments).
5. Identify the following:

    - cultural and technical barriers (e.g., certification requirements, software and hardware incompatibilities, proprietary restrictions imposed by original equipment manufacturers, standards, policies, laws, etc.) to collaboration among the government, the aerospace industry, academia, and others for transferring AEE tools and methods from the development stage to public practice
    - opportunities that may be created by AEEs
    - needs for education and training

6. Recommend an approach for NASA to enable a state-of-the-art engineering environment capability that is compatible with other government, industry, and university programs and contributes to the overall effort to engender a broadly applicable, technology-based, engineering framework.
7. Prepare a report summarizing the key results of Phase 1 (i.e., the committee's Phase 1 report).

PHASE 2

As Phase 1 is nearing completion, NASA, the National Research Council, and the National Academy of Engineering will determine the feasibility of proceeding with Phase 2. Expanding on the results of Phase 1, Phase 2 will focus on assessing the long-term potential and feasibility of developing AEE technologies and systems that would foster increased creativity in the design process, improve processes for multidisciplinary integration, facilitate the interactive examination of new ideas, improve evaluations of technology, etc. Specific tasks are as follows:

1. Building on the recommendations and conclusions of Phase 1, evaluate the potential for AEEs to contribute to NASA's long-term goal of "engendering a revolution in the engineering culture" and the benefits that achieving this goal would produce.
2. At a high level, understand and assess the potential payoffs of AEEs on a national scale.
3. With regard to implementation of AEE capabilities and practices, examine broad issues such as those associated with infrastructure changes, clarity of interdisciplinary communications, and technology transfer and acceptance. Consider approaches for achieving the AEE vision, including the potential role of government, industry, academic, and professional organizations in resolving these issues.
4. Identify the key elements of long-term educational and training strategies that government, industry, and academia could adopt to foster acceptance and application of AEE technologies and systems by the existing and future workforces.
5. Prepare a report summarizing the key results of Phase 2 (i.e., the committee's Phase 2 report).

Appendix B
Biographical Sketches of Committee Members

Robert E. Deemer (chair) has 24 years of industry experience in the fields of simulation modeling, virtual prototyping, collaborative engineering, computer design, product data management, enterprise resource management, and integrated network systems design. He has masters degrees in computer science, management science, business administration, and philosophy from California State University, Colorado Technical College, Pepperdine University and California State University, respectively. He also has undergraduate degrees in engineering, software design, economics, and English literature. Currently, Mr. Deemer is the strategic technology manager for Lockheed Martin Astronautics (LMA) and an adjunct faculty member at Regis University, the University of Colorado, and Colorado State University, where he teaches graduate classes in future technology, international science and technology, and managing change. He helped establish and continues to be involved in using the strategic technology test bed at LMA's Spacecraft Technology Center to support the development of advanced engineering and manufacturing capabilities.

Tora K. Bikson, a senior behavioral scientist at RAND Corporation since 1976, is recognized for her research on the introduction of advanced communication and information technologies and their effects in varied contexts. She recently completed a project to define organizational needs and best practices for creating, managing, and distributing electronic documents (including compound, multimedia, and interactive documents) among United Nations organizations based in Europe, North America, and South America. In projects for other clients, such as the National Science Foundation, the World Bank, the Organization for Economic Co-operation and Development, and the Markle Foundation, she has addressed factors that affect the successful institutionalization of new interactive technologies in ongoing communities of practice, how these innovative media influence intraorganizational and interorganizational structures and group processes, their impact on task performance and social outcomes, and their policy implications. Dr. Bikson has co-authored three recent books addressing these issues: *Teams and Technology* (Harvard Business School Press, 1996), *Universal Access to E-mail: Feasibility and Societal Implications* (RAND, 1995), and *Preserving the Present* (Sdu Publishers, 1993). Her work has also appeared in numerous journals and book chapters. Dr. Bikson holds Ph.D. degrees in philosophy (University of Missouri) and psychology (University of California, Los Angeles).

Robert A. Davis is the retired corporate vice president of engineering for The Boeing Company. His 41-year career started in 1958 with the introduction of the commercial 707 series of aircraft. He has been associated with all Boeing jet transports in both engineering and management capacities. He led the modernization program for the 747 in 1985 as chief project engineer and became engineering vice president for all commercial airplanes in 1991. He participated in the 777 program, which worked exclusively with computer-aided design and has become an industry benchmark. Mr. Davis became corporate vice president of engineering in 1994. He is a registered professional engineer with a B.S. degree from the University of British Columbia and an M.S. degree from the University of Washington. He is a fellow of the American Institute for Aeronautics and Astronautics and the Royal Aeronautical Society and president of the International Federation of Airworthiness, which is headquartered in the U.K.; a member of General Motors Science Advisory Committee; and a member of the National Research Council's Board of Engineering and Manufacturing Design.

Richard T. Kouzes is the director of program development for science and engineering and professor of physics at West Virginia University (WVU). He is responsible for facilitating the growth of research and economic development programs at WVU in the physical and biological sciences and engineering. His current research is in the field of collaborative computing for the enabling of scientific research independent of geographical location. Before moving to WVU, Dr. Kouzes was a staff scientist at the Department of Energy's (DOE's) Pacific Northwest National Laboratory (PPNL) and a principle investigator for the DOE's Distributed Collaboratory Experimental Program initiative. His research program at PPNL was in computer-assisted cooperative work, advanced data acquisition system development, neural network applications, and precision atomic mass measurements. Before going to PPNL, Dr. Kouzes was a senior research physicist and lecturer at Princeton University, where for 15 years he was a leading researcher in solar neutrino and nuclear structure experimentation. Dr. Kouzes earned his Ph.D. in physics from Princeton University in 1974 and did postdoctoral work at Indiana University. He is a founder and past chair of the Institute of Electrical and Electronics Engineers Committee for Computer Applications in Nuclear and Plasma Sciences and the author of more than 70 refereed papers.

R. Bowen Loftin holds a B.S. in physics from Texas A&M University and an M.A. and a Ph.D. in physics from Rice University. He is a professor of computer science and the director of the Virtual Environment Technology Laboratory at the University of Houston and a professor of physics at the University of Houston–Downtown. Dr. Loftin was previously on the faculty of Texas A&M University at Galveston and held a post-doctoral appointment in the Department of Mechanical Engineering at Rice University. Since 1983, Dr. Loftin, his students, and coworkers have been exploring the application of advanced software technologies, such as artificial intelligence and interactive, three-dimensional computer graphics, to the development of training systems. Dr. Loftin is a consultant to both industry and government in the area of advanced training technologies and scientific/engineering data visualization. He serves on advisory committees and panels sponsored by numerous government and professional organizations. Awards received by Dr. Loftin include the University of Houston–Downtown Award for Excellence in Teaching and Service, the American Association of Artificial Intelligence Award for an innovative application of artificial intelligence, NASA's Space Act Award, the NASA Public Service Medal, and the 1995 NASA Invention of the Year Award. He is the author or co-author of more than one hundred technical publications.

James Maniscalco is vice president, engineering and technology for TRW Automotive. As the chief technical officer for TRW's automotive business, Dr. Maniscalco is responsible for strategic technology planning and global development of new products and manufacturing technology. Since joining TRW in 1979, Dr. Maniscalco has held positions of increasing responsibility in TRW's energy, defense, and automotive businesses. In 1990, TRW formed the Center for Automotive Technology, and Dr. Maniscalco was selected to help focus TRW's space and defense capabilities on the global automotive business. In this assignment, he developed new products, such as electrically powered steering and actively controlled suspension. His international experience includes overseeing technology development and leading new product launches for TRW's worldwide automotive operations. Dr. Maniscalco graduated from the U.S. Naval Academy with a B. S. degree. He was selected as a Fulbright scholar and studied physics at the University of Turin in Italy. Dr. Maniscalco received his M.S. and Ph.D. in engineering from Purdue University. He is the author of more than 40 journal publications on lasers, accelerators, and nuclear fusion. Dr. Maniscalco is a member of the Society of Automotive Engineers.

Robert J. Santoro is the director of the Propulsion Engineering Research Center and a professor of mechanical engineering at the Pennsylvania State University. He received a Ph.D. in physics from Boston College, where he also held a one-year position as a lecturer. He then joined the Fuels Research Laboratory in the Department of Mechanical and Aerospace Engineering at Princeton University as a research engineer. His research there emphasized the study of hydrocarbon oxidation and flame spread over liquids and solids. He left Princeton University to join the National Bureau of Standards (now the National Institute of Standards and Technology) in Washington, D.C., where he conducted combustion research until his departure in August 1986. Dr. Santoro was awarded the U.S. Department of Commerce Silver Medal in 1986 for his research on particle diagnostics and soot formation. He is a member of the Combustion Institute, the American Chemical Society, the American Institute of Aeronautical and Astronautics, and the American Physical Society. His research interests include rocket and gas turbine engines, soot formation in flames, liquid spray combustion, laser diagnostics, diesel engine combustion, combustion instability, chemical kinetics, and materials processing. Dr. Santoro collaborates with NASA and the rocket industry on the development of advanced space transportation technology.

Daniel P. Schrage has been a professor in the School of Aerospace Engineering at the Georgia Institute of Technology since 1984, director of the Center of Excellence in Rotorcraft Technology (CERT) since 1986, and codirector of the Center for Aerospace Systems Analysis (CASA) since 1998. Dr. Schrage has served as a member of the Army Science Board, the National Research Council Air Force Studies Board, and NASA's Aeronautics Research and Technology Committees. Dr. Schrage has also served on the Industry Affordability Executive Committee/Task Force of the National Center for Advanced Technologies, which has been industry's voice to the Office of the Secretary of Defense on affordability issues. Dr. Schrage has led much of the executive committee's work on integrated product and process development (IPPD), and the IPPD methodology he developed is being used by the Navy Acquisition Reform Office in much of its IPPD training. Prior to joining the Georgia Tech faculty, Dr. Schrage served for 10 years as an engineer, manager, and senior executive with the U.S. Army Aviation Systems Command. He was the chief of the Structures and Aeromechanics Division and served on the source selection evaluation boards for the AH-64 Apache, UH-60 Black Hawk, and OH-58D Kiowa helicopters. Dr. Schrage led the concept development of the LHX, which is now the RAH-66 Comanche helicoptor

Allan Sherman is the director of advanced development programs for the Space and Strategic Missiles Sector, Lockheed Martin Corporation. He has 37 years of aerospace experience, particularly in technology development and the design, development, and testing of space systems. Prior to joining Lockheed Martin in 1997, Dr. Sherman was the director of engineering at NASA's Goddard Space Flight Center. During his 30 years with NASA, he was awarded the Exceptional Engineering Achievement, Outstanding Leadership, and Distinguished Service awards. Prior to his career in NASA, he held engineering positions with Pratt and Whitney and Aerojet-General corporations. Dr. Sherman earned a B.S. and M.S. in mechanical engineering from Cornell University and a Ph.D. in aerospace engineering from the University of Maryland. He chairs the Industrial Advisory Board for the Aerospace Engineering Department at the University of Maryland.

John Sullivan has been on the faculty of Purdue University since 1975, where he is currently a professor and the head of the School of Astronautics and Aeronautics. His research interests include laser instrumentation (e.g., laser Doppler velocimeters and particle image velocimeters) luminescent sensors for temperature and pressure measurements, and experimental aerodynamics, especially with regard to the comparison of experimental data and the results of computational analysis. Dr. Sullivan has received the John Fluke Award for Excellence in Laboratory Instruction. He holds a B.S. degree in mechanical and aerospace sciences from the University of Rochester and M.S. and Sc.D. degrees in aeronautical engineering from the Massachusetts Institute of Technology.

Gordon Willis is chief engineer of automatic transmissions, powertrain operations for the Ford Motor Company. He joined Ford in 1976 and served in a number of research positions related to computer-aided engineering (CAE) and power train control. In 1987, he was named North American automotive operations CAE manager, a position he held for two years before becoming product and manufacturing systems director. He was the chassis chief engineer from 1992 to 1994. Prior to his current assignment, Mr. Willis was vehicle chief engineer in Europe. He holds B.S. and M.S. degrees in mechanical engineering from the Massachusetts Institute of Technology and an M.B.A. from the University of Michigan.

Michael J. Zyda is a professor in the Department of Computer Science at the Naval Postgraduate School (NPS), Monterey, California. Dr. Zyda is also the Academic Associate Chair of the NPS Modeling, Virtual Environments, and Simulation Academic Group. His research interests include computer graphics; large-scale, networked three-dimensional virtual environments; computer-generated characters; video production; entertainment-defense collaboration; and modeling and simulation. Dr. Zyda was a member of the National Research Council's Committee on Virtual Reality Research and Development and the chair of the Committee on Modeling and Simulation: Linking Entertainment and Defense. He is the senior editor for virtual environments for the MIT Press quarterly, *Presence*, a journal of teleoperation and virtual environments. Dr. Zyda is a member of the Editorial Advisory Board of *Computers and Graphics.* Professor Zyda is also a member of the Technical Advisory Board of the Fraunhofer Center for Research in Computer Graphics, Providence, Rhode Island. He received a B.A. in bioengineering from the University of California, San Diego, an M.S. in computer science from the University of Massachusetts, Amherst, and a D.Sc. in computer science from Washington University, St. Louis.

Dianne S. Wiley, Aeronautics and Space Engineering Board liaison to the Advanced Engineering Environments Committee, is currently manager of materials and processes technology in the Integrated Systems and Aerostructures Sector of Northrop Grumman. She is responsible for research and development in materials and processes and technology transition to production. Dr. Wiley has been with Northrop for 20 years. Previously, as manager of airframe technology in the Business and Advanced Systems Development group of Northrop Grumman, she directed five departments, performing advanced development and technology transition in structural engineering, materials and processes, and manufacturing technology. During this time, she was responsible for transitioning airframe core technologies into three new business areas (space, biomedicine, and surface ships) to offset declines in traditional business. Previously, as a senior technical specialist on the B-2 program, Dr. Wiley was responsible for developing and implementing innovative structural solutions to ensure the structural integrity of the B-2 aircraft. Dr. Wiley's 24 years of technical experience include durability and damage tolerance, advanced composites (organic and ceramic), high-temperature structures, smart structures, low-observable structures, concurrent engineering, and rapid prototyping.

Appendix C
Participants in Committee Meetings

The full committee met three times between July and December 1998. Many smaller meetings were attended by one or more committee members and representatives of public and private organizations involved in the development and/or use of AEEs. The small group meetings were part of the committee's information-gathering process. Outside participants are listed below, grouped by organization:

3Com Corporation
Paul Hartung

The Boeing Company
Scott Pierce

Catalina Research, Inc.
Michael Bonato
Jay Perry
Larry Scally

Deneb Robotics
Robert Brown

Cyra Technologies, Inc.
Lawrence Schrank

Engineering Animation, Inc.
Chris Borman
Bill Boswell
Lance Conard
Michael Jablo
John Langmead

Ford Motor Company
Wayne Hamann
Dick Radtke
Richard Riff

Iowa State University
James Bernard
Thomas Ligouri
Theodore Okiishi

Lockheed Martin Astronautics
Scott Curtis

Lockheed Martin Tactical Aircraft Systems
Woody Sconyers

Massachusetts Institute of Technology
Joseph Baclawski
Edward Crawley

Muse Technologies, Inc.
Doug Harless
Creves Maples

NASA Ames Research Center
Bill Feiereisen
Jack Hansen
Brian Williams
Steve Zornetzer

NASA Headquarters
Randy Connell
Joe Hale
Murray Hirschbein
Dan Mulville
Sam Venneri

NASA Jet Propulsion Laboratory
John Baker
Ken Hicks
Satish Khanna
Pat Liggett

John Peterson
Mike Sander
Steve Wall

NASA Johnson Space Center
Michael Conroy
Hector Delgado
Jim Jaax
Nick Lance
Shelby Lawson
Leonard Nicholson
Alex Pope
Doug Cook

NASA Langley Research Center
Doug Craig
Michelle Garn
Ronnie Gillian
Brantley Hanks
Jerry Housner
John Malone
Don Monell
Arlene Moore
Betty Plentovich

Parametric Technology Corporation
Eric Braun

Jane Thompson
Steve Walske

The Rational Corporation
James Rumbaugh

Technology Builders, Inc.
Larry Boldt

University of California, Berkeley
Lon Addison

University of Colorado
Enid Ablowitz
Paul Bauman
Elizabeth Bradley
William Emery
Carbel Farhat
Dale Lawrence
Michael Lightner
Lee Peterson

University of Houston
Patricia Hyde

University of Utah
Richard Riesenfeld

Acronyms

AEE	advanced engineering environment
CAD	computer-aided design
CAE	computer-aided engineering
CAM	computer-aided manufacturing
CATIA	Computer-Aided Three-Dimensional Interactive Application (a CAD program)
CORBA	common object request broker architecture
CSCW	computer-supported cooperative work
DARPA	Defense Advanced Research Projects Agency
I-DEAS	Integrated Design Engineering Analysis Software (a CAD program)
ISE	Intelligent Synthesis Environment
NASA	National Aeronautics and Space Administration
QFD	quality function deployment
R&D	research and development
SAVE	Simulation, Assessment, and Validation Environment (project)