RETOOLING MANUFACTURING

Bridging Design, Materials, and Production

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

RETOOLING MANUFACTURING
BRIDGING DESIGN, MATERIALS, AND PRODUCTION

Committee on Bridging Design and Manufacturing
Board on Manufacturing and Engineering Design
National Materials Advisory Board
Division on Engineering and Physical Sciences

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

THE NATIONAL ACADEMIES PRESS
Washington, D.C.
www.nap.edu

THE NATIONAL ACADEMIES PRESS 500 Fifth Street, N.W. Washington, DC 20001

This study was supported by Contract DOD-4996 between the National Academy of Sciences and the Department of Defense. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of the organizations or agencies that provided support for the project.

International Standard Book Number 0-309-09266-3 (Book)
International Standard Book Number 0-309-53341-4 (PDF)

Available in limited supply from:

Board on Manufacturing and Engineering Design
500 Fifth Street, N.W.
Washington, DC 20001
bmed@nas.edu
http://www.nas.edu/bmed

Additional copies of this report are available from the National Academies Press, 500 Fifth Street, N.W., Lockbox 285, Washington, DC 20055; (800) 624-6242 or (202) 334-3313 (in the Washington metropolitan area); Internet, http://www.nap.edu

Printed in the United States of America

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

The **National Academy of Sciences** is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. Upon the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Bruce M. Alberts is president of the National Academy of Sciences.

The **National Academy of Engineering** was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. Wm. A. Wulf is president of the National Academy of Engineering.

The **Institute of Medicine** was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, upon its own initiative, to identify issues of medical care, research, and education. Dr. Harvey V. Fineberg is president of the Institute of Medicine.

The **National Research Council** was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both Academies and the Institute of Medicine. Dr. Bruce M. Alberts and Dr. Wm. A. Wulf are chair and vice chair, respectively, of the National Research Council.

www.national-academies.org

COMMITTEE ON BRIDGING DESIGN AND MANUFACTURING

R. BYRON PIPES, University of Akron, Ohio, *Chair*
REZA ABBASCHIAN, University of Florida, Gainesville
ERIK ANTONSSON, California Institute of Technology, Pasadena
THOMAS S. BABIN, Motorola Advanced Technology Center, Schaumburg, Illinois
BRUCE BOARDMAN, John Deere Technology Center, Moline, Illinois
TIMOTHY J. CONSIDINE, Pennsylvania State University, University Park
JONATHAN DANTZIG, University of Illinois, Urbana
MARK GERSH, Lockheed Martin Space Systems Company, Sunnyvale, California
GEORGE T. (RUSTY) GRAY III, Los Alamos National Laboratory, New Mexico
ELIZABETH A. HOLM, Sandia National Laboratories, Albuquerque, New Mexico
DAVID A. KOSHIBA, The Boeing Company, St. Louis, Missouri
MORRIS H. MORGAN III, Hampton University, Virginia
DANIEL E. WHITNEY, Massachusetts Institute of Technology, Cambridge

Staff

ARUL MOZHI, Study Director
EMILY ANN MEYER, Research Associate
LAURA TOTH, Senior Project Assistant

BOARD ON MANUFACTURING AND ENGINEERING DESIGN

PAMELA A. DREW, The Boeing Company, Seattle, Washington, *Chair*
CAROL L.J. ADKINS, Sandia National Laboratories, Albuquerque, New Mexico
GREGORY AUNER, Wayne State University, Detroit, Michigan
THOMAS W. EAGAR, Massachusetts Institute of Technology, Cambridge
ROBERT E. FONTANA, JR., Hitachi Global Storage Technologies, San Jose, California
PAUL B. GERMERAAD, Intellectual Assets, Inc., Saratoga, California
ROBERT M. HATHAWAY, Oshkosh Truck Corporation, Oshkosh, Wisconsin
RICHARD L. KEGG, Milacron, Inc. (retired), Cincinnati, Ohio
PRADEEP K. KHOSLA, Carnegie Mellon University, Pittsburgh, Pennsylvania
JAY LEE, University of Wisconsin, Milwaukee
DIANA L. LONG, Robert C. Byrd Institute for Flexible Manufacturing, South Charleston, West Virginia
JAMES MATTICE, Universal Technology Corporation, Dayton, Ohio
MANISH MEHTA, National Center for Manufacturing Sciences, Ann Arbor, Michigan
ANGELO M. NINIVAGGI, JR., Plexus, Nampa, Idaho
JAMES B. O'DWYER, PPG Industries, Allison Park, Pennsylvania
HERSCHEL H. REESE, Dow Corning Corporation, Midland, Michigan
H.M. REININGA, Rockwell Collins, Cedar Rapids, Iowa
LAWRENCE RHOADES, Extrude Hone Corporation, Irwin, Pennsylvania
JAMES B. RICE, JR., Massachusetts Institute of Technology, Cambridge
ALFONSO VELOSA III, Gartner, Inc., Tucson, Arizona
JACK WHITE, Altarum, Ann Arbor, Michigan
JOEL SAMUEL YUDKEN, AFL–CIO, Washington, D.C.

Staff

TONI MARECHAUX, Director

NATIONAL MATERIALS ADVISORY BOARD

JULIA M. PHILLIPS, Sandia National Laboratories, Albuquerque, New Mexico. *Chair*
JOHN ALLISON, Ford Research Laboratories, Dearborn, Michigan
PAUL BECHER, Oak Ridge National Laboratory, Tennessee
BARBARA D. BOYAN, Georgia Institute of Technology, Atlanta
DIANNE CHONG, The Boeing Company, St. Louis, Missouri
FIONA DOYLE, University of California, Berkeley
GARY FISCHMAN, Biomedical Applications of Materials Consultant, Palatine, Illinois
KATHARINE G. FRASE, IBM, Hopewell Junction, New York
HAMISH L. FRASER, Ohio State University, Columbus
JOHN J. GASSNER, U.S. Army Natick Soldier Center, Massachusetts
THOMAS S. HARTWICK, TRW (retired), Snohomish, Washington
ARTHUR H. HEUER, Case Western Reserve University, Cleveland, Ohio
ELIZABETH HOLM, Sandia National Laboratories, Albuquerque, New Mexico
FRANK E. KARASZ, University of Massachusetts, Amherst
SHEILA F. KIA, General Motors Research and Development Center, Warren, Michigan
CONILEE G. KIRKPATRICK, HRL Laboratories, Malibu, California
ENRIQUE J. LAVERNIA, University of California, Davis
TERRY LOWE, Los Alamos National Laboratory, New Mexico
HENRY J. RACK, Clemson University, Clemson, South Carolina
LINDA SCHADLER, Rensselaer Polytechnic Institute, Troy, New York
JAMES C. SEFERIS, University of Washington, Seattle
T.S. SUDARSHAN, Materials Modification, Inc., Fairfax, Virginia
JULIA WEERTMAN, Northwestern University, Evanston, Illinois

Staff

TONI MARECHAUX, Director

Preface

The Department of Defense, having identified gaps in the communication and feedback processes between design and manufacturing of materiel, requested that the National Research Council conduct a study to develop and define a coherent framework for bridging these gaps through data management, modeling, and simulation. This framework is intended to guide investment decisions in basic research to create better modes and methods of communication and collaboration between the various groups involved in bringing complex products through the design and testing process and into production. The focus of the committee's effort was complex systems composed of a large number of discrete mechanical parts. While the charge to the Committee on Bridging Design and Manufacturing was to concentrate on the research aspects of design and manufacturing, the committee recognizes that bridging the various domains involved will require substantial cultural and organizational changes as well. The committee was charged to:

- Develop a flow diagram to illustrate dependencies and interactions of material data and process models needed to fully characterize virtual manufacturing. This flow diagram may encompass databases and models to characterize material properties; characterize processes; describe design tools; describe simulation tools; characterize life-cycle behavior; describe how products perform in service; describe how a product interacts with its environment; and describe external constraints and objectives.
- Demonstrate, through case studies, generalized practice, or both, how the product design and realization cycle can be made more efficient through this simulation process.
- Analyze what basic research and development on processes, databases, models, sensors, controls, and other tools are most needed to implement a strategy for product realization. Identify critical roadblocks in the access to knowledge, in the availability of knowledge, in the understanding of process, in the ability to describe process, and in other areas, including gaps in knowledge, that currently limit the success of virtual prototyping and manufacturing.
- Describe any tools that currently exist and can be applied to the issue today. Illustrate how these models and databases might be tested for robustness and rigor.

The committee (see Appendix A for members' biographies) conducted two information-gathering workshops and received presentations from the Department of Defense, the National Science Foundation, the National Institute of Standards and Technology, the Department of

Energy national laboratories, the National Aeronautics and Space Administration's Jet Propulsion Laboratory, and other academic and industrial organizations. The committee also conducted a site visit to the Detroit area to gather information on the automotive industry's best practices for closing the design-to-manufacturing gap. The committee received additional presentations at two subsequent meetings (see Appendix B). During the course of its work, the committee drew information from past National Research Council reports, including the following: *Modeling and Simulation in Manufacturing and Defense Systems Acquisition: Pathways to Success* (2002), *Equipping Tomorrow's Military Force: Integration of Commercial and Military Manufacturing in 2010 and Beyond* (2002), *Design in the New Millennium: Advanced Engineering Environments* (2000), *Defense Manufacturing in 2010 and Beyond: Meeting the Changing Needs of National Defense* (1999), and *Visionary Manufacturing Challenges for 2020* (1998).

The scope of this study was broad, and the committee is indebted to the meeting speakers (listed in Appendix B) who took the time to share their knowledge and insights. We also thank the meeting participants, including the DoD study sponsor, John Hopps, Deputy Director, Defense Research and Engineering /Deputy Under Secretary of Defense (Laboratories and Basic Sciences),[1] and the government liaisons (Lewis Sloter, Office of the Deputy Under Secretary of Defense—Science and Technology; Daniel Cundiff, Office of Under Secretary of Defense—Advanced Systems and Concepts; Delcie R. Durham, National Science Foundation; Kevin Jurrens, National Institute of Standards and Technology; Leo Plonsky, Office of Naval Research; Walter Roy, Army Research Laboratory; Charles Wagner, Air Force Research Laboratory; and Steven Wall, Jet Propulsion Laboratory). The committee acknowledges and appreciates input on cost analysis and life-cycle costing from Peter Sandborn, Department of Mechanical Engineering, University of Maryland, College Park, that helped to clarify the section "Systems Engineering Tools" in Chapter 3. The committee also greatly appreciates the support and assistance of National Research Council staff members Arul Mozhi, Emily Ann Meyer, Marta Vornbrock, and Laura Toth during its conduct of this study and development of this report.

The committee notes that mention of product and company names is for purposes of illustration only and should not be construed as an endorsement by either the committee or the institution.

Chapter 1 gives an overview of the history and status of the topic and explains the objectives of this report. Chapter 2 describes the framework for virtual design and manufacturing. Chapter 3 describes the tools that are part of this framework. Chapter 4 discusses the economic dimension of this framework, and Chapter 5 discusses the barriers to its implementation in DoD acquisition. Finally, Chapter 6 provides the study summary, recommendations, and research needed to implement the virtual design and manufacturing framework.

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's (NRC) Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its 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 review comments and draft manuscript remain confidential to protect the integrity of the deliberative process.

The authors wish to thank the following individuals for their participation in the review of this report: Robert W. Bower, University of California–Davis; Darek Ceglarek, University of Wisconsin–Madison; Thomas W. Eagar, Massachusetts Institute of Technology; Robert E.

---

[1] It is with deep regret and sorrow that the committee notes that John H. Hopps, Jr., passed away unexpectedly on May 14, 2004.

Fontana, Jr., Hitachi Global Storage Technologies; Hamish L. Fraser, Ohio State University; Allen C. Haggerty, The Boeing Company (retired); Winston Knight, University of Rhode Island; James F. Lardner, Deere & Company (retired); Prasad Mangalaramanan, Dana Corporation; Mikel D. Petty, Old Dominion University; Michael L. Philpott, University of Illinois, Urbana–Champaign; Subbiah Ramalingam, University of Minnesota; and John Sullivan, Ford Motor Company.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions and recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by George Dieter, University of Maryland. Appointed by the NRC, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

The following individuals also greatly assisted the work of the committee through their participation in many of the committee's activities as liaisons to the NRC boards that initiated the study: Richard L. Kegg, Milacron, Inc. (retired), Cincinnati, Ohio, acted as liaison to the Board on Manufacturing and Engineering Design, and John Allison, Ford Motor Company, Dearborn, Michigan, acted as liaison to the National Materials Advisory Board.

R. Byron Pipes, *Chair*
Committee on Bridging Design and Manufacturing

Dedicated to the memory of

John H. Hopps, Jr.
(1939-2004)

who epitomized the spirit of discovery
in his distinguished career as a scientist, educator, and administrator.
He answered the call to public service and we all benefited.

Contents

APPENDIXES

Executive Summary

The difficulty of bringing a complex product to market, or a complex weapon system to the warfighter, in a short time and at reasonable cost has long been a concern that will become more acute in the future. The production process has been aided by the introduction, beginning in the mid-1990s, of increasingly sophisticated information technology tools in the United States. The creation and widespread use of new information technology promise to enhance the process of communication between customers, engineers, and manufacturers.

One of the ultimate goals of these improved tools and strengthened communication is to provide methods and processes for collaboration that will link groups involved in the various stages of design and manufacturing. In many cases today, designers are not equipped to take advantage of new materials or modern manufacturing processes. Many manufacturing processes are not structured to handle iterative, or spiral, design improvements, and there are limited avenues for the transmission of information from manufacturing processes to designers and engineers. In short, bridging the gaps across the entire process for product realization could mean reduced cost, shorter time to delivery, and better products.

Over the years, what is called "bridging" in this report has been called concurrent engineering, concurrent design, design for manufacturing and assembly, and many other terms with a similar spirit if not necessarily exactly the same meaning or vision for implementation. "Virtual manufacturing," "spiral development," "simulation-based acquisition," and "modeling and simulation" are terms currently used to describe the potential for various technologies to create these bridges. A well-defined framework of data management, modeling, and simulation tools can help to identify gaps in development or implementation, and can also guide investment decisions in basic research and engineering education. Input from several disciplines—systems engineering, engineering design, materials science, manufacturing science, and life-cycle assessment—is needed for success. Finally, changes to the way customer requirements are specified, especially within defense acquisition processes, are also needed to fully bridge design and manufacturing.

FRAMEWORK FOR VIRTUAL MANUFACTURING

The design and manufacturing enterprise can be interpreted using the flow diagram presented in Figure ES-1. This diagram seeks to capture series and parallel activities at several levels of detail over time during the development of a product. At the lowest level (the bottom of the "V"), individual components are designed and manufactured for integration into subsystems. In an automotive context, components might include brake rotors, suspension parts, or engine control computers. At the next level (the middle of the V), these components are assembled into

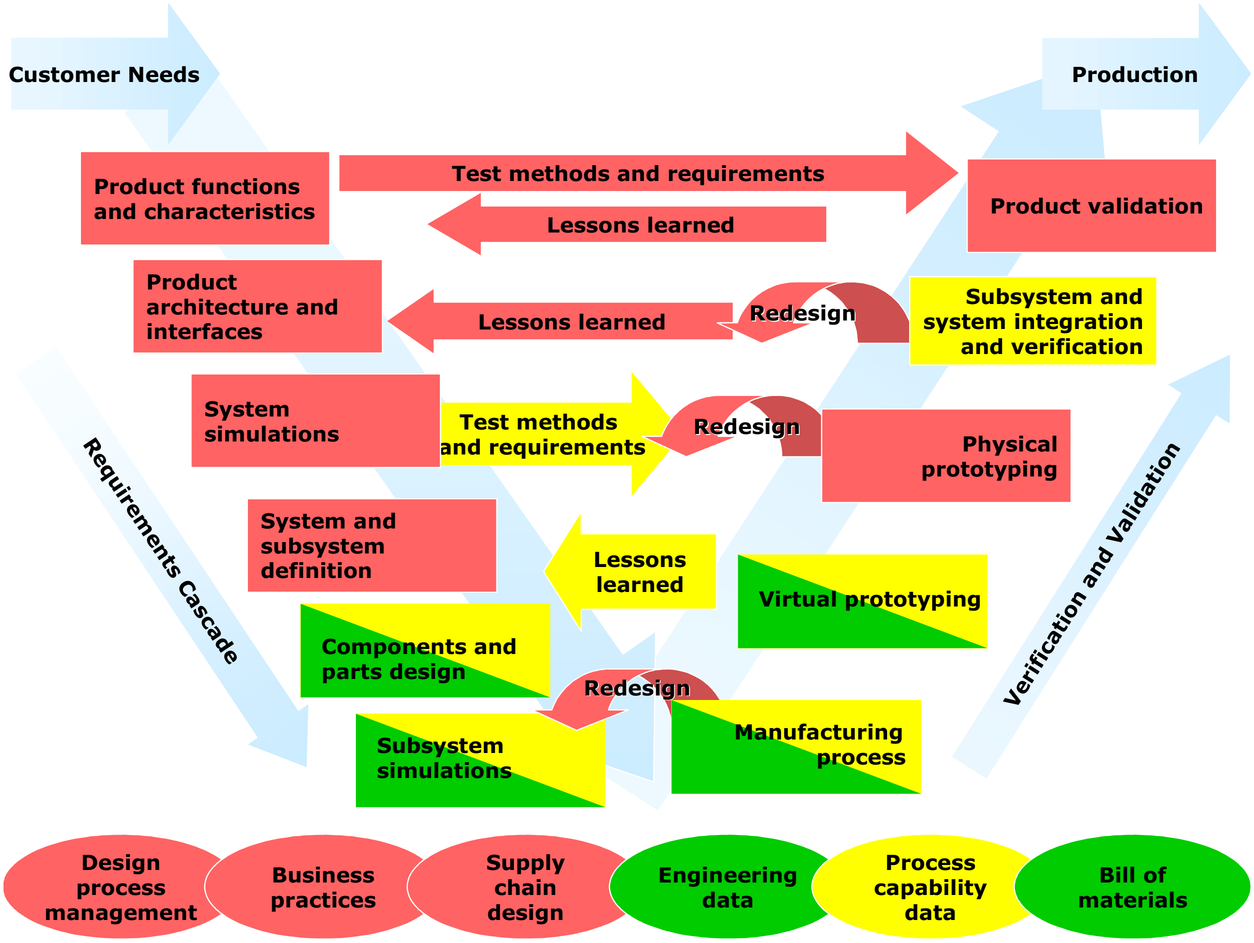


FIGURE ES-1 Flow diagram of product–process development. This diagram seeks to capture series and parallel activities at several levels of detail over time during the development of a product. Some of the required activities are listed along the arms of the V while others, not associated with particular phases of the process, are listed across the bottom. Software tools are not available (red) for many of the required product development activities. For other activities, software tools may be emerging (yellow) or common (green) but are not interoperable or are used inefficiently.

subsystems—the brake subsystem, the suspension subsystem, or the engine. The subsystems are then integrated into a platform, in this example, an automobile. Finally, at the enterprise level (the tips of the V), such matters as marketing, distribution, and life-cycle management are considered.

Bridging design and manufacturing requires the ability to conceptualize, analyze, and make decisions at all levels of the V in Figure ES-1. Using this framework, knowledge and information from several disciplines can be integrated to make intelligent decisions at all levels. New tools can enable the effective application of this process. As depicted by the color scheme in Figure ES-1, software tools are not available (red) for many of the required product development activities. For other activities, software tools may be emerging (yellow) or common (green) but are not interoperable and so are not used together, or are used inefficiently. When tools are fully interoperable, designers and engineers can use and link various data and models for a given activity as well as across different activities required for product realization. For example, tools that allow data to be easily shared instead of being regenerated or re-entered are more efficient, as are tools that allow information at all levels to be viewed with an appropriate amount of abstraction.

TOOLS FOR VIRTUAL MANUFACTURING

Recommendation 1. Systems Engineering: The Department of Defense should develop tools to facilitate the definition of high-level mission requirements and systems-level decision making.

Tools to create, visualize, and analyze design and manufacturing alternatives can facilitate systems-level decision making. A specific opportunity is to develop tools for converting customer needs into engineering specifications, and for decomposing and distributing those specifications to subsystems and components.

The design and manufacturing process leading to product realization is essentially a system of systems. Performance requirements set at the highest level flow down to the other levels in the form of system and interoperability specifications. Conceptual designs are broken down into subsystem and component designs. Decisions are then made about materials, assembly, and manufacturing processes. Information may also flow back up this chain to modify the design.

Such a sequential approach, however, can lead to inefficiencies. Decisions may be made at one level without full consideration of the implications for other levels. For example, parts may be designed that cannot be manufactured or parts can be manufactured that are difficult to assemble. Simple manufacturing processes may be impossible to use because of an arbitrary design specification. A systems engineering approach can avoid these consequences by requiring collaboration at different levels and collective decision making.

Moving from a linear approach to an integrated systems-level approach may require substantial cultural and organizational changes. In order for such an approach to work, all of the participants require access to sufficient and timely information.

Recommendation 2. Engineering Design: The Department of Defense should develop interoperable and composable tools that span multiple technical domains to evaluate and prioritize design alternatives early in the design process.

Improving interoperability,[1] composability,[2] and integration of design and manufacturing software is a complex problem that can be addressed with near-, mid-, and long-term objectives. In the near term, developing translators between existing engineering design environments and simulation tools can solve problems with minimum effort. In the mid term, a common data architecture can improve interoperability among engineering design environments and simulation tools. Key long-term research goals include (1) the development of interoperable modeling and simulation of product performance, manufacturability, and cost; (2) the creation of tools for automated analysis of design alternatives; and (3) the application of

---

[1] In this context, interoperability is the ability to integrate some or all functions of more than one model or simulation during operation. It also describes the ability to use more than one model or simulation together to collaboratively model or simulate a common synthetic environment.

[2] In this context, composability is the ability to select and assemble components of different models or simulations in various combinations into a complex software system.

iterative optimization using both new and legacy codes.[3]

Almost 70 percent of the cost of a product is set by decisions made early in the engineering design process. If system integrators have the ability to see and work with a large design space, they can better analyze trade-offs between alternatives. Designers need to be able to work within a multidimensional space where design alternatives can be effectively compared. While adequate design tools exist for making decisions within a narrow framework, mature tools do not exist for making decisions over the broad range of design and manufacturing shown in Figure ES-1.

The ability to integrate modeling and simulations across multiple domains is yet to be demonstrated. Domains may include geometric modeling, performance analysis, life-cycle analysis, cost analysis, and manufacturing. If such simulations were able to integrate system behavior and performance in multiple domains, performance, manufacturability, and cost information could be considered and optimized early in the design process. Such integration will require giant leaps in interoperability among various software packages and databases.

Recommendation 3. Materials Science: The Department of Defense should create, manage, and maintain open-source, accessible, and peer-reviewed tools and databases of material properties to be used in product and process design simulations.

Integrated tools and databases for materials design, materials selection, process simulation, and process optimization are key to virtual manufacturing. Data gathered from manufacturing and materials processing using a variety of sensors can validate and improve design, modeling, simulation, and process control.

Effective use of today's materials can be greatly enhanced by using software tools. In particular, databases of accurate and well-characterized material properties would have a significant impact on the quality and speed of product design and manufacturing. Validation by peer review of such databases is essential for their acceptance.

Materials that are currently used in defense systems will continue to be the most important ones used in production in the near term. However, the relationships between structure and properties in even the most common materials are yet to be completely understood, and their potential has not been fully realized. Thus, continued funding of fundamental research aimed at characterizing the relationships between processing, structure, properties, and performance in these materials is warranted. Both experimental investigations and fundamental simulations are necessary to understand these relationships.

The variety of forming processes by which materials are converted into products—casting, forging, stamping, cutting, molding, and welding, for example—can all be simulated by modeling and analysis. However, the fidelity of these analyses depends strongly on the properties of the material in a variety of states and under different external conditions. This dependence makes a strong case for an extended database of materials properties. In addition, even when databases exist, many analysis codes suffer from a lack of interoperability with each other and with specific databases.

Any simulated process is only valid within prescribed boundary conditions. Often, the boundary conditions are not well characterized or are unnecessarily limited, and this limits use of the generated data. Sensors can be deployed in both research and manufacturing environments to improve the fidelity of the simulations of various manufacturing processes. As

---

[3] Legacy codes are programs and databases prepared years ago that may lack support from computer hardware or the people who created them.

an example, solidification processing is an area where sensors are used effectively. Because the interfacial heat transfer characteristics cannot be completely predicted, temperature sensors embedded in the mold are used to adjust the simulation parameters. The use of such sensor data in conjunction with modeling can provide control for many other manufacturing processes as well.

Validated data can also be used to develop methods to predict material properties from fundamental physics and to develop constitutive models that predict behavior for a wide range of materials and conditions that are outside measured boundary conditions. Success in this area will greatly enhance the next generation of virtual manufacturing.

Recommendation 4. Manufacturing: The Department of Defense should assess the role and impact of outsourcing on the integration of manufacturing and design functions.

Assessing the impact of outsourcing key activities can help determine how to minimize complexity and maximize coordination in various organizational structures between manufacturing systems. Tools that include efficient algorithms for production scheduling and procedures for flexible factory design can ease the difficulties of outsourcing.

Improvement in the coordination of design and manufacturing involves both technical and organizational actions. Within a single company, coordination between design, materials supply, production scheduling, and process control, for example, can be difficult; outsourcing of tightly coupled design and manufacturing activities adds complexity to an already complex communication process. For example, software tools in use across many organizational boundaries may not communicate without substantial effort.

Creation of new technical knowledge in manufacturing will not be sufficient without accompanying improvements in management methods and organizational arrangements used for outsourcing. These include how to structure cross-functional teams, how to transfer information in a timely manner between team members, and how to identify and resolve conflicts and discrepancies. Implementing the results of research in this area from both business and engineering schools will help improve design–manufacturing coordination. Organizational and managerial structures that facilitate teamwork can make manufacturing efficient and can overcome the tendency toward decentralization that is magnified by outsourcing.

Economic models can estimate the private and public rate of return for investments in virtual design and manufacturing tools and help characterize how incentives and organizational structures affect the adoption of these tools. Economic models of outsourcing choices can also help to assess the strategic impacts on companies, industries, and national defense. The loss of national capability due to outsourcing to offshore companies may become clearer with more appropriate models. Outsourcing of software development, in particular to offshore companies, may represent a substantial barrier to interoperability.

Recommendation 5. Life-Cycle Assessment: The Department of Defense should develop tools and databases that enable life-cycle costs and environmental impact to be quantified and integrated into design and manufacturing processes.

Establishing and maintaining peer-reviewed databases for environmental emissions and impacts of various materials and manufacturing processes will be critical for the government to integrate these factors into acquisition processes. Environmental *performance metrics that combine multiple impacts are most useful for design decisions. The development of high-level optimization methods can allow analysis of the trade-offs between cost, performance, schedule, and environmental impact.*

In a systems approach to design and manufacturing, the cost of a product over its entire life is considered. Cost can be viewed from several dimensions. First, there is the acquisition cost of a product that includes design, development, and manufacturing. After acquisition, operating, or ownership cost is incurred by operators of the product, which is particularly relevant for defense systems that may last generations. In this case, design decisions can have a profound impact on the adaptability of defense systems to modification or retrofits. Third, there is the environmental impact of manufacturing processes and end-of-life recycling or disposal.

The metrics for quantifying all of these assessments are challenging. Accurate assessment is difficult because gathering the necessary data is expensive and also may be subjective or arbitrary. One reason is that recycling is often done by widely distributed small businesses that operate with a variety of business models, making the economics of the industry opaque.

COMMON THEMES

Different disciplinary areas are directly involved in the design and manufacturing process—systems engineering, engineering design, materials science, manufacturing, and life-cycle assessment. Other supporting infrastructures are involved indirectly and affect all of these specific fields in an overarching way.

Recommendation 6. Engineering Education: The Department of Defense should invest in the education and training of future generations of engineers who will have a thorough understanding of the concepts and tools necessary to bridge design and manufacturing.

Integrating knowledge of virtual manufacturing into university curricula to train new engineers can help them use tools to bridge design and manufacturing. To ensure an adequate supply of such trained engineers, the DoD can help to develop programs to increase the quality and the number of graduating engineers available to work in these fields. It is also critical to retain U.S. capability in contributing disciplines, such as materials science and engineering.

The availability of an educated domestic workforce is crucial to the quality of life, to the national defense, and to the economic security and competitiveness of the nation, and a key part of this workforce is in the manufacturing sector. The education and training of tomorrow's workforce becomes even more critical when one considers that the entire design and manufacturing field has expanded greatly in knowledge in recent years and will continue to do so, most likely at an even faster pace, in the foreseeable future.

Information technology is rapidly enhancing the process of communication between customers, engineers, and manufacturers. The broadening of the arena requires an integrated and well-balanced science and engineering curriculum that covers systems, design, materials, and manufacturing. An integrated approach for traditional educational institutions as well as for certification programs for practitioners will ensure that the workforce is able to use the new tools and strategies for efficient product realization.

Recommendation 7. Defense Acquisition Processes: The Department of Defense should define best practices for government ownership rights to

models, simulations, and data developed during system acquisitions.

Formal guidelines and best practices for transferring models, simulations, and data between the government and its contractors are essential for competitive procurement. Instituting common model access, common model databases, and common document controls will ensure that information generated under government funding is available to multiple program managers.

Incentives for program managers to develop integrated design and manufacturing tools can make simulation-based acquisition become a reality for DoD programs. Well-defined metrics for integration of design and manufacturing can help the program managers use simulation-based acquisition. Metrics that are compatible with different acquisition programs will allow these investments to be leveraged in the future. Also, specifying the modeling and simulation techniques that will be used in the proposal evaluation process, especially the cost structure analysis and affordability models, will facilitate simulation-based acquisition. Integrating the concept-of-operations definition into the modeling and simulation program plans can bring end users into the acquisition process and thus foster a more successful transition to military capability.

Given the codified support of simulation-based acquisition by the DoD, modeling and simulation plans could become a central requirement in all defense acquisition programs. Common tools and plans will naturally emerge, and these can be reused to ensure real growth and progress in acquisition. As the quality, accuracy, and applicability of modeling and simulation tools grow, the simulation-based acquisition policy will be realized. Instituting incentives for program managers to use modeling and simulation tools can help this vision become reality.

Collaborative environments support the integration and interoperability of models, simulations, and data through an overarching structure that facilitates the secure linkage of modeling and simulation across distributed locations and organizations. The establishment of such collaborative environments can link modeling and simulation between phases in the product realization process (such as requirements definition, design, manufacturing, live-fire testing, and acquisition), as well as connect distributed locations and organizations, thus facilitating the sharing of models, simulations, and data.

Modeling and simulation tools used in the acquisition process should also be able to be integrated into increasingly complex performance simulations. The Secretary of Defense, Donald Rumsfeld, has indicated that transformations in defense acquisition will be required in order to support an agile and evolving warfighter. Establishing strong connections between the levels of existing expertise and capabilities already available within the DoD's modeling and simulation infrastructure is a critical step, and includes establishing the role of the government research and development service laboratories in this process.

Modeling and simulation will become more valuable and widespread when the tools and data developed in one DoD program can be reused in others. The modeling and simulation tools include not just codes, but also supporting data, databases, environments, and the associated validation and verification test results. Negotiating incentives to provide models, simulations, and data as contract deliverables will provide program managers and their integrated product team staff with insight into the design, engineering, manufacturing, and performance trade-offs in a way that is not available in current procurement schemes. It also provides a starting point on the path to establishing modeling and simulation as a method for ensuring that design requirements are met. These deliverables would lead to a reduced amount of validation testing, and thus lower overall cost and faster product delivery times.

1

The Need to Bridge Design, Materials, and Production

The realization of complex products requires a huge amount of knowledge about customers' needs, the characteristics of technologies, the properties of materials, and the capabilities of manufacturing methods. The capabilities of different firms in different countries also must be known and compared. Bringing complex products to market or complex weapon systems to users in a short time at reasonable cost is a long-lasting concern and one that will become more acute in the future.

This report investigates potential as well as the recognized accomplishments of information technology to enhance the process of communication between customers, engineers, and manufacturers, in short, to strengthen the bridge between design and manufacturing of goods. In this chapter, the committee looks at prior approaches to this important issue and sketches a vision for the future.

HISTORY AND STATUS

Over the years, what is called "bridging" in this report has been called concurrent engineering, concurrent design, design for manufacturing and assembly, and many other terms similar in spirit if not necessarily exactly the same in meaning or a vision for implementation. In "The Historical Roots of Concurrent Engineering Fundamentals," Robert Smith shows that manufacturers were conscious of the need for bridging over 100 years ago.[1] In many companies, a few skilled people, such as Henry Ford or Cyrus McCormick, held all the decisions in their minds and coordinated the intellectual effort of both design and manufacturing. By and large, these companies made all or nearly all of the items that went into their products.

As the 20th century advanced, products became more complex, companies became larger, and the ranks of capable suppliers grew. All of these processes led to the division of labor in both design and manufacturing, not only within companies but also along supply chains. New materials, new manufacturing processes, complex engineering calculations, and increasing customer expectations all have led to the creation of specialties in all aspects of product realization. As individuals have become more specialized, they have become more dependent on the knowledge of others. As a result, a shortage of individuals who know about multiple aspects of this process has developed. In many companies and industries, the process of creating a product is done linearly, passed from person to person with no backward or forward integration. Although this process may be successful if the product is simple or repeats past

---

[1] Robert P. Smith, "The Historical Roots of Concurrent Engineering Fundamentals," *IEEE Transactions on Engineering Management,* Vol. 44, No. 1, pp. 67-78, 1997.

designs and manufacturing methods, it can lead to problems on the factory floor, delays in product launch, higher costs, and dissatisfied customers.

In the last 30 years, information technology has become more and more important to the processes for product creation. Computers are essential in the design of parts, the calculation of stresses and strains, the estimation of costs, and the simulation of performance. Nevertheless, the overall process remains somewhat fragmented. More software tends to be developed for aspects of the process that have mathematical representations or cover one or two physical phenomena. These aspects include computer-aided design, finite element analysis of loads and deformations in solids and flows in liquids, animation of mechanical motions, simulations of operations on a factory floor, behavior of robots, and even motions and stresses on human operators. This approach has limitations when it is applied to products that are increasingly multifunctional and contain multiple technologies. Further, efficient manufacturing, including customizing and responding rapidly to customer orders, requires increasing integration between design and manufacturing.

The need is especially great in areas where product technology is advancing rapidly, such as national defense, where the commercial notion of competition is replaced by the notion of threat. It is well known that technology can give the warfighter a huge advantage, and staying ahead technologically is essential. Thus, development of defense systems is always on the cutting edge and must utilize every available tool to bring new systems to users quickly and affordably.

BENEFITS

Efforts to integrate design and manufacturing in both the commercial and national defense sectors could have profound impacts on productivity and economic growth. After languishing for nearly 15 years, multifactor productivity growth in U.S. manufacturing, which is a broad measure of the efficiency for all inputs including labor, materials, energy, and supplies as used in production, staged an impressive resurgence during most of the 1980s and especially after the early 1990s (see Figure 1-1).

There is accumulating evidence that the upsurge in productivity during the 1990s was due largely to the development and application of information technology.[2] If successfully adopted, the changes identified in this report could prolong and perhaps even accelerate this turnaround in productivity growth. In the committee's opinion, integrating manufacturing simulation models promises to substantially improve the efficiency of the design process, reducing the time to deployment and most importantly overall system cost.

The additional capabilities made possible by adopting integrated manufacturing models could lead to the creation of new products and services, further expanding the nation's economic base and increasing international competitiveness. Adoption of integrated systems, along with the necessary technologies and incentives, will not only benefit our economy as a whole but also improve the efficiency and profitability of firms, the effectiveness of DoD programs and weapon systems, and the satisfaction of customers and users.

FUTURE VISION

A future with enhanced bridging of design and manufacturing must address four domains: technical capabilities, the organization of companies and work within companies, the cultural dimension, including incentives for people to work together, and the regulatory dimension that seeks standards for data exchange and other unifying aspects.

---

[2] National Research Council, *New Directions in Manufacturing,* National Academies Press, Washington, D.C., 2004.

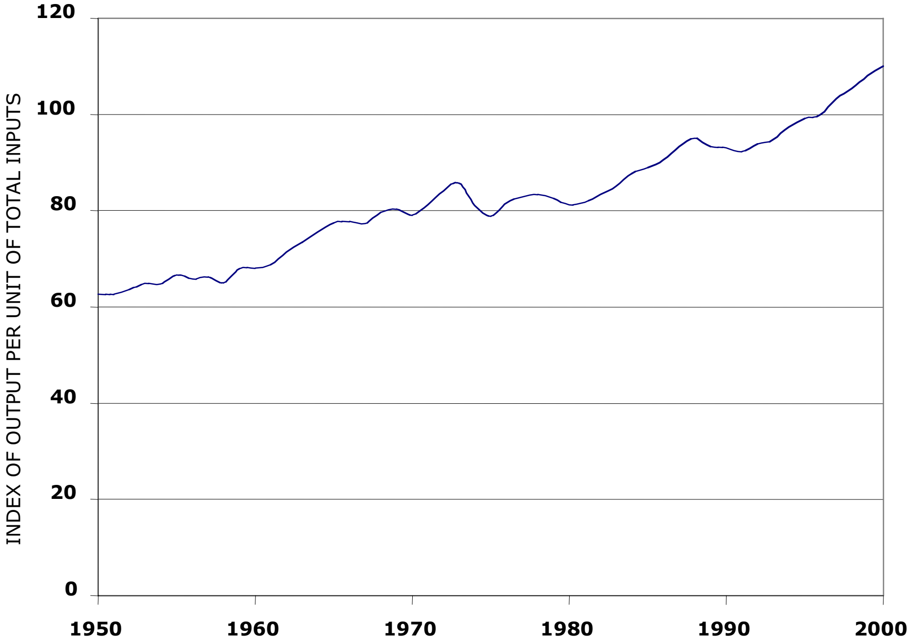


FIGURE 1-1 Multifactor productivity in U.S. manufacturing. Source: U.S. Department of Labor, Bureau of Labor Statistics.

On a technical level, a basic need exists for a more thorough understanding of the complex interactions between design decisions and manufacturing options. This includes the need for a way to capture, quantify, and convey the needs of users of advanced products and systems. Second, the areas of developed information technology need to be integrated in a staged process that overcomes incompatibilities and will enable designers to expand the range of phenomena covered. More powerful computers may also be needed.

Organizationally, better definitions of the roles and responsibilities of individuals and groups are needed as the concepts of product and process are increasingly integrated. This is especially critical given the increasingly fragmented and international economic structure that has developed in the last decade. This will require revised management practices and educational agendas. Incentives may be needed to encourage investment in research and new work methods, training, processes, and facilities. Because there are currently no incentives for companies or governments to use one standard program or approach, both national and international cooperation will be needed to facilitate the improved interoperabiity of software and the integration of data created by different companies.

The committee has formulated its vision in terms of a coherent framework that describes an integral system for bridging design and manufacturing through both new and improved data management, modeling, and simulation. This framework assumes a central role for information technology in the form of virtual design and manufacturing. Virtual design and manufacturing constitute an engineering process that integrates computational modeling, simulation, and visualization to design, develop, and evaluate products with their manufacturing processes to meet customers' life-cycle needs.

The committee also recognizes the need to provide complementary improvements in the organization of companies and supply chains as well as changes in company culture, government and regulatory incentives, and the education of engineers and managers so that improved technologies will be both developed and implemented successfully.

2

Framework for Virtual Design and Manufacturing

Product development is a complex process involving a multitude of tools and technologies as well as nontechnical issues. In the past, there was considerable optimism that technological advances would solve all engineering and manufacturing problems. Today we understand that the integration of technical and nontechnical approaches is necessary, especially where people with different skills and responsibilities need to reach accommodation in complex domains.

In this report, the term "virtual design and manufacturing" is used to describe the use of information technologies (such as databases, rapid network-driven communication, and modeling and simulation software) to aid in the creation of products and systems.[1] "Manufacturing" refers broadly to all the activities required to conceive a product that will meet the needs of a customer, convert those needs into a producible design, deliver products to the customers, support products in the field, upgrade or repair them as needed, and eventually retire and recycle them. This broad definition provides the opportunity to fully exploit the emerging virtual technologies to their full potential.

To give an example of the scope of manufacturing activities, out of a total of about 250,000 employees worldwide the Ford Motor Company has more than 30,000 engineers and skilled designers involved in the design of its products and manufacturing systems. Bringing a new car from concept to production can take 48 months and cost upward of $3 billion. In the process, a company like Ford must make use of many computer-powered tools to determine what customers want and whether its engineering and manufacturing processes will do the job.

This chapter briefly describes the steps in this process in a generic way and identifies the virtual manufacturing tools in use. It also predicts the potential for performing more of the steps virtually, that is, by substituting simulations for physical prototypes, and distance communication for face-to-face meetings. Particular steps needed in the mechanical parts and electronics industries are described separately where they differ substantially from a generic template.

It is unlikely that every step in such a complex process as design will ever be completely virtual because many critical trade-offs and decisions must be made based on experience and judgment. But it is likely that computer-based tools could aid even these unpredictable steps. To accomplish this, it is also necessary to take account of the nontechnical aspects of manufacturing, such as program management and managerial methods and incentives, which are necessary in order to make the best use of new design technologies.[2]

---

[1] "Virtual" is defined broadly here to include any method that involves computing, electronic data, or communication.

[2] Drew Winter, "Shrinking Product Development Time," *Ward's Auto World*, June 1, 2003. Available at: http://www.wardsauto.com/ar/auto_shrinking_product_development/. Accessed March 2003.

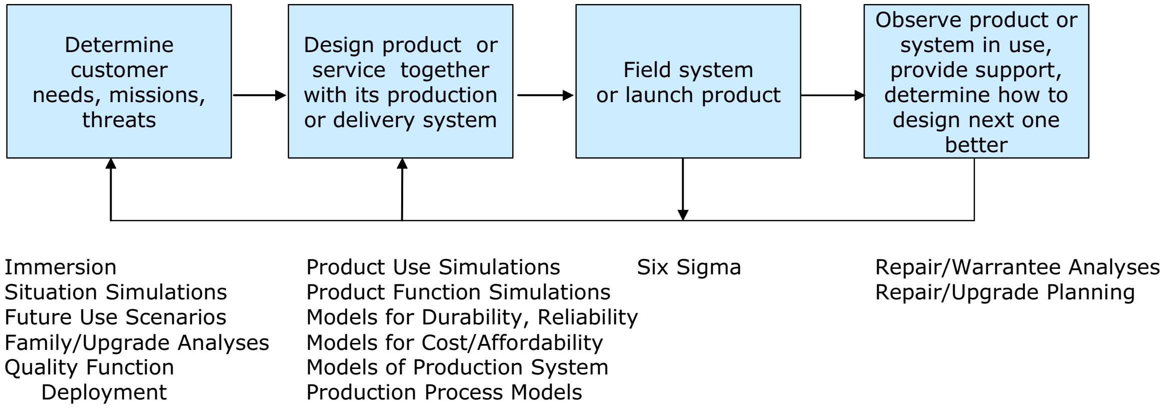


FIGURE 2-1 Simplified diagram of activities in product development. This diagram denotes the main activities in the life cycle of a product from conception to use and retirement, shown as a time sequence with feedback at various stages. Along the bottom are examples of computer-based tools that are used to varying degrees in each stage. Note that while these steps are shown as occurring serially, significant overlap is possible.

PROCESSES AND TOOLS COMMON TO MANY INDUSTRIES

Figure 2-1 presents the basic steps in developing a new product or service.[3] Along with these steps are shown a few of the computer-based tools that are in use, both commonly and in the most advanced companies and government laboratories. The basic steps are as follows:[4]

- Determine the customer's needs. This often involves negotiations and reality checks, which can be aided by simulations and other computer-based tools.
- Design products and services, including:
  - Convert the customer's needs into engineering specifications, including requirements for production speed and accuracy. Engineering and manufacturing models and simulations are used routinely in this and the following steps to verify performance, predict failure modes, and match production plans and equipment to requirements.
  - Specify the requirements for reliability, maintainability, and other customer use and life-cycle support requirements.
  - Determine that the specifications can be met by manufacturing processes or suppliers; modify the design as necessary to be sure.
  - Plan manufacturing operations and equipment.
- Launch the product into production.
- Monitor performance of the product in use and update designs.

There is a growing similarity between DoD systems acquisition and commercial industry's methods of developing new products. In particular, where commercial industry seeks to

---

[3] Even though services are developed via a process broadly similar to products, this report concentrates on products.

[4] Karl Ulrich and Steven Eppinger, *Product Design and Development,* Third Edition, McGraw-Hill, New York, N.Y., 2004, p. 9.

understand customer needs, the DoD seeks to understand potential threats, missions, and warfighting plans. Where commercial industry differs from past DoD methods is that commercial industry considers cost and cost–performance trade-offs much earlier in the product development process. The DoD's recent interest in this approach is evidenced by initiatives like cost as an independent variable (CAIV), and driven by increased awareness of affordability issues.

Figure 2-2 goes into more detail about how a product and its processes are designed. This figure follows the motif of the "system engineering V," which is used by many companies to explain and manage their product development process.[5] Time flows from left to right, while the level of detail increases downward, as does the level of decomposition of the product into systems, subsystems, and parts. Top-level requirements are broken down into requirements on subsystems and parts. Methods of determining whether these items will deliver their requirements are also designed at the same time. As each item is designed, it is compared to its requirements, and occasionally some redesign is necessary. As more items are completed, they are integrated, and more verification tests are performed. Again, some redesign may be needed. At the highest level, the complete product is subject to validation tests.[6] Ideally, the lessons learned during this complex process, as well as data from the field, are recorded and applied to the next product.

Modeling and simulation play large roles on both sides of the V. Both the product and the various production processes are designed and tested using computer models. Tests and prototypes produce data that are used to improve the design and the accuracy of the simulations. Data from users and repair activities (not shown) also contribute to learning and improvement of models, such as data on long-term durability and safety. As indicated by the colors in Figure 2-2, new software tools are needed (red) for many of the required product development activities. For activities where software tools are emerging (yellow) or are common (green), the tools need to be made interoperable to improve the integration of design and manufacturing.

A number of activities that support product development and are listed across the bottom of the diagram also make use of computer models and simulations. The status of these tools and methods is discussed in detail in Chapter 3. It is important to understand that the required tools cover many nontechnical domains such as human resource management, program management, cost analysis, market analysis, and so on. Some, like immersion or virtual reality caves, are used to help customers decide what they really want and whether they have asked for self-consistent requirements. Others, like cost models, help customers decide how badly they want certain features or performance metrics. Elsewhere in this report it is noted how vital it is to define requirements carefully with the participation of the customer, so advances in tools of this type will be particularly important.[7]

The degree to which the process illustrated in Figure 2-2 is actually used varies from industry to industry, and from company to company within each industry. As industries become more confident in their ability to accurately simulate the behavior of their products, fewer physical prototypes will be needed for validating a product's design. The potential for elimination of prototypes also varies from industry to industry. In hardware systems, system complexity

---

[5] Andrew Sage and William Rouse, *Handbook of Systems Engineering and Management*, John Wiley and Sons, New York, N.Y., 1999, p. 78.

[6] "Verification" usually refers to tests to see that a product meets specifications. "Validation" seeks to determine that the customer is satisfied and that the correct specifications were in fact incorporated into the product.

[7] Considerable debate surrounds the question of whether requirements should be complete and clear *before* product development begins. When a product's technologies are well understood and the market's needs are evolving slowly, then efficient and effective product development benefits from an up-front declaration of requirements. When the technology is explorative and the market is changing rapidly, requirements are hard to clarify. In this situation, a development process that can quickly adapt to changes is often preferred.

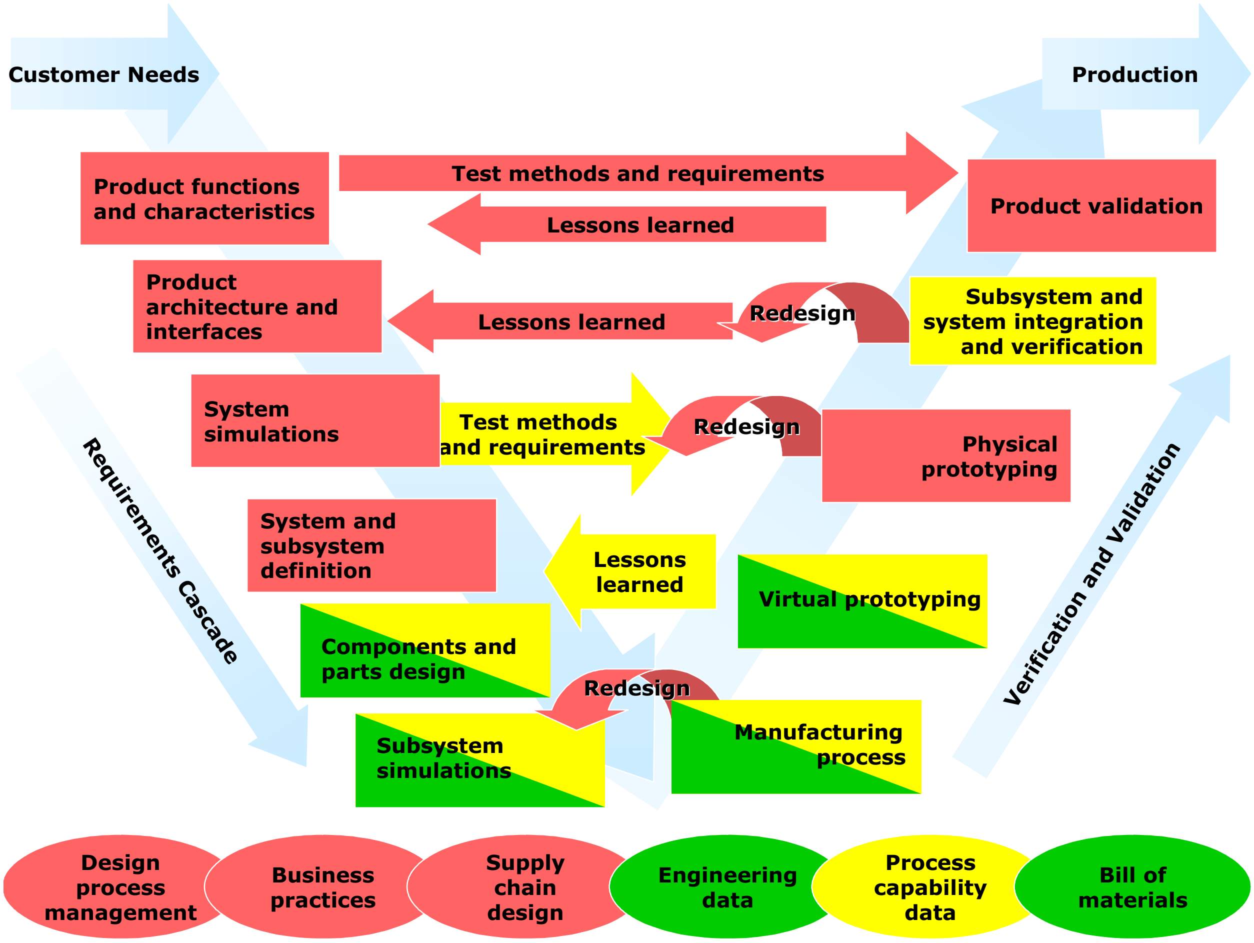


FIGURE 2-2 Flow diagram of product–process development. This diagram seeks to capture series and parallel activities at several levels of detail over time during the development of a product. Some of the required activities are listed along the arms of the V while others, not associated with particular phases of the process, are listed across the bottom. Software tools are not available (red) for many of the required product development activities. For other activities, software tools may be emerging (yellow) or common (green) but are not interoperable or are used inefficiently.

leads to uncertainties in materials properties and processes and can contribute to unexpected behavior. Prototypes may be needed to detect some of these uncertain events. Regulatory agencies often require safety tests prior to the production and sale of certain products (e.g., automobiles and aircraft). Microprocessors can be completely designed in software using design rules, once the production processes have been verified on test chips that have the required device sizes, materials, and line widths and spacing. Verification of these processes still requires hardware. In software development, prototypes are used to test the new software against customers' expectations. Thus, even if programming aids eliminate bugs, there will still be a need for prototypes.

In some industries, development of prototypes and computer simulations go hand in hand. In aircraft jet engine design, simulations are used to make conceptual, preliminary, and detailed designs of fans, compressors, combustors, and turbines. Each of these components is built in prototype form and tested, as is the final engine. These tests not only determine whether the engine meets its requirements but also provide essential information for updating the simulations for use on the next engine.[8]

Further, Thomke argues that every experiment, whether it is a physical prototype or a computer simulation, has the potential to provide learning and knowledge as long as the opportunity is taken.[9] Thus, in the future, one should expect that simulation and experimentation would continue to be partners in product development.

The main differences between prototypes and simulations are as follows:

- Prototypes provide the ability to detect issues that are not contained in the models or simulations.
- Simulations can provide information earlier in the design process.
- Simulations reduce the marginal cost of experimentation to the point where thorough exploration of the design options becomes economically feasible.

The main drawback in using simulations instead of prototypes is that simulations are likely to be less accurate, something that must be traded off against early availability of the information. Even so, accurate prototype results are often available much too late to be of any use in a tightly scheduled development project. Thus, a judicious combination of simulations and prototypes for validation and verification is the most effective approach.

Models and simulations are also used to help design and operate the design processes themselves. Virtual methods include dynamic project management simulations, engineering resource and scheduling allocation algorithms, and methods for tracking requirements and their achievement. Software is also used to manage the huge amounts of data associated with design of a product and its processes. It is estimated that for every geometric feature on a mechanical part that is made, there are upwards of 1000 geometric features on manufacturing equipment and supporting apparatus.[10] Bill of materials systems are used to manage the data. A typical automobile has about 10,000 parts containing as many as 10 geometric features each. A Boeing 777 has more than 100,000 part numbers. Thus the amount of data needed to represent just the mechanical parts is huge. In addition there are miles of wire and pipes in aircraft and ships, all of which are represented by layout diagrams, circuit analyses, parts lists, and so on. All of these must be represented in databases so that the systems can be simulated and their production can be planned. At present most of these databases interoperate only on nontechnical data such as part numbers, and even these can be inconsistent. There is no common data architecture that can hold and exchange technical information such as part shapes, bills of materials, product configurations, functional requirements, physical behavior, and much else that is required for deep exploitation of virtual manufacturing.

Specific opportunities for bridging design and manufacturing occur at many places in the process illustrated in Figure 2-2. At the highest levels, the design must accommodate available processes and methods used by the manufacturing prime contractor and its suppliers. Product planners need to assess available factories to determine if they have the capacity and flexibility to meet future needs. Tests and validation procedures need to be in place or designed to ensure that the product will perform as required. At lower levels of product decomposition, individual parts and assemblies must be designed so that they can be produced efficiently, economically, and within tolerances. Fabrication and assembly processes must be designed to

---

[8] Geoff Kirk, Chief Design Engineer, Commercial Engines, Rolls Royce, "Every Engine Attribute Has Its Model," presentation at University of Cambridge, U.K., July 10, 2003.

[9] Stefan Thomke, *Experimentation Matters: Unlocking the Potential of New Technologies for Innovation,* Harvard Business School Press, Boston, Mass., 2003.

[10] William Powers, VP of Research, Ford Motor Company, Keynote speech to Japan–USA Symposium on Flexible Automation, Boston, Mass., July 7, 1996.

meet the requirements for cost, speed, and capability.

It commonly occurs that desired requirements cannot be met in a timely or economic manner with existing processes and facilities. For this reason, requirements often must be revised. Understanding how to arrive at a suitable compromise is very difficult, especially because it involves managerial, organizational, and economic consequences. It is also essential to be able to discover the need for revision early in the product development process. Otherwise, very costly design or manufacturing changes will be needed, delaying the deployment of the product and increasing its cost.

Accomplishing bridging requires exploring a huge space of interacting design and manufacturing options.[11] Virtual tools are the only way of supporting a thorough exploration. Thus virtual tools play important or essential roles in conceptualizing products, conducting the design, planning the production, ensuring manufacturability, and carrying out production, deployment, and field management of the product.

PRODUCT DEVELOPMENT, MANUFACTURE, AND LIFE-CYCLE SUPPORT ACTIVITIES

Table 2-1 lists a number of activities involved in creating, producing, and supporting a product (expanding on the activities shown in Figure 2-2). While details may differ, most of these steps are carried out in every industry, even including those industries whose outputs are services rather than artifacts. The steps cover both engineering and managerial activities. The table comments on the way the step is or has been done nonvirtually and how it might be done using computing or electronic data or communication.

To support ongoing activities of engineering, computer-aided design systems and allied analysis systems can look at stress, fluid flow, heat transfer, mechanical motions, electronic phenomena, and so on. Examples include:

- an aircraft that is analyzed to see whether the landing gear will move smoothly into and out of the storage bay;
- an automobile that is virtually crash tested;
- a helicopter blade that is analyzed for adverse fatigue; and
- a microprocessor that is analyzed to determine how much heat it will generate and whether information can be transferred fast enough between its computing elements.

In addition to virtual tools to help design the product functionally, there are ways to evaluate the designs from other points of view. One of the most important methods is design for manufacture or assembly. This type of evaluation helps engineers to see where trouble might arise during production and can help them simplify the design. Close cooperation with manufacturing and assembly experts is needed to ensure proper use of these tools. Other tools help predict failure modes of the product in use as well as issues that can arise during manufacturing. While many tools exist, experienced people generally conduct most of this type of activity manually. In addition, existing tools are mostly stand-alone and thus prevent essential integration and management of complex interactions between them.

---

[11] Elsewhere in this report, this space is referred to as a "design space" or a "trade space."

TABLE 2-1 Activities Involved in Creating, Producing, and Supporting a Product

Step or Process	Non-Virtual Methods	Virtual Methods
Obtain customer needs, including performance, cost, and schedule expectations	Interviews, observations	Web questionnaires, very realistic simulations combined with self-design
Develop performance requirements	Interviews, observations	Requirements-tracking software combined with tools for tracking interactions
Expand requirements to include such things as reliability, flexibility, and expectations regarding upgrades	Interviews, review of past product needs	Data mining, lessons-learned databases
Develop concepts	Sketches on paper, brainstorming	Digital sketches, data searches, cognitive aids, videoconferences, knowledge-based tools
Generate functional and physical decompositions to meet performance and capabilities requirements	Sketches, notes, brainstorming, technology surveys, interviews	Decomposition simulations, links to technology data, links to interaction data; architecture evaluation systems
Assign quantitative specifications to top-level requirements	Calculations from requirements; existing design histories	Computer simulations of system and component behavior; simulations of user environment
Assign targets to distributed requirements such as cost, weight, reliability, safety, and durability	Existing stand-alone calculations, past field data, guesses	Preliminary cost models, technology histories and roadmaps, tabulated field data
Identify top-level risks: maturity of the technology, performance, cost, schedule	Past field data, data on past similar products, discussions with experts	Risk models based on data
Assess in-house and vendor design, modeling, testing, manufacturing, and assembly capabilities	Internal audits, use of ISO 9XXX protocols	Real-time data on machines, processes, statistical process control, process capabilities and costs
Decide what will be made in-house and what will be outsourced	Internal audits	Strategic and tactical models
Identify critical vendor–partners and long lead items	Discussions with experts, past project data	None
Generate program plan with tasks, schedule, information exchanges, design reviews	Gantt charts, precedence diagrams, existing project templates	Task and behavior interaction models that predict possible rework and schedule delays

continues

TABLE 2-1 continued

Step or Process	Non-Virtual Methods	Virtual Methods
Flow top-level requirements down to subfunctions and subsystems	Analysis by experts	Detailed multifunctional models of technical behavior
Generate derived requirements defined as consequences of top-level decisions but not requested by customers	Analysis by domain experts, subsystem engineering	None
Identify risks at subsystem levels and below	Analysis by domain experts	None
Generate verification and validation plans	Analysis by domain experts	None
Do detailed design of components and subsystems	Drawings	CAD plus functional performance simulations, tolerance analysis software
Determine that detail design specifications can be met by available and economical processes	Discussions between domain experts in engineering and manufacturing	Simulations, process algorithms, cost analysis and comparison algorithms, process capability data
Identify and evaluate suppliers, get and evaluate bids	Request qualifications, past experience	Use virtual data exchange, online bidding and negotiation
Generate manufacturing, assembly, and test plans	Use of manually collected data from past projects, standard templates, vendor capabilities, and domain experts	Simulations and cost-estimating systems, discrete-event simulation
Verify and validate component and subsystem performance	Multiple tests, including accelerated life prototypes	Cross-functional factory simulations, stress analysis software, heat simulations
Design manufacturing and assembly systems to make, assemble, and test each part and assembly	Use experts and domain specialist suppliers to physically make, assemble, and test each part and assembly	Use simulations of materials processing, material handling, assembly, human operators
Obtain and train employees	Drawing from existing staff, recruitment, direct training	Use models to choose the right people, and simulations and videos to train them
Integrate product subsystems and verify performance	Testing of subsystems, prototype assemblies, mockups	3D solids CADCAM plus CFD, computer analysis and simulation
Install and validate manufacturing and assembly systems	Installation and validation done on-site and reworked until they are correct	Simulation and validation tools to check correctness and safety

TABLE 2-1 continued

Step or Process	Non-Virtual Methods	Virtual Methods
Integrate product systems and validate that customer needs have been met	Testing of product, identification of problems, discussions and decision making with customer	Use tools for decision making, utility balancing, budget projections, time estimates
Begin production, find problems, and fix them	Production by engineers and vendors on site	Data acquisition, comparison of simulations and actual operations of systems and machines
Operate and improve manufacturing, logistics, assembly processes, and systems	Application of lean manufacturing principles by supervisors, manufacturing engineers, and operators	Full online monitoring and analysis of processes, measurements, and test results
Field product, gather user and repair data, manage product operation, and monitor health	Read warranty reports, query repair staff, construct lessons-learned databases	Automated monitoring and statistical analyses, remote sensing and diagnosis, remote repair
Manage product upgrades	Read warranty reports, query repair staff, construct lessons-learned databases	Automated product registry
Manage recall, safety upgrades, and retirement of products	Mandated by law for some products and is done manually	None

SPECIFIC ACTIVITIES IN MECHANICAL PARTS INDUSTRIES

The mechanical parts industries make diverse products with multiple modes of energy, including mechanical motions, combustion, fluid pressure and flow, and so on. Thus the term "mechanical parts" is used for convenience rather than to limit the phenomena involved. In fact, it is the multiplicity of phenomena that makes simulation of these products difficult.[12] In many cases the state of the art is a set of individual simulations whose interpretation involves human expertise to combine the separate results.

The kinds of things simulated include the following phenomena:

- Mechanical vibration, noise, and acoustics of machinery, including interior cabin noise in aircraft and automobiles
- Fluid flow in compressors, pumps, and other aerodynamic surfaces, to determine mechanical and thermodynamic efficiency
- Fluid noise, such as wind rushing over the exterior of an automobile or fluid flowing in pipes in a submarine
- Optical ray tracing in telescopes, gun and missile sights, and cameras
- Kinematics of mechanisms such as car engines, aircraft landing gear, telescope mounts,

---

[12] Elsewhere in this report, such multiple phenomena, including electrical, electromagnetic, and other phenomena, as well as the disciplines that deal with them, are referred to as "multiple domains."

and suspensions of trucks and tanks

- Stress and strain, including prediction of sources of cracks and other fatigue phenomena
- Production processes, including solidification, deformation, machining, and joining
- Motions of production equipment such as robots and assembly setup, to determine feasibility of geometry and timing
- Motions of logistical equipment such as forklifts and conveyors that transport materials in factories, to determine production capacity
- Motions and loads on people while doing physical work, to determine timing and avoid injuries, or while operating the product, to study ergonomics

The committee agrees that the most accurate and definitive simulations are those that involve only geometry. However, some mixed phenomena simulations are also remarkably accurate. For example, the fuel consumption of a jet engine can be predicted within about 2 percent using simulations that involve mechanical, aerodynamic, and combustion phenomena.[13] The crashworthiness of a car can be well predicted for frontal collisions. These simulations predict crushing patterns of the structure as well as the path taken by the engine as the front crushes. The point at which the wing of the 777 broke under test to destruction was predicted to the extent that the failure load, location of failure, and kind of failure all were correct.[14] But many of these simulations are purposely built by experts and are honed over many years, making them quite expensive and accessible only to large companies.

What is needed is a set of robust, verified, and validated simulation codes, accessible to nonexpert users. Specialty codes exist for the various aspects of the simulations listed above. A significant improvement in design could be achieved if each of these codes could use a common database describing product geometry and other essential data. Longer range, what is needed is consistent engineering representations of a variety of physical phenomena so that different simulations do not have to be used for each phenomenon separately. Only then will fully functional simulations of multiphenomena systems be possible.

Furthermore, models of production processes today encompass what happens in a restricted area of a factory. Broader models of entire factories are made less often, and models of entire supply chains are rarer still. Commercial software provides some facilities for managing existing supply chains and for passing orders and payments back and forth, but these are more adapted to supply chain operation than to design.

SPECIFIC ACTIVITIES IN ELECTRONICS PARTS INDUSTRIES

Electronics parts industries cover the spectrum from such discrete devices as capacitors and resistors through integrated semiconductor devices and up to such complete systems as microprocessors. Modeling, simulation, and sensing requirements therefore span a broad spectrum of activities across multiple levels. These include a wide array of techniques for modeling the performance of individual semiconductor devices as well as simulations of entire systems. Today's products could not be designed without these simulations and design aids, but there is additional potential for significant interaction between some technical domains. Opportunities arise in the following areas:

---

[13] Jon Niemeyer and Daniel Whitney, "Risk Reduction of Jet Engine Product Development Using Technology Readiness Metrics," *ASME Design Engineering Technical Conference,* paper no. DETC2002/DTM 34000, September 29–October 2, 2002.

[14] Karl Sabbagh, *21st Century Jet: The Making of an Airplane*, Pan MacMillan Australia, Sydney, N.S.W., 1995.

- Materials—prediction of physical properties of materials and their resulting electrical properties
- Semiconductor wafer fabrication—crystal growth, cutting/sawing operations, grinding, polishing, cleaning
- Oxidation processes—oxidation furnaces, wet/dry oxidation
- Deposition processes—physical vapor deposition, chemical vapor deposition, sputtering
- Lithography—equipment, photoresist characteristics
- Etching processes—chemical/wet etching, plasma/dry etching, reactive ion etching
- Diffusion—chemical/vapor, ion implantation, doped oxide
- Interconnect—mechanical, electromagnetic, thermal, die attach/wire bonding
- Circuit level modeling—active, passive, and parasitic circuit elements
- Package level—mechanical, electrical, thermal, radio frequency, digital
- Board level—reflow process, screen printing, component placement, routing, layout, layers, substrates (e.g., organic, flex, ceramic, glass), component and board test
- System level—factory scheduling and resource management, acoustics, safety, radiation, network, yield, supply chain, system test

MODELING AND SENSING

Simulations will always be limited by the input data they use. Let us consider this in the context of production processes that transform raw materials into another form. Examples include:

- casting, where chemical composition is set by alloying ingredients in the liquid state and form is set by solidification in a mold;
- deformation processes such as forging and sheet metal forming, where a combination of thermal and mechanical forces shape an initial blank; and
- machining, where tools remove material to produce a final shape.

Simulation of each of these processes requires detailed models to predict materials' response to thermal and mechanical loads. Further, the process simulations also require models for the transfer of heat and mechanical forces across the interface between the part and tooling. The quality of the simulation results depends on the quality of these input data.

In most cases, the interfacial properties are not well enough understood to be completely reliable. Modelers generally lump all unknown variables into "interfacial transfer coefficients," which are meant to characterize the transport processes. It is important to understand that simulations will *never* be able to completely capture these interface characteristics without external data. For example, both interfacial heat transfer and interfacial friction properties depend on the detailed distribution of asperities on the contacting surfaces, surface contamination, and a variety of other surface properties that change from part to part, and perhaps moment to moment, in real production processes.

Simulations can be used effectively in such an environment to assess the sensitivity of the design to variations in parameters whose values are uncertain. Further, they can be used to guide the design process into those regions of the design space where the sensitivity is low. This process can be formalized mathematically, and the codes can be used to produce an optimal design, where such sensitivities are minimized. The implementation of optimal design methods early in the design process represents a significant opportunity to improve design methods using simulations. Such case studies are presented in Chapter 3.

In most production parts, however, the final product will still depend strongly on the interfacial processes. Sensors can be deployed in prototypes (or in production) to provide measurements that can be used with the aid of simulations to characterize those properties that are uncertain. The simulation results can be used in turn to control the process.

For example, interfacial heat transfer characteristics are very important in many solidification processes. The microstructure of the product depends on the local thermal history, which can depend in a very complicated way on the surface heat transfer characteristics. Since the interfacial characteristics cannot be completely predicted, temperature sensors embedded in the mold can be used to "tune" the simulation parameters. The data from such sensors can also be used in conjunction with modeling to provide process control. In a similar way, temperature sensors can be embedded in machine tools to determine tool wear.

The ability to use sensors to detect the process is still rather limited. Temperature and displacement can be measured rather easily using a variety of well-established techniques. Sensors that measure the condition of a part, such as internal defects and cracks, would greatly improve the reliability of parts in service.

3

Tools for Virtual Design and Manufacturing

Five technical domains have been identified in which virtual design and manufacturing tools exist or where important areas of knowledge and practice are supported by information technology: systems engineering, engineering design, materials science, manufacturing, and life-cycle assessment. However, progress is needed in order to more fully take advantage of these models, simulations, databases, and systematic methods. Each of the domains is largely independent of the others, although links are being made, bridges are being built, and practitioners and researchers in each domain recognize the value of knowledge in some of the other domains. Intercommunication and interoperability are two prerequisites for serious progress. Formidable technical and nontechnical barriers exist, and the committee offers recommendations in each domain.

TOOL EVOLUTION AND COMPATIBILITY

Throughout human history tools have evolved, typically driven by technological availability, market dynamics, and fundamental need. In agriculture, teams of oxen have been replaced by sophisticated tractors with specialized attachments. Computing tools have morphed from fingers and toes to abacuses to slide rules to calculators to high-performance computers. The software used within these computing systems has evolved in terms of programming levels of abstraction and overall functionality. Software not only is written as an end item that operates within a product, but now also gets developed as models and simulations to emulate the end item itself in order to perfect its eventual production, field use, and retirement. Software-based tools are developed to create and use these models and simulations to best perform design, engineering analyses, and manufacturing. Table 3-1 lists examples of available tools and the areas in which they operate.

Advanced engineering environments (AEEs) are integrated computational systems and tools that facilitate design and production activities within and across organizations. An AEE may include the following elements:

- Design tools such as computer-aided design (CAD), computer-aided engineering (CAE), and simulation
- Production tools such as computer-aided manufacturing (CAM), manufacturing execution system, and workflow simulation

TABLE 3-1 Representative Tools Used in the Industry

		System Life Cycle						
				Engineering/Technical Cost Analysis				
				Systems Engineering				
	Activity	*Marketing*		*Product Engineering*		*Industrial Engineering*		*Marketing*
	Function	**Mission, or Customer Needs**	**Product Planning**	**Product Architecture**	**Engineering Design**	**Manufacturing Engineering**	**Manufacturing Operations**	**Field Operations**
	Action	*Requirements Analysis*	*Functional Analysis*	*Synthesis*	*Analysis, Visualization, and Simulation*	*Analysis and Visualization*	*Production and Assembly*	*Use, Support, and Disposal*
Business case	Forecasting	@Risk, Crystal Ball, Excel, i2, Innovation Management, JD Edwards, Manugistics, Oracle, PeopleSoft, QFD/Capture, RDD-SD, SAP, Siebel	Arena PLM, Eclipse CRM, Innovation Management, MySAP PLM, RDD-SD, specDEV, TRIZ	Arena PLM, Innovation Management, MySAP PLM, RDD-IDTC, specDEV, TRIZ	Arena PLM, Innovation Management, MySAP PLM, RDD-IDTC, specDEV, TRIZ	Arena PLM, Innovation Management, MySAP PLM, specDEV, TRIZ	Arena PLM, MySAP PLM, specDEV, TRIZ	Innovation Management
	Product Life-Cycle Planning and Management	Innovation Management, QFD/Capture, RDD-RM	Geac, I-Logix, Innovation Management, Invensys, JD Edwards, Oracle, PeopleSoft, RDD-SA, SAP, Windchill	Innovation Management, RDD-SD	Functional Prototyping, RDD-SD	Functional Prototyping		Innovation Management, RDD-SD
	Resource Planning	Project, RDD-DVF, RDD-SD, TaskFlow Management	Innovation Management, RDD-DVF, RDD-SD	DSM, Geac, Invensys, JD Edwards, Oracle, People Soft, RDD-SD, SAP, TaskFlow Management	DSM, Project, RDD-SD, TaskFlow Management	TaskFlow Management, HMS-CAPP	TaskFlow Management	TaskFlow Management
Computer-aided engineering	Modeling	Caliber, DOORS, RDD-SD, RDD-OM, Innovation Management, Statemate	Caliber, DOORS, Innovation Management, RDD-OM, Statemate	ADAMS, Caliber, DADS, DOORS, Dynasty, EASA, Engineous, Innovation Management, LMS, MatLab, MSC, Opnet, Phoenix, RDD-OM, RDD-SD, Statemate, VL	Abaqus, AML, Ansys, AutoCAD, AVL, Caliber, CATIA, DOORS, EASA, EDS, Engineous, Fluent, Functional Prototyping, IDEAS, MSC, Opnet, Phoenix, ProE, RDD-SD, StarCD, Statemate, Unigraphics, Working Model	Caliber, DFMA, DOORS, Functional Prototyping	Caliber, DOORS	Caliber, DOORS, Innovation Management

		System Life Cycle						
				Engineering/Technical Cost Analysis				
				Systems Engineering				
	Activity	*Marketing*		*Product Engineering*		*Industrial Engineering*		*Marketing*
	Function	**Mission, or Customer Needs**	**Product Planning**	**Product Architecture**	**Engineering Design**	**Manufacturing Engineering**	**Manufacturing Operations**	**Field Operations**
	Action	*Requirements Analysis*	*Functional Analysis*	*Synthesis*	*Analysis, Visualization, and Simulation*	*Analysis and Visualization*	*Production and Assembly*	*Use, Support, and Disposal*
Computer-aided engineeing	Simulation	Caliber, DOORS, Innovation Management, RDD-DVF, Statemate	Caliber, DOORS, Innovation Management, RDD-DVF, Statemate, Working Model	Caliber, DOORS, CATIA, Delmia V5, Enovia V5, RDD-SD, Innovation Management, Statemate	Abaqus, AML, ANSoft, Ansys, Caliber, DICTRA, DOORS, DYNA3D, EASA, EDS, Engineous, Functional Prototyping, ICEM CFD, LMS, ModelCenter, MSC, NASTRAN, Phoenix, RDD-SD, Statemate, Stella/Ithink	Caliber, DOORS, Functional Prototyping, HMS-CAPP	Caliber, DOORS	Caliber, DOORS, Innovation Management
	Visualization	Innovation Management, RDD-OM, Statemate	Innovation Management, RDD-OM, RDD-SD, Statemate	CATIA, Delmia V5, EDS, Enovia V5, Innovation Management, Jack, RDD-SA, Slate, Statemate	Abaqus, ACIS, Amira, Ansys, EDS, EnSight, Fakespace, Functional Prototyping, Ilogix, Jack, MatLab, Open-DX, RDD-SD, Rhino, SABRE, Simulink, Slate, Statemate, VisMockup	Functional Prototyping, Statemate		Innovation Management
Computer-aided manufacturing	Product Data Management	Innovation Management	Innovation Management	CATIA, Delmia V5, Enovia V5	CATIA, Dassault, Delmia V5, EDS, Enovia V5, Metaphase, PTC, Windchill			Innovation Management
	Electronic Design Automation	Caliber, DOORS	Caliber, DOORS, MatLab	Caliber, Doors, Integrated Analysis, Simulator, Verilog-XL	Cadence, Caliber, Dassault, DOORS, Integrated Analysis, Neteor Graphics, PTC, System Vision	Caliber, DOORS	Caliber, DOORS, PADS	Caliber, DOORS, Integrated Analysis
	Manufacturing System Design	Functional Prototyping, RDD-ITDC, RDD-SD	Innovation Management, RDD-ITDC, RDD-SD	Integrated Data Sources, RDD-ITDC, RDD-SD	CimStation, Envision/Igrip, Integrated Data Sources, RDD-ITDC, RDD-SD	CIM Bridge, EDS, Tecnomatix		Functional Prototyping

continues

TABLE 3-1 continued

Computer-aided manufacturing	Manufacturing System Modeling	Functional Prototyping, RDD-ITDC, RDD-SD	Functional Prototyping, RDD-ITDC, RDD-SD	DICTRA, Functional Prototyping, Pandat, RDD-ITDC, RDD-SD, Thermo-Calc	Abinitio, CimStation, Dante, DEFORM, Envision/Igrip, Functional Prototyping, MAGMA, ProCast, RDD-ITDC, RDD-SD, SysWeld	Abinitio, Arena, Dante, DEFORM, Extend, Functional Prototyping, MAGMA, Pro/Model, ProCast, Simul8, SysWeld, TaylorED, Witness	Abinitio, Dante, DEFORM, Functional Prototyping, MAGMA, ProCast, SysWeld	Functional Prototyping
	Manufacturing System Simulation		Functional Prototyping	Caliber, DOORS, Functional Prototyping	Abinitio, Caliber, CimStation, Dante, DEFORM, DOORS, Envision/Igrip, MAGMA, ProCast, SysWeld	Abinitio, Arena, Caliber, Dante, DEFORM, DOORS, Extend, MAGMA, Pro/Model, ProCast, Simul8, SysWeld, TaylorED, Witness	Abinitio, Dante, DEFORM, MAGMA, ProCast, SysWeld	
	Manufacturing System Visualization	Functional Prototyping	Functional Prototyping	Functional Prototyping	CimStation, Envision/Igrip, Functional Prototyping	Arena, Extend, Functional Prototyping, Pro/Model, Simul8, Taylor ED, Witness	Abinitio, Functional Prototyping, MAGMA, ProCast, SysWeld	Functional Prototyping
	Reliability Models	RDD-ITDC , RDD-SD	Functional Prototyping, RDD-ITDC, RDD-SD	DEFORM, DisCom2, Functional Prototyping, RDD-ITDC, RDD-SD	CASRE, Functional Prototyping, RDD-ITDC, RDD-SD		JMP, Minitab, SAS, WinSMITH	RDD-ITDC , RDD-SD
	Logistics	Eclipse ERP, Integrated Analysis, RDD-ITDC, RDD-SD	Integrated Analysis, RDD-ITDC, RDD-SD	RDD-ITDC , RDD-SD	Integrated Analysis, RDD-ITDC, RDD-SD	Integrated Analysis	JD Edwards, Logistics, Manugistics	Integrated Analysis, RDD-ITDC, RDD-SD
	Purchasing	Purchasing plus					I2, Invensys, JD Edwards, Oracle, PeopleSoft, PTC, SAP	
	Supervisory Control				QUEST		Invensys, Siemens	
	Machine Control				Virtual NC		Labview, MATLAB, Unigraphics	

- Program management tools such as configuration management, risk management, and cost and schedule control
- Data repositories storing integrated data sets
- Communications networks giving participants inside and outside the organization secure access to data

As shown in Table 3-1, most of these tools exist today, but an AEE is more than just a collection of independent tools. Tools must be integrated to provide interoperability and data fusion. Organizational and interorganizational structures must be configured to reward their use and workforce skills must be enhanced to make effective use of their capabilities.[1]

The Carnegie Mellon University Software Engineering Institute (SEI) studied the use of AEEs and concluded that they exist within a broad domain, across all aspects of an organization. AEEs provide comprehensive coverage of and substantial benefits to design and manufacturing activities:

- Office applications such as word processing, spreadsheets, and e-mail, are already familiar to nearly everyone.
- Computer-aided design and integrated solid modeling not only improve the quality of the engineering product but also provide the basis for the exchange of product data between manufacturers, customers, and suppliers.
- Computer-aided engineering enables prediction of product performance prior to production, providing the opportunity for design optimization, reducing the risk of performance shortfalls, and building customer confidence.
- Manufacturing execution systems provide agile, real-time production control and enable timely and accurate status reporting to customers.
- Electronic data interchange provides up-to-date communication of business and technical data among manufacturers, customers, and suppliers.
- Information security overlays all operations to keep data safe.

Figure 3-1 is a modification of an SEI chart presented to the committee that helps show the widespread and pervasive use of software that bridges many functions and levels throughout the design and manufacturing enterprise. Enterprise viewpoints concentrate on near-term, mid-term, and far-term perspectives in the context of factory floor execution, tactical analysis, and strategic thinking, respectively.

A product's evolution typically is split into many phases to show its various stages, and most tools can be categorized in terms of the temporal nature of their use. In this case, the committee has elected to view a product's life cycle as shown here in seven stages, from mission needs to field operations. Figure 3-1 shows that there is little overlap between manufacturing modeling and simulation tools, or manufacturing process planning, and engineering design tools, reflecting the lack of interoperability between these steps with currently available software.

Many vendors sell tools that are now beginning to offer intriguing solutions toward overlap of key functions. Table 3-1 shows representative examples of some of these tools now being used in industry.[2] For example, to address CADCAE interoperability, process integration and

---

[1] National Research Council, *Advanced Engineering Environments: Achieving the Vision, Phase 1,* National Academy Press, Washington, D.C., 1999.

[2] In addition, Appendix C describes some of the current engineering design tools and Appendix D provides a list of representative vendors of computer-based tools used for design and other functions.

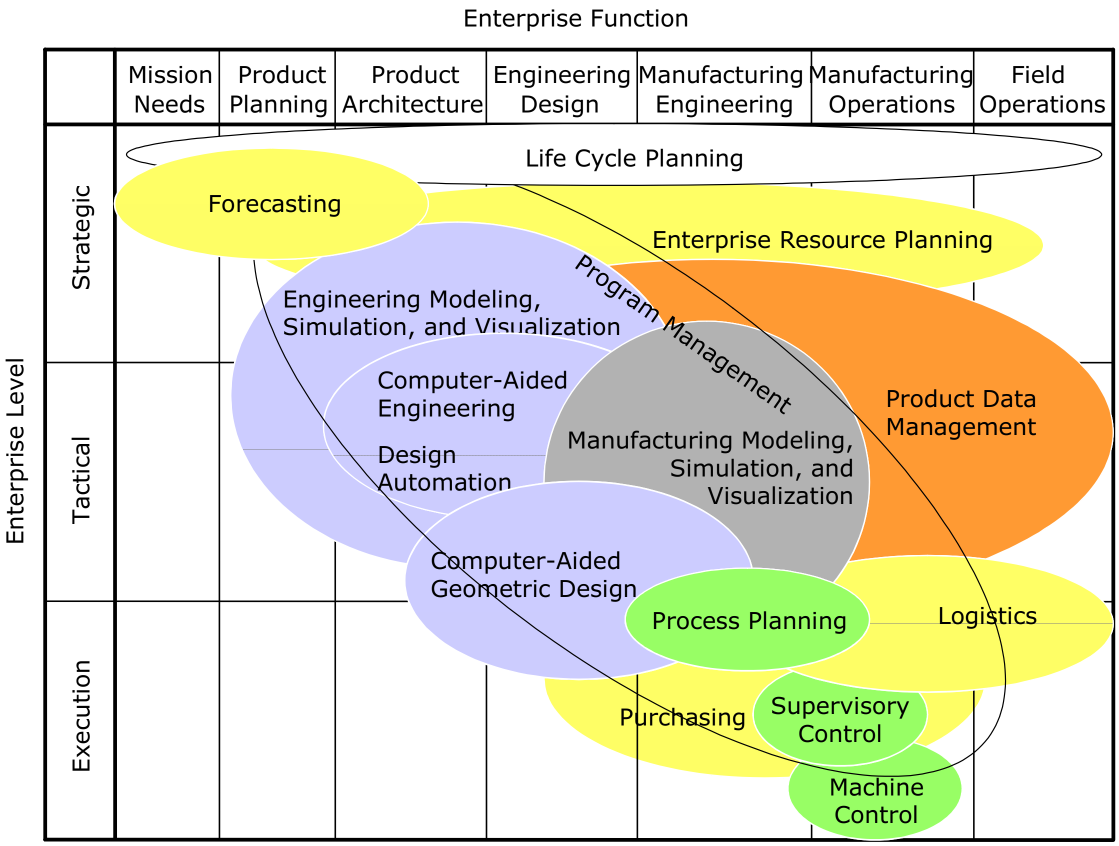


FIGURE 3-1 Overlay of tools that bridge design and manufacturing. Each ellipse within the chart represents a different tool category. Ellipse size connotes the comprehensiveness of the capabilities of those tools within the matrix, and color shading (or lack thereof) highlights the focus of the various tools' strengths in design, manufacturing, business operations, or management. Blue shades indicate a concentration in design, while green trends into manufacturing. Yellow hues show a proclivity toward business operations. Orange indicates the prominence and importance of data management. Ellipses void of color detail project management functions. Source: Special permission to reproduce figure from "Advanced Engineering Environments for Small Manufacturing Enterprises," © 2003 by Carnegie Mellon University, is granted by the Software Engineering Institute.

design optimization software tools that bundle discrete tools in order to facilitate multiprocess optimization are being introduced. Examples of such software are Synaps/Epogy, Isight, and Heeds from Red Cedar Technology. While these software packages look attractive in principle, human input still becomes essential to bridge the gaps between various analytical tools.

This chapter covers in depth the state of affairs within each of five different tool categories:

- The section titled "Systems Engineering Tools" explains how philosophies are expanding from narrow discrete-element minimization to design-trade-space optimization strategies and, while many tools exist within their own specialized field, recommends the need for supervisory control and common links between individual routines.
- "Engineering Design Tools" discusses the current capabilities of engineering design methods and software and their general lack of interoperability. It makes recommendations to improve communication between design and manufacturing software so that engineering models can be exchanged and simulated in multiple

environments.

- "Materials Science Tools" describes how properties of materials limit the design process and recommends improved physical models and property databases to support virtual design and manufacturing.
- "Manufacturing Tools" portrays advances in software ranging from detailed process planning and simulation models through production and enterprise management systems, focusing explicitly on issues related to the scope and scale of tools to design for X (DfX), where X is a variety of manufacturing parameters. It recommends organizational and algorithmic approaches for addressing obstacles.
- "Life-Cycle Assessment Tools" measures the total environmental impact of manufacturing systems from the extraction of raw materials to the disposal of products and evaluates product and process design options for reducing environmental impact.

SYSTEMS ENGINEERING TOOLS

The phrase, topic, and discipline "systems engineering" in the context of industrial manufacturing has evolved over the last several decades such that it now includes more topics and encompasses a far greater portion of the product life cycle than Henry Ford probably could have envisioned in 1914. By 1980, systems engineering thinking in this context was expanding; but it was still essentially limited to the industrial engineering skill of maximizing production to minimize cost by minimizing the time required to perform each individual manufacturing step or assembly action. The underlying assumption was that minimizing the time required for each discrete event would also minimize the total cost to manufacture an item. As such, the concepts were not applicable until production commenced and then they were only applied to minimize the cost after the product was designed and the manufacturing process or assembly line was defined. Systems engineering and the discrete event minimization strategy in the early 1900s could not have predicted Henry Ford's departure from a traditional batch assembly philosophy to the assembly line concept. Even though the resultant unit cost was dramatically reduced, the significant increases in time to first article, cost to design, and cost of construction were seen as insurmountable barriers. The assembly line was an unpredictable revolutionary change from the evolutionary manufacturing improvements associated with discrete event minimization.

During the last two decades, systems engineering has evolved to include the cost of automated machine tools as alternatives to labor and has developed several very different cost profiles; but the optimizations were still being performed at the simple part or discrete work element level. And the evaluations were being conducted on an essentially static, or already designed and about to be built, factory. While computers had become readily available in the 1980s, there were no fundamental changes in the process of minimizing the discrete events to minimize the total cost. The computers only crunched more numbers. Today's hardware and software are capable of simulating multiple, if not essentially unlimited, factory designs and equipment variations, giving the systems engineer the ability to affect both prior to a factory's construction.

When the full costs of labor, shipping, and work in process are included in the evaluations, the systems engineer can also affect the manufacturing site selection. But the same discrete-element minimization mentality remains. Current thinking and research in systems engineering are beginning to expand the scope from focusing on discrete work elements to analyzing entire operations, lines, factories, or enterprises to optimize the total cost of a given design or set of designs. With the continuously increased speed and lowered cost of computing, this is generally possible. But the task is being performed by brute-force methodology whereby all known permutations and combinations of discrete events are tried and all but the best are excluded.

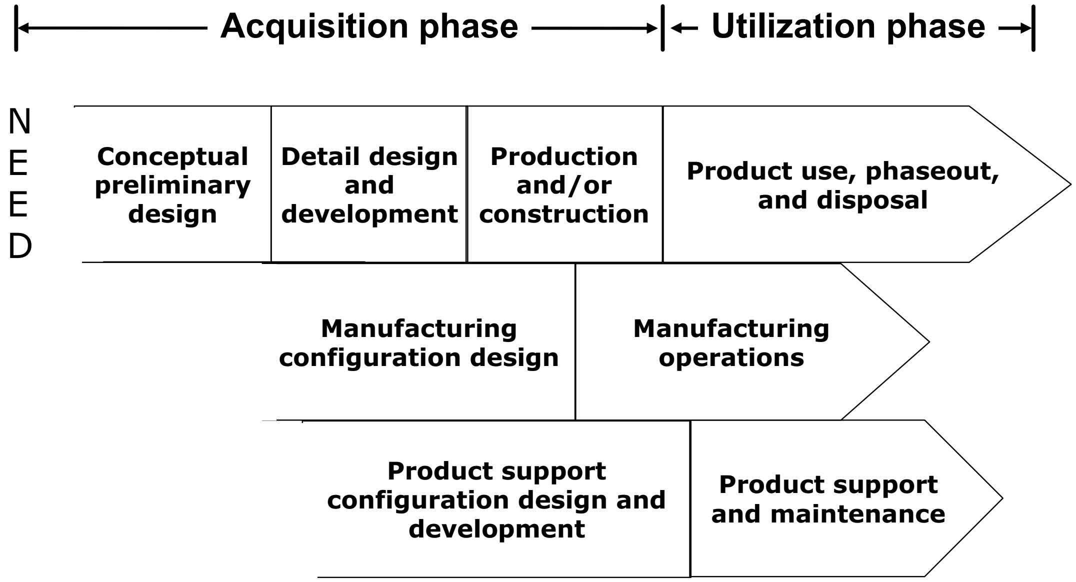


FIGURE 3-2 Expanded systems engineering phases. Source: B.S. Blanchard and W.F. Fabrycky, *Systems Engineering and Analysis*, 3rd Edition, © 1998. Reprinted by permission of Pearson Education Inc., Upper Saddle River, N.J.

During the last 10 years, systems engineering has matured to the point that it is not an uncommon degree program in universities. Industry and defense both utilize the discipline, and there is a globally recognized organization that represents the practitioners. The International Council on Systems Engineering (INCOSE) defines the subject as ". . . an interdisciplinary approach and means to enable the realization of successful systems." Further, INCOSE lists seven functional areas included in systems engineering (operations, performance, testing, manufacturing, cost and scheduling, training and support, and disposal).[3]

Blanchard and Fabrycky bring many of the systems engineering concepts and phases together in their book as shown in Figure 3-2. Other authors have described systems engineering as having four (Figure 3-3), seven (Figure 3-1), and even eight (Figure 3-4) phases. The important factors to observe from all this are that systems engineering can include everything from determination of the need for a product to its disposal, and that there are significant overlapping phases (notably design and manufacturing) that require interconnections and the sharing of data and information.

Engineering Cost Analysis

The next logical advance is what is referred to as an engineering or technical cost analysis. In its simplest form, it may be no more than a spreadsheet listing the phases found in the product concept through product realization cycles on one axis and identifying the many functional areas, costs, or even software tools on the other. This committee elected to settle on seven phases and portray the traditional flow of effort (time) from left to right as shown in Table 3-1: function; mission or customer needs; product planning; product architecture; engineering design; manufacturing engineering; manufacturing operations; and field operations.

---

[3] International Council on Systems Engineering. Available at: http://www.incose.org. Accessed April 2004.

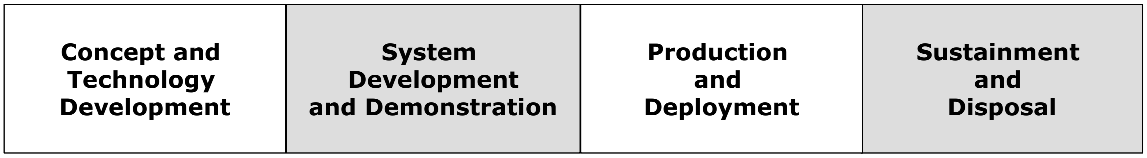


FIGURE 3-3 Life-cycle phases collapsed into four. Source: R. Garrett, Naval Surface Warfare Center, "Opportunities in Modeling and Simulation to Enable Dramatic Improvements in Ordnance Design," presented to the Committee on Bridging Design and Manufacturing, National Research Council, Washington, D.C., April 29, 2003.

A significant number of companies are already identifying where there is a need to communicate and work together both within the company divisions and with other companies. In its second-generation form, engineering cost analysis software will approximate the costs associated with each phase of the product development–realization cycle. In its ultimate form, the engineering cost analysis will include and improve upon all of systems engineering's current discrete event optimization functions; but, more importantly, it will extend forward in time to include accurate estimates for various design, material, and process selection options. In some instances, it may also include the determination of the optimum product concept to satisfy the intended customers' needs and cost constraints. Numerous presentations to the committee made the point that increased and improved communications between all phases will significantly reduce the time from concept to first article.

Some examples of time savings that have already been achieved were presented to the committee:[4]

- Chrysler, Ford, and GM have reduced the interval from concept approval to production from 5 to 3 years.
- Electric Boat has been able to cut the time required for submarine development in half—from 14 years to 7 years.
- 38 Sikorsky draftsmen took 6 months to develop working drawings of the CH-53E Super Stallion's outside contours. With virtual modeling and simulation, a single engineer accomplished the same task for the RAH-66 Comanche Helicopter in 1 month.
- 14 engineers at the Tank and Automotive Research and Development Center designed a low-silhouette tank prototype in 16 months. By traditional methods this would have taken 3 years and 55 engineers.
- Northrop Grumman's CAD systems provided a first-time, error-free physical mockup of many sections of the B2 aircraft.
- The U.S. Navy's modeling and simulation processes for the Virginia-class submarine reduced the standard parts list from ~95,000 items for the earlier Seawolf-class submarine to ~16,000 items.

It is necessary to provide the engineer at the CAD terminal with new and improved software tools that can give guidance regarding the life-cycle costs of each design decision in both preliminary and detailed design. For example, specific data could be made available to the designer regarding the alternative costs of various manufacturing approaches such as

---

[4] M. Lilienthal, "Observations on the Uses of Modeling and Simulation," presented to the Committee on Bridging Design and Manufacturing, National Research Council, Washington, D.C., February 24, 2003.

CONCEPT EXPLORATION
Analysis of Alternatives
Operational Analysis
Business Process Reengineering

COMPONENT ADVANCED DEVELOPMENT
Advance Concept Tech Demonstration
Systems Architecture Developed
Component Technology Demo

SYSTEM INTEGRATION
System Definition Effort
Preliminary Design Effort
Functional Baseline
Allocated Baseline

SYSTEM DEMONSTRATION
Product Baseline
Detail Design Effort

RATE
Establish Manufacturing Capability
Low Rate Initial Production
Initial Operational Test and Live Fire Test
Full Rate Production
Deployment

SUSTAINMENT
Block Modifications
Engineering Change Proposals
Evolutionary Requirement Development
Test and Evaluation
Tech Manual Development

DISPOSAL
Environmental Compliance

FIGURE 3-4 Life-cycle phases expanded into the eight indicated at the top of the figure. Source: A. Adlam, U.S. Army, "TACOM Overview," presented to the Committee on Bridging Design and Manufacturing, National Research Council, Washington, D.C., June 25-26, 2003.

automatic tape lay-up, injection molding, or electron beam welding, which could be selected to reduce unit manufacturing costs. In addition, reliability data for such proven components as hydraulic actuators, electrical connectors, and generators could easily be made available through interconnected databases to achieve a first-cut design that was reliable, maintainable, and low cost. This would be a huge step towards giving customers low total life-cycle costs.

It is critical to note, and generally ignored, that the geometrical shape of a part or assembly will determine the subsequent manufacturing processes by which it may be made and will, inadvertently, limit the materials to just those few that are suitable for those processes. This limitation has led to the rule of thumb that the majority of cost reduction opportunities are lost at the time a part is designed. Frequently, multiple design concepts or design/material combinations will satisfy a desired function. For that reason, it is imperative that all design options, along with their associated manufacturing processes and materials, be evaluated prior to committing to a final design strategy.

Again, several presentations to this committee emphasized the importance of improving the assessment of needs and the exploration of the design trade space and a means to minimize total life-cycle costs. Figure 3-5 shows one author's views on when and where the full cost of a product is locked in. Other authors provided additional guidelines to support the value of up-front design analysis.

Some guidelines presented to the committee[5,6] are listed below:

---

[5] J. Hollenbach, "Modeling and Simulation in Aerospace," presented to the Committee on Bridging Design and Manufacturing, National Research Council, Washington, D.C., February 24, 2003.

[6] A. Haggerty, "Modeling the Development of Uninhabited Combat Air Vehicles," presented to the Committee on Bridging Design and Manufacturing, National Research Council, Washington, D.C., April 29, 2003.

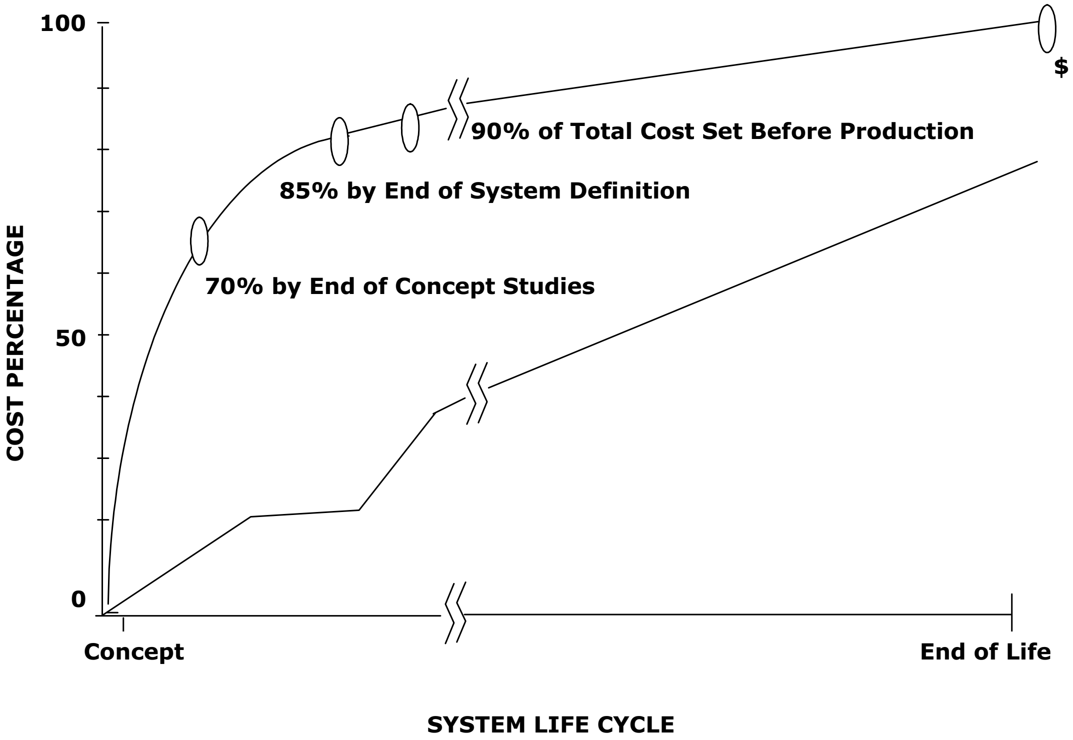


FIGURE 3-5 Product cost locked in very early in process. Source: M. Lilienthal, Defense Modeling and Simulation Office, “Observations on the Uses of Modeling and Simulation," presented to the Committee on Bridging Design and Manufacturing, National Research Council, Washington, D.C., February 24-25, 2003.

- Continue the early collaborative exploration of the largest possible trade space across the life cycle, including manufacturing, logistics, time-phased requirements, and technology insertion.
- Perform assessments based on modeling and simulation early in the development cycle—alternative system designs built, tested and operated in the computer before critical decisions are locked in and manufacturing begins.
- Wait to develop designs until requirements are understood.
- Requirements are the key. Balance them early!
- Once the design is drawn, the cost and weight are set.
- No amount of analysis can help a bad design get stronger or cheaper.
- Remember that 80 percent of a product's cost is determined by the number of parts, assembly technique, manufacturing processes, tooling approach, materials, and tolerances.

The linkages between design, manufacturing, and materials, combined with the value of reaching the customer in the least amount of time, support a robust business case for quick development of initial products. This increased effort at the start would be at a higher than optimal initial cost, but with scheduled updates and design changes would result in future improved reliability and cost while maintaining service part commonality. This approach could also result in the discovery of design and manufacturing strategies corresponding to an immediate need; when the product development cycle is shortened, products can be designed to be more responsive to specific customer requirements.[7] Design and manufacturing concepts that factor in the initial cost to design and manufacture as well as the cost to maintain production and service parts far into the future could be discovered as well.

In its early forms, engineering cost analysis will be forced to simplify the details of most steps of the process, from concept to realization, by assuming generalized time and cost models. While this may seem crude, a manufacturing engineer frequently can make a relatively accurate estimate of a part cost based on its general shape, size, and function, just as a product engineer can provide a similarly accurate estimate of the cost to design a product (or number of parts) based on its complexity, size, and intended use. In this early form, the engineering cost analysis is unlikely to provide an accurate final cost, but it is expected to accurately rank the various options examined. As computing power and cost continue to follow Moore's law and as individual program data input/output structures are modified to complement each other, more refinements and accuracy will be obtained and more options may be explored. However, today's state of the art in cost analyses is still inadequate. Development of refined cost analysis tools is vitally needed in the aerospace industry where "dollars per pound" of airframe is still used for many calculations.

Whether engineering cost analysis is only another in a series of evolutionary improvements in the industrial systems engineering business process or truly a step function improvement, there will still be significant unknowns and effort required to bring it to fruition and realize its value. Unifying the description of parts (two-dimensional vs. three-dimensional, or solid vs. surface), characterizing manufacturing process effects, designing and developing materials and verifying their properties, creating complementary interprogram data structures, and developing virtual visualization tools will not be easy and will require significant research. However, these developments still only require appropriate funding, time, and discipline to complete. In order to take advantage of these developments, it will be necessary to change the design and manufacturing business culture, so that it focuses on the total life-cycle cost rather than the cost of discrete events. Without this change, designers and manufacturing engineers will remain within their disciplines and continue to suboptimize their portion at the expense of the whole.

Manufacturing Cost Modeling

During conceptual design and concurrent with all other design-for-X (DfX) activities, the life-cycle cost of a product should be addressed. Twenty years ago engineers involved in the design of products may not have concerned themselves with the cost-effectiveness of their design decisions; that was someone else's job. Today the world is different. All engineers in the design process for a product are also tasked with understanding the economic trade-offs associated with their decisions. At issue are not just the manufacturing costs but also the costs associated with the product's life cycle.

Several different types of cost-estimating approaches are potentially applicable at the conceptual design level where engineering decisions about the technology and material content of a product are made.

Traditional material cost analysis uses parametric methods to determine the quantity of a material required in a product. The model then applies a cost policy that includes how the manufacturer does quoting, inventory methods, and method of purchase of commodity materials. To determine the total manufacturing cost, material costs are combined into traditional cost accounting methods where labor costs are included and overhead is applied. Variations in how material, labor, and overhead costs are computed and combined abound and

---

[7] An example might be a switch from a desert to an arctic conflict or simply between armed conflicts.

are summarized in the following paragraphs.

Activity-based costing[8] (ABC) focuses on accurate allocation of overhead costs to individual products. Other methods include function or parametric costing[9] in which costs are interpolated from historical data for a similar system. Similarly, empirical or cost-scaling methods[10] are parametric models based on a feature set. Parametric-based models are applicable to evolutionary products where similar products have previously been constructed and high-quality and large-quantity historical data, exist.

Sequential process flow models[11] attempt to emulate the actual manufacturing process by modeling each step in sequence and are particularly useful when testing, reworking, and scrapping occurs at one or more places in the process. Resource-based cost modeling[12] assesses the resources of materials, energy, capital, time, and information associated with the manufacture of a product and aims to enable optimum process selection. Resource-based modeling is similar to the specific process step models embedded within sequential process flow models. Each process step model sums up the resources associated with the step—labor, materials, tooling, equipment—to form a cost for the step that is accumulated with other steps in sequence. Resource-based modeling is the same as sequential step modeling except that use of a specific sequence is not necessarily required.

Technical cost modeling carries cost modeling one step further by introducing physical models associated with particular processes into the cost models of the actual production activities. Technical cost modeling[13] also incorporates production rate information.

With the advent of products such as integrated circuits, whose manufacturing costs have smaller materials and labor components and greater facilities and equipment (capital) components, new methods for computational cost modeling have appeared such as cost of ownership (COO).[14] Cost of ownership modeling is fundamentally different from sequential process flow cost modeling. In a COO approach, the sequence of process steps is of secondary interest; the primary interest is determining what proportion of the lifetime cost of a piece of equipment (or facility) can be attributed to the production of a single piece part. Lifetime cost includes initial purchase and installation costs as well as equipment reliability, utilization, and defects introduced in products that the equipment affects. Accumulating all the fractional lifetime costs of all the equipment for a product gives an estimate of the cost of a single unit of the product. Labor, materials, and tooling in COO are included within the lifetime cost of particular equipment.

As one might expect, there are pros and cons associated with all the approaches outlined above. Also, nearly all of the basic manufacturing cost models are supplemented by yield models, learning curve models, and test/rework economic models. Many commercial vendors exist for manufacturing cost modeling tools. Some examples are listed here:

---

[8] P.B.B. Turney, "How Activity-Based Costing Helps Reduce Cost," *Journal of Cost Management for the Manufacturing Industry*, Vol. 4, No. 4, pp. 29-35, 1991.

[9] A.J. Allen, and K.G. Swift, "Manufacturing Process Selection and Costing," *Proceedings of the Institute of Mechanical Engineers Part B—Journal of Engineering Manufacture*, Vol. 204, No. 2, pp. 143-148, 1990.

[10] G. Boothroyd, P. Dewhurst, and W.A. Knight, *Product Design for Manufacture and Assembly*, Marcel Dekker, Inc., 1994.

[11] C. Bloch and R. Ranganathan, "Process Based Cost Modeling," *IEEE Transactions on Components, Hybrids, and Manufacturing Technologies*, pp. 288-294, June 1992.

[12] A.M.K. Esawi and M.F. Ashby, "Cost Ranking for Manufacturing Process Selection," *Proceedings of the 2nd International Conference on Integrated Design and Manufacturing in Mechanical Engineering*, Compiègne, France, 1998.

[13] T. Trichy, P. Sandborn, R. Raghavan, and S. Sahasrabudhe, "A New Test/Diagnosis/Rework Model for Use in Technical Cost Modeling of Electronic Systems Assembly," *Proceedings of the International Test Conference*, pp. 1108-1117, November 2001.

[14] R.L. LaFrance and S.B. Westrate, "Cost of Ownership: The Suppliers View," *Solid State Technology*, pp. 33-37, July 1993.

- Cognition—process flow cost modeling
- Wright Williams & Kelly—cost of ownership modeling
- Savantage—conceptual design cost modeling
- ABC—ABC cost modeling
- IBIS—technical cost modeling
- Prismark—Niche parametric manufacturing cost modeling (for printed circuit boards)

Another area that is often overlooked is cost modeling for software development. Systems are a combination of hardware and software. Ideally hardware and software are "codesigned." Codesign allows an optimum partitioning of the required product functionality between hardware and software. Cost needs to be considered when these partitioning decisions are made. Several commercial tools allow the cost of developing new software, qualifying software, rehosting software, and maintaining software to be modeled. Historically, many of these tools are based on a public domain tool called COCOMO[15] and later evolutions of it.

Life-Cycle Cost Modeling

While manufacturing costing is relatively mature, life-cycle cost modeling is much less developed. For many types of products, manufacturing costs only represents a portion, sometimes a small portion, of the cost of the product. Nonmanufacturing life-cycle costs include design, time-to-market impacts, liability, marketing and sales, environmental impact (end of life), and sustainment (reliability and maintainability effects). While reliability has been addressed by conventional DfX activities, rarely are other sustainability issues such as technology obsolescence and technology insertion proactively addressed.

There are existing commercial tool vendors in the life-cycle cost modeling space as well; for example:

- Price Systems: parametric life-cycle management costing
- Galorath: parametric life-cycle management costing (SEER tools)
- NASA: well developed parametric cost modeling capabilities

One particular example of a life-cycle cost contributor for many types of systems is the lack of design-level treatment of technology obsolescence and insertion. This problem is already pervasive in avionics, military systems, and industrial controls and will become a significant contributor to life-cycle costs of many other types of high-technological-content systems within the next 10 years. Unfortunately, technology obsolescence and insertion issues cannot be treated during design today because methodologies, tools, and fundamental understanding are lacking.

Systems Engineering Issues

Box 3-1 shows four case studies of the use of systems engineering software tools in industry. In addition, the National Defense Industrial Association Systems Engineering Division Task Group Report,[16] issued in January, 2003, listed the top five issues in systems engineering:

---

[15] B. Boehm, *Software Engineering Economics*, Prentice-Hall, Inc., Upper Saddle River, N.J., 1981, p. 1.

[16] The National Defense Industrial Association, *The National Defense Industrial Association Systems Engineering*

- Lack of awareness of the importance, value, timing, accountability, and organizational structure of systems engineering programs
- Lack of adequate, qualified resources within government and industry for allocation within major programs
- Insufficient systems engineering tools and environments to effectively execute systems engineering within programs
- Inconsistent and ineffective application of requirements definition, development, and management
- Poor initial program formulation

Similarly to curriculum modification in the educational system, the business and employee reward system will also need overhauling to ensure that it rewards those who think strategically rather than those who function in the old but safe ways. So long as the ones receiving the greatest rewards are the designers who turn out the greatest number of prints and models, or the purchasing agents who negotiate the lowest price for a given part, process, or material, no one can justify spending any significant amount of time or effort in the development of a better method to achieve design goals.

Initially, this cultural change may require a totally separate organizational unit with a reward structure tailored to recognize enterprise successes rather than discrete events. To be fully successful, this new culture ultimately has to infect all levels and units of an organization. For that to happen incentives are needed for the manufacturing leadership to change both itself and the culture. The saving aspect of such a sea-change is that, once it is a part of the culture, all the participants—both old and new—will win. The need to focus a portion of product development on minimizing time and costs in the traditional ways will remain but will be incorporated into the larger picture.

Systems Engineering Opportunities

While the committee found many areas where there is need for data structure, program interconnectivity, and visualization, the entire area of systems engineering presents new opportunities to rethink what process an organization or institution utilizes as it proceeds from the needs assessment phase through design and manufacturing to use, support, and ultimately disposal. Several significant and valuable characteristics become routine through the rigorous application of systems engineering. A few of the most significant are listed here:

- Forces discipline
- Creates multidimensional, conceptual design trade space
- Enables multidisciplinary optimization
- Promotes and requires interoperability

Other related factors include the following:

- Forces cultural change in rewards

Division Task Group Report, February, 2003. Available at http://www.ndia.org/committees/MandS/February2003/top_5_issues.pdf. Accessed February 2003.

- Tools exist but not in widespread use
- Training required (academic and industrial)

Recommendation 1. Systems Engineering: The Department of Defense should develop tools to facilitate the definition of high-level mission requirements and systems-level decision making.

Tools to create, visualize, and analyze design and manufacturing alternatives can facilitate systems-level decision making. A specific opportunity is to develop tools for converting customer needs into engineering specifications, and for decomposing and distributing those specifications to subsystems and components.

Box 3-1
Four Case Studies on the Use of Systems Engineering Software Tools

Case Study 1

A simple example that illustrates trade-offs in design is the device that locates and carries the bearings and wheels that support the track on a tracked vehicle (such as a tank). This carrier can be designed either as an assembly of welded plates or as a casting. The welded version can be designed and placed into production in a fraction of the time required for a casting but is more costly to produce. An engineering cost analysis could predict that, for initial production and for long-term future service parts availability, the welded assembly would be preferred. That same analysis could predict that for many large-scale production applications, a casting would be preferred. The costs and value of each option could be evaluated and the lowest total cost option selected. And that analysis could predict that both options need to be developed: the welded version for initial production, and a scheduled update to replace it with a casting for the majority of its production life followed by reverting to a weldment when it goes into service-parts-only production.

Case Study 2

Siemens Transportation Systems utilized collaborative virtual product development software to create a complete cross-functional product definition and system-level simulation environment to validate total product functionality during the crucial concept phase of railway car manufacturing. Heinz-Simon Keil, Department Head, Corporate Technology, Production Processes Virtual Engineering: ". . . functional prototyping has enabled Siemens Transportation Systems to accelerate the overall virtual prototyping process and correct potentially costly errors on the fly before such errors are discovered in manufacturing."[a]

Case Study 3

Conti Temic Product Line Body Electronics utilized software tools to standardize model-based development for electronic control units (ECUs). It selected an integrated tool suite, the Statemate MAGNUM and Rhapsody in MicroC tool chain (or suite), to graphically specify designs, improve communication within its development team and with customers, reduce time to market through component reuse, and reduce costs by validating systems and software designs up front prior to implementation. This integrated tool suite provides Conti Temic with a development process from requirements to code, ensuring its applications are complete and accurate.

Conti Temic Body Electronics committed to the model-based approach due to the complexity and diversity of body control ECUs. Conti Temic system engineers create formal requirements specifications and then test their models in a virtual prototyping environment, ensuring that their ECU models are error free. The system behavior is validated as an integral part of the design process, before anything is built. Conti Temic is able to execute, or simulate, the design—either complete or partially complete—prior to implementation. Analyzing its specifications up front, Conti Temic ensures that behavior is correct and captures test data that will be used later to test the implementation. Conti Temic benefits from the ability to automatically generate high-quality target code, easily capture and use features or functions throughout the development process, and automatically generate documentation from the completed specification model. Working with supplier requirements, Conti Temic is able to visually express systems functionality and ensure, up front in the design process, that the product will meet the specifications.

In many cases, automotive original equipment manufacturers (OEMs) provide Conti Temic actual requirements models. The use of a standard tool between OEM and supplier could greatly reduce miscommunication common within the automotive industry. "In addition to facilitating communication, Conti Temic Body Electronics is able to quickly make changes and ensure their designs are solid if issues arise in ECU integration, functionality is changed late in the game, cost reductions are mandated, or variant derivation has to be incorporated and validated within the product," said Andreas Nagl, Software-Engineering, Conti Temic Product Line Body Electronics. "Due to the complexity of our products, the synchronization effort for requirements, analysis/design models, code and test cases increased exponentially with conventional static CASE tools. The Statemate MAGNUM and Rhapsody in MicroC tool chain (or suite), unlike static CASE tools, allows us to ‘feel' the systems behavior, make changes on the fly, validate our design, generate code and conduct tests much more quickly."[b]

Case Study 4

An aerospace contractor used requirements management software to model the systems architecture of a winner-take-all proposal to build a new cost-efficient AWACS aircraft for the Royal Australian Air Force. The contractor realized that using its standard document-driven methodology would not be successful and so it modeled the architecture at both a high level of abstraction and according to scenarios with lower levels of fidelity. The contractor also modeled its business processes and other key mission-critical items. This allowed the company to uncover and rectify many unforeseen issues significantly earlier in the design process and to reduce the risk to the proposal. The company realized that the use of both static and dynamic modeling had become indispensable to reducing program risk.

The contractor also decided to build multiple segmented and secure baselines for future use because it wanted to capture all of the key design knowledge of this project for use in developing future proposals. This data included classified, vendor proprietary, and customer-specific information that could not be shared in a single repository. This approach reflects the understanding that the ability to capture and reuse design knowledge is critical for long-term program evolution.

In the first design review, the customer found no discrepancy reports and the results of the final design review mirrored the first. The contractor team won the proposal on both technical merit and cost. The cost savings were so significant that the customer was able to purchase additional options once thought beyond its budget. Key to this success was project-level collaboration among all team members—systems engineers, software engineers, and managers—including translating among subcontractor design process methods and standards.

---

[a] Siemens Transportation Systems. Available at http://www.sts.siemens.com/aboutus/designbuild/peoplemover/index.html. Accessed October 2003.

[b] I-Logix, Press Release, October 15, 2002. Available at http://www.ilogix.com/news/press_detail.cfm?pressrelease=2002_10_15_025522_697127pr.cfm. Accessed May 2004.

ENGINEERING DESIGN TOOLS

Engineering design is the process of producing a description of a device or system that will provide a desired performance or behavior. Figure 3-6 is a typical chart depicting the steps in this process. The process begins with the determination or assessment of a need. Next, a set of requirements and constraints is established for the device or system, often also including a list of desired performances. At this stage in the process, the engineering team begins to propose alternative configurations. A series of calculations and analyses are performed to estimate how well each of the proposed configurations will satisfy the requirements and constraints, and deliver the desired performances. These analyses typically range from hand calculations to simple analytic expression to more sophisticated modeling and simulation, such as finite element modeling, thermal modeling, and computational fluid dynamics.

The results of these simulations are interpreted by the design engineers and used to refine the proposed configurations, and to reject those that appear to not satisfy the requirements and constraints. It is common to construct at least one prototype to verify the simulated performance of the proposed configuration(s). In this process, design engineers focus their attention primarily on achieving the desired performances, while meeting the requirements and constraints. Questions of manufacturability are typically a secondary consideration during the design process.

Engineering design is an iterative process between every step in the design process. Figure 3-6 does not proceed linearly downward. Instead, there are iterations back and forth between all the steps in the engineering design process, as shown by the long column box at the left in Figure 3-6.

Once a design configuration is selected, analyzed, simulated, prototyped, and validated, the design information is passed to the manufacturing engineers to design the manufacturing systems and processes to fabricate the design in the desired quantities. This manufacturing engineering process entails many of the same steps as in the engineering design process, including the application of sophisticated modeling and simulation.

Relationship of Engineering Design Tools to Manufacturing

Since the device or system must be fabricated in order to deliver a desired performance or behavior, engineering design should be closely linked to manufacturing. Indeed, frequently questions of manufacturability severely limit the range of design options available. However, in current engineering practice, as described above, the link between design and manufacturing is largely informal, based on the knowledge and experience of the engineers involved. While many engineering design and analysis software packages exist, and several powerful manufacturing simulation software packages exist, the link between these two domains remains weak. Appendix C describes some of the current engineering design tools, and Appendix D provides a list of representative vendors of computer-based tools used for design and other functions.

Current Status of the Bridge Between Design and Manufacturing

Figure 3-1 depicts the current status of the link, or bridge, between engineering design and manufacturing. The columns represent many of the identifiable stages in the design of a new product or system, with time proceeding from left to right. The rows indicate whether the tool or process depicted in the diagram contributes to strategic planning and decisions, or applies to tactical decisions and steps, or plays a role in carrying out the execution of the stage in the process. The width of the ellipse surrounding the name of each tool indicates the stages in the process in which the tool can play a role. The height of the ellipse indicates where the tool is effective, along the range from purely strategic planning to execution of individual process steps. Blue ellipses indicate engineering design processes. Green ellipses indicate manufacturing-related processes. Yellow ellipses indicate business functions, orange ellipses indicate data management, and empty ellipses represent overarching processes. The degree of overlap between ellipses indicates how much interaction there should be between tools.

As can be seen in Figure 3-1, engineering modeling, simulation, and visualization can play a strategic role in product architecture planning, and also a tactical role in guiding the detailed design processes. The detailed design process is initiated from the results of product

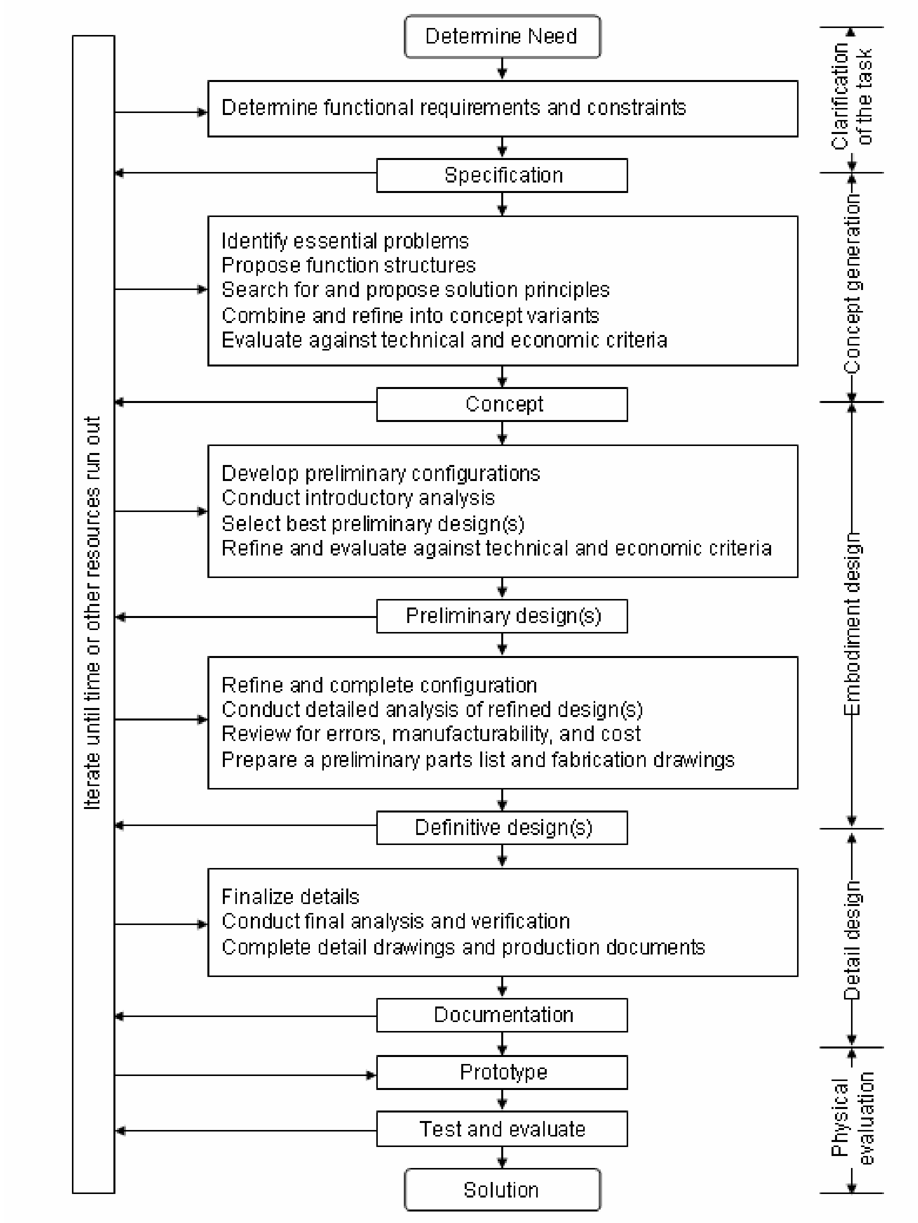


FIGURE 3-6 Steps in the engineering design process. Source: Adapted from G. Pahl and W. Beitz, *Engineering Design*, p. 41. Copyright © 1984 Springer-Verlag. Reprinted by permission of Springer-Verlag GmbH, Heidelberg, Germany.

architecture planning, and it results in a precise description of the product to be manufactured. The diagram shows that there is little overlap between manufacturing modeling and simulation tools, or manufacturing process planning, and engineering design tools, reflecting the lack of interoperability between these steps with currently available software. However, there are efforts being made to change this situation.

Box 3-2 shows a case study of an integrated design approach applied to unmanned undersea vehicles (UUVs). Past research and development activities to create a highly flexible and responsive design environment include the Defense Advanced Research Projects Agency's (DARPA) Rapid Design Exploration and Optimization (RaDEO) program.[17] Unigraphics NX is one example of an end-to-end product development solution for a comprehensive set of integrated design, engineering, and manufacturing applications.[18]

Roles for Computational Tools

As Figure 3-1 illustrates, the intercommunication and interoperation of engineering design and manufacturing computational tools can play a key role in establishing a strong bridge between design and manufacturing. During the study, the committee received multiple presentations that outlined a future vision of a stronger bridge and identified key difficulties that such a bridge could overcome, including:

- *Multiple models:* During the engineering and manufacturing process, each stage of the process, and each engineering discipline, typically employs computational tools, and builds computational models, that are unique to that activity. A key challenge is the time and effort required to create multiple models, and the difficulty in ensuring that the models are consistent. It is common for a change in configuration of a design to be introduced in one model but not propagate to others, leading to inconsistent analyses of performance and failures in the field.
- *Design reuse:* Because of the large number of noninteroperating engineering design and manufacturing software packages in use, it is not common for models of earlier similar designs to be reused and improved. Typically, a new model of an improved component or subsystem is constructed. In this environment, the incentive for engineers to reuse portions of earlier designs is limited.
- *"No-build" conditions:* One of the key roles for a stronger bridge between engineering design and manufacturing was repeatedly identified during the course of the study as the need, particularly early in the engineering design process, to be able to easily identify designs that cannot be fabricated or assembled (no-build conditions). Without the ability to analyze early designs for their capability to be fabricated and assembled, unrealizable designs can persist late into the design process.
- *Early manufacturing considerations:* Decisions made during the early engineering design stages typically determine 70 to 80 percent of the final cost of a product. Without a strong bridge between design and manufacturing, these decisions are commonly made with little information relating to costs and degree of difficulty of fabrication and assembly of a proposed design. This lack of manufacturing information in the early engineering design decision-making process is a key contributor to cost overruns late in the development cycle of a product.

Advancing the interoperability[19] and composability[20] of design and manufacturing software, particularly modeling and simulation, will contribute significantly to reducing the

---

[17] Defense Advanced Research Projects Agency, *Rapid Design Exploration and Optimization*. Available at: http://www.darpa.mil/dso/trans/swo.htm. Accessed February 2003.

[18] Unigraphics PLM Solutions, an EDS company, *NX: Overview*. Available at: http://www.eds.com/products/nx/. Accessed May 2004.

[19] In this context, interoperability is the ability to integrate some or all functions of more than one model or simulation during operation. It also describes the ability to use more than one model or simulation together to collaboratively model or simulate a common synthetic environment.

[20] In this context, composability is the ability to select and assemble components of different models or simulations in various combinations into a complex software system.

difficulties enumerated above.

- Multiresolution[21] interoperable models will reduce or eliminate the problems of multiple models and inconsistent analyses.
- Intercommunication between multiple engineering and manufacturing software packages will greatly enhance the ability of engineers to retrieve models of earlier designs and establish a starting point for a next-generation product.

Box 3-2
Integrated Design of Unmanned Undersea Vehicles

Technological innovations are facilitating the expanded use of UUVs to perform complex and dangerous missions.[a] Improvements in sensors, guidance and control, power systems, and propulsion systems have dramatically improved the functionality, flexibility, and performance of these vehicles. As a result, commercial and military interest in these vehicles and in the potential dual-use capability of these enabling technologies is keen. Another important technological innovation involves the design process itself.

Researchers at the Applied Research Laboratory (ARL) at Pennsylvania State University recently developed an integrated design process utilizing advanced computational methods and successfully applied it to develop a UUV system. Development of a new design methodology was made necessary by contractual requirements that mandated substantially shorter design time and lower design and ownership costs than traditional design methodology could deliver. Another inducement was the expectation that this investment in developing an integrated system could spill over to other applications and projects in the future. By several measures the effort was a success, reducing project cost and development time from 3 to 4 years to 12 to 18 months.

The integrated design tools developed by ARL minimize the need for numerous and expensive interim experiments, relying more on fundamental, physics-based computational models of fluid dynamics. The design path is conceptually similar to conventional design paths, with tunnel testing replaced with computer simulations. For example, the propulsor design and analysis tool (PDAT) and Reynolds-averaged Navier-Stokes (RANS) analysis are used extensively to simulate the drag and stability of a vehicle under different design parameters, such as length, diameter, and nose and tail contours. Computer automated design is also used for mechanical design and structural analysis. The maneuverability of the vehicle is simulated using an ocean dynamics model and pitching motion simulations, essentially replacing physical with numerical experiments.

The first vehicle designed with this integrated approach was completed in 14 months below projected cost and verified at Lake Erie. The UUV requirements, however, are generally far less demanding than many other defense and commercial products. The mission requirements for the UUV include low speed, variable payloads, a small fleet of 15 to 20 vehicles, and long-endurance missions. The design criteria, in order of importance, include reliability, cost, maneuverability, efficiency, and stealth. Simulation-based design approaches are also under development for advanced torpedoes and submarines but are likely to be more challenging because stealth and other design criteria that are more difficult and costly to achieve are relatively more important in these applications.

In committing to such an effort, ARL had to assume the risk of failure to deliver the product by the imposed deadline at the contractual cost. Risk, therefore, is a major consideration in devoting the necessary time and money to develop integrated design tools. In ARL's case, it had the experience and scientific knowledge to assess these risks and decided that they were worth assuming given the expected benefits, including the immediate goal of meeting the contractual specifications and the longer-term goals

---

[21] Multiresolution modeling is defined as the representation of real-world systems at more than one level of resolution in a model with the level of resolution dynamically variable to meet the needs of the situation.

of enhanced design capability and the greater likelihood of future contracts arising from improved goodwill with the project sponsors.

This case study illustrates that the keys to success of a new design strategy are advanced system requirements, reduced traditional development cycle times, reduced design and development costs, and reduced life-cycle or total ownership costs. These can be accomplished by early application of the systems design approach to increase the number and fidelity of design trade-off analysis.

The development of the UUV offers several lessons for bridging the gap between design and manufacturing. The physics-based models developed at ARL will play an important role in future integrated design efforts, particularly in simulating product performance. The UUV project at ARL also illustrates that tool development is not the result of a targeted research and development program but rather a means to an end. Perhaps this approach provides for more efficient tool development and integration. On the other hand, the lack of targeted research and development funding for tool integration may hinder the development of truly path-breaking integrated design simulation tools.

Another constraint encountered by ARL was computer resources. The computations were performed using networked computer workstations. Supercomputer resources were accessible but not as available on a real-time basis. Both computing environments, however, pose limits on the degree of accuracy in the models, particularly those that model cavitation and acoustics. As computer speeds increase in the future, modeling these processes at finer resolution will be possible.

Finally, the availability of U.S. citizens to work on these projects is limited and poses some real constraints on system integration development. This last constraint raises a number of training and education issues that may be particularly vexing for policy makers as they seek ways to foster a more efficient design process.

---

[a] M.J. Pierzga, "ARL Integrated Design Approach Using Computational Fluid Dynamics," and C.R. Zentner and W.M. Moyer, "Unmanned Undersea Vehicle Technology," *Applied Research Laboratory Review*, Pennsylvania State University, University Park, Pa., pp. 21-22, May, 2001.

- Testing and resolving no-build conditions early in the design process will reduce or eliminate the costs of maturing a design that cannot be fabricated or assembled late into the design process.
- Perhaps the most critical improvement that can result from the integration of design and manufacturing models is that early design decisions can be made with consideration of the manufacturing ramifications. This integration can have a dramatic impact on the total product cost.

Recommendation 2. Engineering Design: The Department of Defense should develop interoperable and composable tools that span multiple technical domains to evaluate and prioritize design alternatives early in the design process.

Improving interoperability, composability, and integration of design and manufacturing software is a complex problem that can be addressed with near-, mid-, and long-term objectives. In the near term, developing translators between existing engineering design environments and simulation tools can solve problems with minimum effort. In the mid term, a common data architecture can improve interoperability among engineering design environments and simulation tools. Key long-term research goals include (1) the development of interoperable modeling and simulation of product performance, manufacturability, and cost; (2) the creation of tools for automated analysis of design alternatives; and (3) the application of iterative optimization using both new and legacy codes.

MATERIALS SCIENCE TOOLS

The goal of materials science and engineering is to link the structure and composition of materials with their manufacturing and properties—in other words, to develop models for materials behavior and performance during and after manufacturing. To achieve this, materials engineers utilize various tools that extend the entire length scale—from the electronic through the continuum scale. In fact, a long chain of successful models punctuates the history of materials science. Some models, such as those based on semiconductor device theory, rely on fundamental physics; others, such as annealing curves, arise from phenomenology; and most, such as phase diagrams, combine theory and observation. Within the past two decades, the subspecialty of computational materials science has provided additional modeling tools to the materials scientist. With applications ranging from empirical (expert systems) to fundamental (ab initio electronic structure calculations), computational materials science enables a more integral link between materials, design, and manufacturing as illustrated in Figure 3-7.

Current Tools

Research Codes

The purview of materials science and engineering is scientifically and technologically vast. Everything is made from materials, and the responsibilities of materials scientists range from the extraction of raw materials through processing and manufacturing to performance and reliability. Because of its broad scope, materials engineering is a decade or so behind other engineering disciplines in developing a core set of computational tools. For example, mechanical engineers are trained as undergraduate students in using finite element modeling (FEM) for heat and mass transfer, and a variety of commercial FEM packages are in wide industrial use. Materials scientists have no comparable computational training or tools. Even in cases where extensive scientific tools are available for prediction of basic materials properties or structures, their connectivity to real-life products and large-scale applications remains highly inadequate.

While computational materials science continues to progress, most of its applications remain research codes, with a few notable exceptions that are discussed below. Research codes are created for a variety of reasons, but their common characteristic is that they are written for a limited, specialized user base. Since users are assumed to be experts in both the scientific and computational aspects of the code, most research codes suffer from poor documentation, lack of a friendly user interface, platform incompatibility, no user support, and lack of extendibility. Furthermore, because research codes are usually written for a single purpose and customer, they may not even be numerically stable or scientifically correct. Of course, there are many examples of research codes that are well supported and responsive to customers, such as Surface Evolver, a code that calculates the wetting and spreading of liquids on surfaces.[22] These are often labors of love, supported by a single researcher or group; the danger is that there is no guarantee of continuity of support as funding or personal circumstances change. On the positive side, many research codes are available without cost, and many researchers are delighted to reach new customers for their codes.

As a research code adds capabilities and demonstrates its utility to more users, it may graduate to a more sophisticated, stable, and supported application, either through commercialization[23] or through the open-source paradigm.[24] While a few materials science

---

[22] Ken Brakke, "The Surface Evolver, Version 2.20," August 20, 2003. Available at: http://www.susqu.edu/facstaff/b/brakke/evolver/. Accessed April 2004.

[23] An example is Accelrys, a leading computational science company, developing and delivering software applications and services for materials research. More information is available at: http://www.accelrys.com/index.html.

codes have made this transition, none pervade the field, particularly within the ranks of the practicing materials designers and engineers.

Materials Science Models

While computational materials models are quite diverse, they can be loosely classified by length scale and scientific content into five categories: atomic-scale models, mesoscale models, continuum models, thermodynamic models, and databases. Within these categories, physics-based models, which utilize scientific theory to predict materials behavior, can be distinguished from empirical models, which rely on experimental observation and prediction of trends to do the same. Of course many models are hybrids, and include both fundamental science and empirical data.

Atomic-Scale Models. Atomic-scale simulations were among the first scientific computer applications. From simple early simulations, which treated atoms as classical hard spheres, these models have evolved into sophisticated tools for predicting a wide range of material behavior. As such, they represent a well-developed area of computational materials science.

Atomic-scale models are divided into two types: ab initio electronic structure calculations and empirical atomistic simulations. Electronic structure models solve simplified versions of the Schrödinger equations to generate the electron density profile in an array of atoms. From this profile, the position and bonding of every atom in the system can be determined. In theory, ab initio simulations provide a complete description of a system: its structure, thermodynamics, and properties for idealized situations and limited size.

In practice, ab initio simulations are limited in two ways. First, because the many-electron Schrödinger equation cannot be solved in closed form, all ab initio simulations utilize approximations. A major focus of researchers in this area is improving the approximations and quantifying their effects. However, their limitations remain important; for example, ab initio calculations are typically accurate to within 0.1 eV. This resolution limit can mean prediction of incorrect equilibrium crystal structures and errors in calculating melting points of up to 300 K. Second, electronic structure calculations are extremely computing intensive. Current heroic calculations may simulate 10^5 atoms for a nanosecond. Even with geometrically increasing computer resources, the capability to simulate a mole of atoms in an hour remains a long-term goal.

Despite their limitations, electronic structure calculations are valuable tools for elucidating the underlying physics of materials behavior. They have been particularly successful in calculating phase diagrams, crystal structures, solute distribution, and the structure and properties of internal defects. Because they include electronic bonding, ab initio simulations are the only first-principles method for predicting chemical interactions, including alloy chemistry, structure, and surface interactions. A large number of ab initio electronic structure codes have been developed, and several, such as VASP[25] and WIEN2k,[26] are commercially available and widely utilized. These simulations are still research codes; generating meaningful results requires graduate-level knowledge of both the technique and the particular code. However, both packages can be considered robust and supported tools.

Accessed April 2004.

[24] An example is the ABINIT code, whose main program allows one to find the total energy, charge density, and electronic structure of systems. More information is available at: http://www.abinit.org/. Accessed April 2004.

[25] G. Kresse, "Vienna Ab-initio Simulation Package," October 12, 1999. Available at: http://cms.mpi.univie.ac.at/vasp. Accessed April 2004.

[26] P. Blaha, K. Schwarz, G. Madsen, D. Kvasnicka, and J. Luitz, "WIEN2k," 2001. Available at: http://www.wien2k.at/. Accessed April 2004.

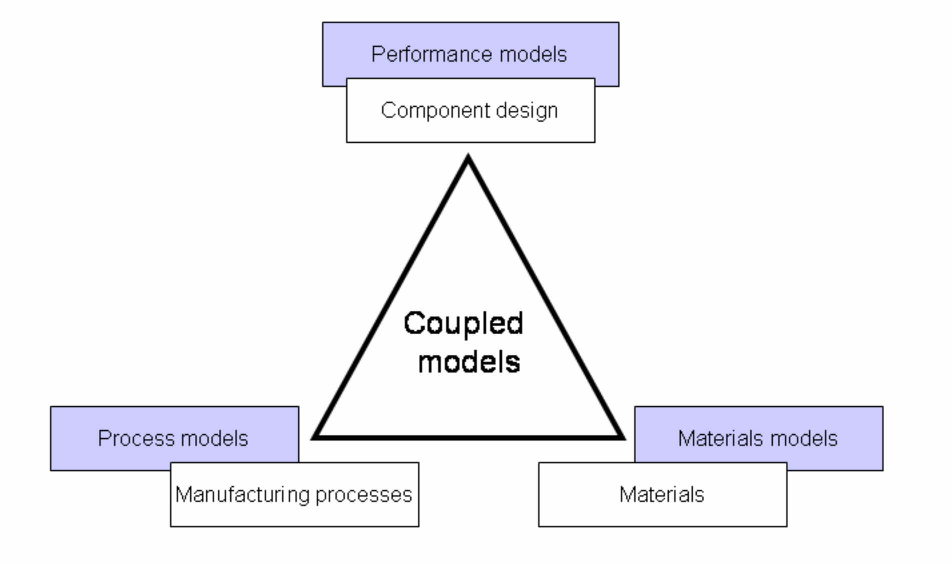


FIGURE 3-7 Models for linking design, manufacturing, and materials.

For larger atomic systems, up to 10^{10} atoms for a microsecond, scientists have developed empirical atomistic simulations. These models use a classical, empirically derived function for the potential energy between every pair (or in some cases, triplet) of atoms. These potential functions may be derived from the electron density profiles, but they do not include electronic terms explicitly. Like ab initio simulations, empirical atomistic models yield a map of all the atoms in a system. With their larger length and time scales, empirical atomistics are particularly useful in examining the dynamics and interactions of atomic features, including defects and solutes. However, because the potential functions ignore nonclassical and electronic effects, the accuracy of the models is necessarily limited.

The most commonly used empirical potential model for metallic materials is the embedded atom method (EAM). Several EAM research codes are publicly available.[27] Similar empirical codes are used for polymeric materials.[28]

Both the strengths (fundamental science basis) and weaknesses (limited system size, timescale, and accuracy) of atomic-scale models are well understood. Developing new techniques to increase simulation size and duration, possibly via coupling with the mesoscale, and exploring new scientific formulations to increase accuracy are the challenges that industry must overcome to widen the use of these methods in design and manufacturing.

---

[27] Nuclear Energy Agency, "DYNAMO, Structure and Dynamics of Metallic System by Embedded Atom Method," March 25, 2002, available at: http://www.nea.fr/abs/html/ests0788.html, accessed April 2004; and S.J. Plimpton, "Fast Parallel Algorithms for Short-Range Molecular Dynamics," *J. Comput. Phys.*, Vol. 117, pp. 1-19, 1995, available at: http://www.cs.sandia.gov/~sjplimp/codes.html, accessed April 2004.

[28] S.J. Plimpton, R. Pollock, and M. Stevens, "Particle-Mesh Ewald and rRESPA for Parallel Molecular Dynamics Simulations," in *Proceedings of the Eighth SIAM Conference on Parallel Processing for Scientific Computing*, Minneapolis, Minn., March 1997. Available at: http://www.cs.sandia.gov/~sjplimp/lammps.html. Accessed April 2004.

Mesoscale Models. The mesoscale—encompassing length scales between the atomic and the continuum—is the traditional and more application-oriented purview of the materials scientist. However, it is at these length scales that computational tools are most rudimentary.

Because microstructural development is critically important to materials processing and properties, mesoscale models at the polycrystalline grain scale (usually 1 to 1,000 μm) have been the subjects of extensive industrial and research efforts over the past decade or so. A plethora of models have been developed, including dislocation dynamics models for plastic deformation, grain-scale evolution models for annealing, polycrystal plasticity deformation simulations, deposition models, solidification models, and many others. Almost every mesoscale-mediated process or property has been the subject of a computational model. Some common denominator phenomena have been the subject of multiple, competing models; for example, no fewer than five different well-established models describe grain growth in polycrystalline metals.

Mesoscale models are based on combinations of fundamental physics and empirical data, with different models occupying different parts of the spectrum. However, nearly without exception, current mesoscale models are research codes. While they may be more or less available, usable, and supported, they all require specialized scientific and computational knowledge, well beyond the undergraduate materials science curriculum. Moreover, most of these tools have not been validated for realistic, complex materials systems; their accuracy and applicability remain unknown. Because of this, mesoscale models remain a research opportunity but are little used in the manufacturing design process.

Continuum Models. During the design process, the behavior of a material in a component is often the most important unknown factor, impacting both design and manufacturing decisions. The designer needs to know whether a material can be formed into a particular shape, and how that material will perform after forming. Continuum material response models, usually based on an empirical constitutive material model implemented in a finite element solver, are widely used to simulate the mechanical response of materials in arbitrary geometries and environments.

Unlike smaller length scale models, FEM-based solvers are commercially available. Abaqus,[29] NASTRAN,[30] DYNA3D,[31] and ANSYS[32] are four examples of widely utilized FEM solvers. Not only do commercial applications offer extensive user support, but also because of the widespread use of these models, undergraduate engineering curricula often include FEM modeling units. These methods are a near-universal component in the engineering design process at large and small companies alike, and are an important component of CAE.

FEM solvers require a model for material response; this is usually a set of constitutive equations. These equations take a form that may be motivated by the underlying physics of the response being modeled, or that may simply be a curve fit to experimental data. In either case, the numerical quantities in the equations are determined by fitting them with experimental data. Depending on the response being modeled, the data in question may be a simple stress–strain curve, or may be the results of a complex set of time- and rate-dependent experiments. While constitutive models for simple materials are often included in solver packages, the design process frequently requires more complex and realistic models, many of which are available in the open literature. More problematic is the data required to fit the model for a particular material and process. Some material response data are available in the open literature, although finding and validating them can be challenging; other data may be available but undocumented; still

---

[29] ABAQUS, Inc., Pawtucket, Rhode Island. Available at: http://www.hks.com/. Accessed April 2004.

[30] MSC Software, Santa Ana, California. Available at: http://www.mscsoftware.com/. Accessed April 2004.

[31] Lawrence Livermore National Laboratory, Livermore, California. Available at: http://www.llnl.gov/eng/mdg/Codes/DYNA3D/body_dyna3d.html. Accessed April 2004.

[32] ANSYS, Inc., Canonsburg, Pennsylvania. Available at: http://www.ansys.com/. Accessed April 2004.

other data may be proprietary. The need for easily accessible and accurate material data, which is the greatest limitation of continuum modeling for design, is discussed in more detail below.

Thermodynamic Models. The compilation and application of phase diagram data has been a traditional responsibility of the materials engineer. Undergraduate students learn that because thermodynamics constrains phase diagrams, one need not sample every point in composition space to determine the entire diagram. In fact, thermodynamic models can calculate accurate phase diagrams from a few select data points.

Commercial thermodynamic models such as Thermo-Calc[33] are in routine use by alloy designers as well as process engineers. These models permit the engineer to determine phase information for simple alloys, to explore new compositions, or to tailor a process for a particular heat. For complex alloys, however, the models cannot predict the existence, composition, and/or structure of the constituting phases a priori. Indeed, without experimental verification, these predictions are highly questionable. Even for simple alloy systems, the models depend on the availability of thermodynamic properties of the alloy components, and the interaction between them. Ideally, it is preferable to acquire such information from experimentally determined and verified databases. Otherwise, the models depend on the use of the available phase diagrams.

Kinetic models, such as DICTRA,[34] apply chemical kinetic models to such thermodynamic information in order to determine phase transformation rates for process control. Here again, however, the models are inadequate in predicating complex situations where various processes may take place simultaneously. Box 3-3 illustrates how such models and sensor measurements are used in commercial gas carburizing heat treatment processes.

While both of these (admittedly limited) models are mature applications, with a wide user base and education support, they are data-limited. To produce accurate results, both models require accurate input in sufficient quantities. During the 1960s and 1970s, when U.S. alloys dominated the metals markets, industry and government together funded broad programs to generate thermodynamic data for steel, aluminum, and specialty metals. However, those efforts ended three decades ago.

Now, because performing the experiments to generate thermodynamic data is considered a mature technology, there is little public funding available to do it, so it is performed in-house. Moreover, despite the need to certify new materials, there is little thermodynamic data for new alloy systems. Both absent and inaccessible data, discussed below, are barriers to the widespread use of thermodynamic models.

Databases. A pervasive theme in any discussion of computational materials science tools is the need for data. Data enable model development, validation, and application. In a real sense, useful, accessible data, not models or computer codes, are the desired end product of materials science research.

Unfortunately, the product is often lost or hidden. Consider three scenarios for some data—a stress–strain curve, for example—generated to support a design program:

- Ideally, the stress–strain data, along with its supporting information on alloy composition and testing methodology is stored in a central database. In the current system, this database is likely proprietary, so while this scenario gives a good chance for data survival and usefulness, it is at the cost of external accessibility.

---

[33] Thermo-Calc Software, Stockholm, Sweden. Available at: http://www.thermocalc.com/. Accessed April 2004.

[34] Thermo-Calc Software, Stockholm, Sweden. Available at: http://www.thermocalc.com/Products/Dictra.html. Accessed April 2004.

Box 3-3
Gas Carburization Heat Treatments in Industry

The prehistoric manufacturing process of carburizing is one of several economical forms of surface hardening. The process is applied to a wide variety of parts where very high levels of surface and near-surface strength, crushing resistance, toughness, and wear are required in combination with significantly lesser requirements for the part's center or core, therefore not justifying the added material costs associated with through-hardening. Gears, bearings, latches, hammers, tools, and spindles are but a few of the many thousands of parts that are carburized daily.

The typical gas carburizing process involves the solid-state diffusion of carbon through the surface into a low-carbon steel part that is subsequently quenched and tempered to result in a stronger, tougher, and more wear-resistant part. Today's most common versions use one or more of several carbon source gases (e.g., natural gas, methane, propane) mixed with one or more of several neutral, carrier gases (e.g., carbon monoxide, carbon dioxide, nitrogen, argon) at a moderately high temperature (approximately 900 to 950ºC). Dozens of measurements, sensors, models, and predictions are utilized throughout the manufacturing cycle.

Starting with an initial part geometry and anticipated field/customer duty cycle, the designer models the expected load history onto the part geometry to determine the required performance properties at each location within the part. Other models are used to predict the strength and/or fatigue performance based on the measurable attribute of hardness. The final hardness profile will be a function of the carbon profile, alloy content, cooling rate after carburizing, and tempering temperature. The carbon profile developed during heat treatment will be a function of the initial carbon of the steel, the carburizing gas mixture, surface conditions, carbon diffusion rate, and the time in the furnace. Since neither the carbon diffusion rate nor the carbon profile can be measured nondestructively or in real time, sensors and their associated models are used to predict what is actually occurring during the carburizing cycle, and statistical, destructive sampling is used only to confirm the predictions after the process has been completed.

The area of largest concern during the carburizing process is the prediction, at each instant in time, of the rate of introduction of the carbon into the steel surface and the rate of diffusion of that carbon into the part. Therein lies the opportunity for improvements. For decades, the determination of "dew point"—primarily a function of moisture, CO/CO_2, temperature, and pressure—was used to determine the carburizing potential of the furnace atmosphere. More recently, oxygen sensors have been utilized with measurable improvements in process control and yield. Improvements in process control through better sensors permit increases in furnace temperature, yielding substantial reductions in cycle time and cost. Current research is seeking to utilize laser and other advanced sensing techniques to measure the carbon potential of the atmosphere even more accurately. With typical 4- to 8-hour or longer carburizing cycle times, even minor reductions in cycle time become significant cost reductions while concurrently the improved process control yields quality improvements, such as controlled grain growth.

In a large-scale captive heat treatment shop, use of a process optimization scheme for gas carburizing decreases batch time and increases throughput. This higher efficiency permits smaller capital outlay for furnaces; one anonymous shop saw a 20 percent decrease in furnace acquisitions, yielding a capital cost savings of $2 million, with commensurate operational cost decreases.

- Another possibility is publishing the data in the open literature. Because stress–strain data are usually presented in graphical form in scientific papers, the numerical values of this data will not be preserved, and without the standard data format enforced by a database, some of the supporting information will not be reported. In addition, finding the data will depend on literature search engines not tailored to data, but to concepts. While publication assures the data will survive and be (theoretically) accessible, the practical utility of the data may suffer.
- In the most likely scenario, the data are recorded in a lab notebook or on a desktop

> computer. They are used for the current investigation, and perhaps referred back to while remembered, but ultimately, with staff or computer system changes, they are forgotten. In this case, the data are not accessible, useful, or enduring, and the stress–strain experiments will have to be repeated each time this alloy is considered.

Examining the current options, it is easy to define an ideal distributed data storage system. It would be a database format structure that permits storage of entire data sets as well as supporting information. It would be publicly accessible, with a tailored search capability. Finally, it would be stored in a format immune to hardware or software changes.

It is important that any materials property database be verified and validated through a peer review process. The database also needs to be routinely updated to include additional data for new materials or processes, and to replace the existing ones with new and more accurate data. Obviously, any modifications to the database will need to go through peer review as well.

Although approximations of this ideal exist in some proprietary industry databases, there is no such data repository for all the nonproprietary data generated in industry, universities, and government laboratories. The creation of such a database could trim redundant experimental efforts to decrease cost and increase productivity.[35] This is a particularly compelling argument for defense acquisitions.[36] Because the DoD contracts its design and manufacturing work, it often pays for data acquisition to support the design process. However, there are limitations to transferring those data among DoD contractors, so the DoD generally pays each contractor to generate its own set of design data.

In addition to eliminating redundancy, a materials property database provides a mechanism to collect multiple data sets for statistical analysis. Over time, the accumulation of data on common materials can improve data quality and validity; in essence, the database provides a mechanism to vet new data.

Finally, it should be noted that databases themselves can function as material models when combined with expert system software. For example, expert systems for casting[37] link with a database of casting data generated by experiment and modeling to optimize casting parameters for specialty alloys. Such data-driven expert systems are used in a wide variety of industrial process control models. Box 3-4 illustrates how such models have been further developed and used for aluminum castings in the automotive industry.

Roles for Computational Tools

The opportunities for using computational materials tools in bridging the gap between design and manufacturing fall broadly into three categories: the *design* of new materials, the *selection* of existing materials, and the *processing and manufacturing* of all materials. In each of these categories, we make a recommendation for the most critical research needs.

Materials Design

From jet turbine blades to stealth airfoils, new materials enable new products. However, the insertion time for a new material is measured in years—up to a decade for high-reliability applications—while the product realization cycle is measured in months. The lengthy material

---

[35] National Research Council, *Materials Technologies for the Process Industries of the Future*. National Academy Press, Washington, D.C., 2000, p. 22.

[36] National Research Council, *Materials Research to Meet 21st-Century Defense Needs*. The National Academies Press, Washington, D.C., 2003, pp. 21-25.

[37] Walsh Automation, Princeton, New Jersey. Available at: http://www.walshautomation.com/anglais/metals/1_3_4_1.htm. Accessed April 2004.

insertion time is governed primarily by the time necessary to perform the experimental tests required for certification.

If computational simulations replaced some tests, the material insertion time could be greatly diminished. This is, in fact, the theme of several active, government-sponsored research programs, most notably the DARPA Accelerated Insertion of Materials (AIM) program.[38] The potential cost and time-saving benefits of utilizing physics-based models in materials design are well documented.[39]

The goal of an accelerated insertion program is to minimize (but certainly not eliminate) experimental trials. The materials models most suited to design and analysis of new materials are those that contain fundamental physics, although they often lack applicability to real materials and products. Empirical models are more reliable at the product level, but cannot be extended to other material classes or to predict behavior beyond certain bounds. To overcome these shortcomings, a combination of models is called for. For example, electronic structure calculations, supported by larger atomistic simulations, can provide phase diagrams and some property information to steer designers toward promising alloys. Mesoscale models can suggest target microstructures and processing routes. Armed with data at smaller length scales, materials scientists can start the conventional continuum design and analysis process.

Finally, the committee notes that due to the cost of modifying established infrastructures, there is not a widespread call to replace commodity materials despite potential economic and competitive advantages. Thus, the insertion of new materials is important only in a small, though critical, subset of products and should not be the sole focus of physics-based modeling efforts. The vast majority of products, including defense acquisitions, are successfully produced from conventional materials. In these commodity materials, physics-based models at the atomic and microstructural scales can help designers better understand and optimize material properties for improving yield, cost, performance, and reliability.

Materials Selection

Manufacturing of a new component inevitably begins with the selection of a material. Such a selection requires an in-depth knowledge of the behavior and performance of the material at the component level as well as after the material's integration within the system. Equally important in the selection process is the processing technique and manufacturability of the components.

For selection of the proper materials, designers rely heavily on databases cataloging the properties and performance of various materials. Examples include publicly available databases for structural and mechanical properties, thermophysical parameters, and phase diagrams, such as Alloy Finder Electronic DataBook, AMPTIAC, CAMPUS Web View, CES Selector 4.0, CINDAS, Key to Metals, Key to Steel, and MatWeb. (Appendix D provides the Web sites for these databases.) There are also proprietary databases, held mostly by materials manufacturers and suppliers. Most of the publicly available databases contain outdated information and are of limited use to materials designers, particularly for the design of functional and advanced structural materials. For example, among the most recently updated databases, the ASM International binary phase diagrams were compiled after a critical peer review process about 20 years ago. Even for this case, the diagrams for most of the commercial

---

[38] Defense Advanced Research Projects Agency, Arlington, Virginia. Available at: http://www.darpa.mil/dso/thrust/matdev/aim.htm. Accessed April 2004.

[39] National Center for Manufacturing Sciences, Ann Arbor, Michigan, available at: http://springback.ncms.org/, accessed April 2004; Defense Advanced Research Projects Agency, Arlington, Virginia, available at: http://www.darpa.mil/dso/thrust/matdev/aim.htm, accessed April 2004; National Research Council, *Modeling and Simulation in Manufacturing and Defense Systems Acquisition: Pathways to Success,* National Academy Press, Washington, D.C., 2002.

multicomponent alloys are entirely missing. Other structural, compositional, mechanical, and processing data for materials selection, given mostly in handbooks, also either are outdated or have been compiled without a critical review process.

Structural materials constitute the backbone of all manufacturing processes, from plastics to ceramics and metals. Detailed databases are required for predicting the behavior of these materials, and consequently their performance, during manufacturing. Such information will enable materials designers to improve processing and manufacturing methods. Such a tailored approach would enable more affordable products as well as providing for unique combinations of structural and functional capabilities. Detailed databases would also enable organizations to use modeling to better effect for manufacturing processes.

Processing and Manufacturing

All manufacturing processes begin with raw materials that are converted into semi-finished products, and then various forming and finishing operations turn those products into manufactured components. Materials science informs design and manufacturing engineers how the materials they select will perform during processing into products and, later, over the product's lifetime.

Component design begins with a set of requirements and constraints, such as the required load-bearing capability, weight limits, and space constraints. After selecting materials for the product, the designer uses a CAD system to produce a geometric model of the part, which is then analyzed, using material properties obtained from handbooks and databases of the kinds discussed in the preceding sections. The analysis typically entails both product and process simulations at the continuum scale. In current practice, such analyses are often done separately and performed by different analysts, and there can be duplication of effort. Most such analyses require a computed model for use in the CAD system, usually represented by a registered mesh, or grid, that covers the surface of the modeled part. While relatively simple objects can be enmeshed automatically, for complex objects this is a time-consuming and expensive process.

Box 3-4

Virtual Aluminum Castings: Atoms to Engines

Ford Motor Company developed software to use physics-based materials models to link manufacturing, design, and materials. Automotive engines are continually being developed and refined to meet the rapidly changing needs of customers and to deal with competitive and regulatory pressures. Two of the most important components in any engine are the cylinder head and the block. The development of these large and complex aluminum castings is often the rate-limiting step in any engine development program.

Baseline

These components are generally designed using empirical databases which assume that material properties are not affected by the details of the manufacturing process and are constant throughout the component. The reality is that the key properties are highly dependent on the location within the casting. Currently analytical techniques for design (e.g., durability analysis) and manufacturing are completely unconnected and are conducted by analysts in different organizations. Castability constraints are input early in the design process by manufacturing engineers using engineering "rules of thumb" that are imperfect and are imperfectly applied. Analytical software for assessing castability is typically run late in the component development process and often in response to problems that are encountered in manufacturing.

This situation results in costly iterations in dies and part geometry, late changes, and program delays. Engine failures that occur during engine testing due to imperfect analysis can lead to major and costly setbacks in program timing. Opportunities for optimizing a component, such as by reducing its weight or optimizating casting or heat treatment cycle time, are missed.

Accomplishments

Ford Research Laboratories has developed a comprehensive and integrated suite of computer-aided engineering tools, called Virtual Aluminum Castings (see figure), for use by company CAE analysts. There are three key aspects of this development:

- The computational materials models for predicting mechanical properties were physics-based and involved linking materials models that account for metallurgical phenomena occurring at vastly different length and time scales.
- The tools were developed, were substantially augmented, and acted as links between commercial software used for casting analysis and durability analysis.
- To use these tools in an effective manner, an organizational culture shift was required.

The physics-based computational materials models had to be able to accurately extrapolate and interpolate existing empirical understandings of mechanical properties while also being simple to use and computationally efficient. To accomplish this goal a wide range of materials modeling tools were used and the results linked and embedded in easy-to-use subroutines. Modeling approaches that were used included ab initio calculation of interatomic potentials and free energies, thermodynamic phase equilibria calculations for phase stability and segregation, microstructural evolution models involving diffusion and phase morphology, and micromechanical models for calculation of properties from a variety of mechanisms, such as precipitation hardening, solid solution hardening, and fatigue crack propagation. Development of these models required establishment of a unique mix of research expertise including experimentalists, theoreticians and numerical modeling experts, metallurgists, physics researchers, and mechanical engineers.

Ford-proprietary subroutines and linkage programs were developed because these were not available elsewhere and there appeared to be insufficient return on investment for current software vendors to develop the empirical and theoretical knowledge required to accomplish this goal. The development of the Virtual Aluminum Castings suite of tools was enabled by the existence of commercial software, such as Abaqus and ProCast, with open architecture allowing user-defined subroutines. This development was considerably more difficult in other areas due to commercial codes that did not have this feature (e.g., MagmaSoft).

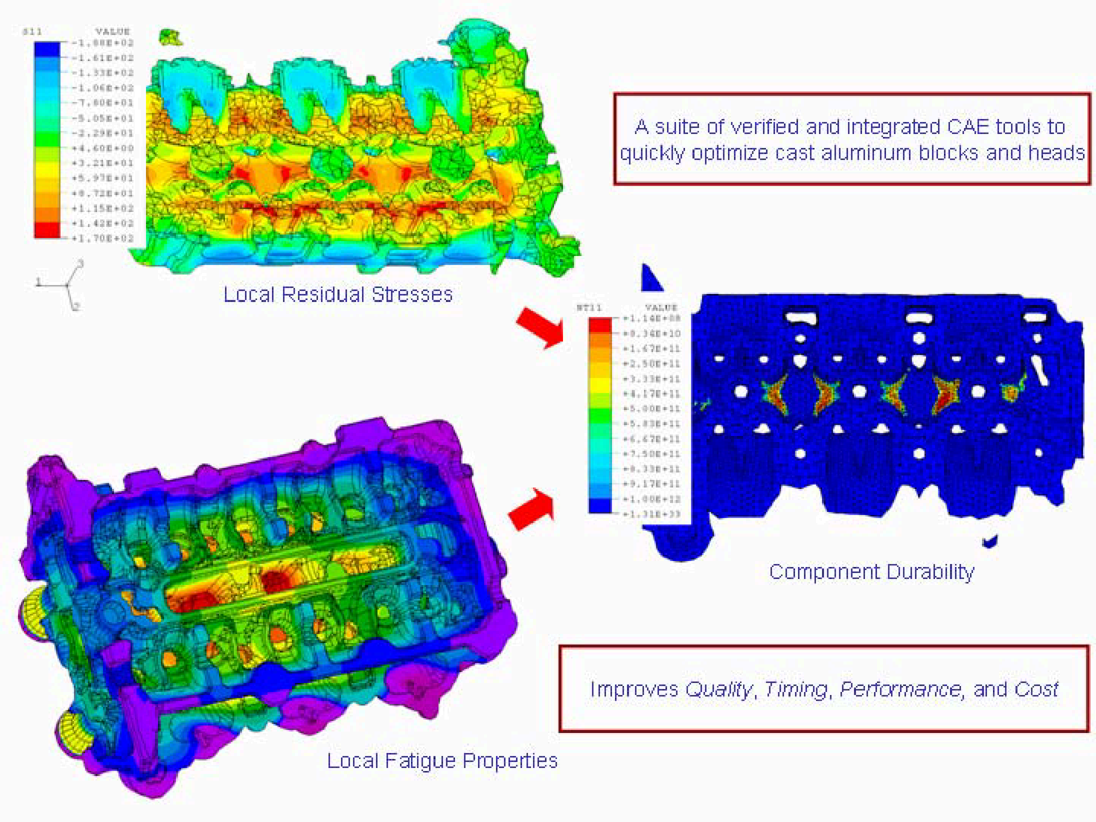
Benefits

These tools have recently been developed and are in the process of being implemented at Ford CAE groups around the world. Using these tools, Ford has experienced an improved ability to launch new cast aluminum products with a minimum of iteration and tooling. This has allowed a decrease in the amount of durability testing required and a decrease in program development timing. Ford has embedded significant knowledge of cast aluminum metallurgy into these models and is able to provide it to CAE analysts worldwide on a consistent and common basis. These tools have only recently been implemented within Ford so their benefits cannot be quantified. However, Ford estimates that they have the potential to reduce costs of $45 million to $70 million on an approximately $500 million annual expenditure for new cast aluminum components.

Lessons Learned

- Linking manufacturing and design via physics-based materials models to allow two-way analytical feedback between manufacturing, materials, and design has significant economic benefits both for industry, in the form of reduced development costs and faster timing, and for society, in the form of more efficient products and reduced waste.

- A commercial framework and software with open architecture are needed to facilitate the future development of such models.
- Sufficient fundamental knowledge exists for selected mature metallic systems and selected properties so that with focused effort and judicious selection of experiments, hierarchical, physics-based materials modeling across length and time scales can be accomplished expeditiously and with sufficient accuracy to be useful to industry.
- It is difficult and rare for any company to amass the expertise required to fully bridge design and manufacturing with materials modeling. This suggests that government coordination of a larger effort, for a wider range of materials and processes, would accelerate the development of such models, minimize the cost by reducing redundancy, and yield substantial benefits to society and U.S. industries.



Ford Research Laboratories' comprehensive and integrated suite of computer-aided engineering tools, called Virtual Aluminum Castings.

Further, the product performance and process analyses may use different geometric models. For example, forming processes such as casting, forging, and sheet metal forming produce components using dies or molds that differ in shape from the final product to accommodate such effects as solidification shrinkage, elastic springback, and trim allowances. Generating both an interim and final geometric model is also a significant bottleneck in the overall product design process. In addition, design changes introduced by one analyst to improve the product must be updated and transmitted to the other codes. There is rarely sufficient interoperability between the various analysis codes and the CAD program to transmit the design changes effectively.

Once the computer model of the part is created, the component is analyzed—generally using FEM analysis—to determine its behavior in service and its response during processing. Supports and loads are applied. Material properties are then entered, and product performance is simulated. The material properties take the form of constitutive relations, and as discussed above, these are critical to the fidelity of the simulations.

In addition to incorporating material properties, the simulations apply external loads and interactions in the form of boundary conditions. Often these boundary conditions represent interactions between the component and its environment that are not well understood. Examples include friction and thermal transport, both of which depend on the nature of the contacting surfaces and on local thermal and pressure conditions that may change during the process. Experience and databases are helpful for estimating these properties, but true knowledge that is time- and condition-dependent will always be inexact. Models can be used to identify those properties that the model is most sensitive to, and sensors can be deployed to advantage in quantifying the exact conditions when physical prototypes are built.

Once the simulations are performed, the designer can evaluate the results and modify the design to improve it. While there are some examples of fully automated design optimization, this process is usually done by trial and error. Facilitating this optimization represents a real opportunity to improve the design process. In such an approach, the designer may specify an objective such as minimum weight; constraints, such as part topology and maximum stress; and design variables, such as product dimensions. The simulation process would then automatically make changes to optimize the design. This type of analysis might have the further benefit of identifying sensitivities, i.e., those product features that are most important to the objective. These features might then be candidates for sensing and control during processing or service.

One reason that optimization is not used more widely is that individual simulations take too long and cost too much to perform. Depending on the complexity of the analysis, optimization may require 20 or more separate analyses, and designers may be unwilling to wait for the results. It would seem that increases in computing power would eliminate this problem over time. However, the committee has observed that as computing power increases, the detail and the size of the simulations seem to increase in proportion, so that the clock time for performing simulations really has not changed very much over time.

Research is needed to allow optimization techniques to be used effectively for modeling and simulation of manufacturing processes. One approach is to systematically reduce the model complexity in evaluating initial designs, so that the simulations can be done in much less time. Final designs could then be perfected on the full models. Automated tools for reducing model complexity, for example by removing small features, are lacking. Further, tools for linking results from various software platforms with optimization codes are lacking. Directed research in this area could significantly change the way in which design and manufacturing are done. Some contractors, for example Boeing, have privately funded integrated structural analysis and optimization techniques that have been used successfully on the X-32 JSF prototype, the X-45 UCAV, and the F/A-18E/F Super Hornet.

All simulations must be supported by verification and validation.[40] Verification of codes can be done by providing a suite of test problems with known solutions; validation involves comparison of the results of a simulation to the results of experiments to determine the quality of the data that is input to the models, such as material constitutive models, loads, and other boundary conditions.

---

[40] "Verification is the process of determining that a model implementation, or simulation, accurately represents the developers' conceptual description and specifications. Validation is the process of determining the degree to which a model and associated data are an accurate representation of the real world, with respect to the model's intended use." From National Research Council, *Modeling and Simulation in Manufacturing and Defense Systems Acquisition: Pathways to Success*, National Academy Press, Washington, D.C., 2002, p. 95.

Recommendation 3. Materials Science: The Department of Defense should create, manage, and maintain open-source, accessible, and peer-reviewed tools and databases of material properties to be used in product and process design simulations.

Integrated tools and databases for materials design, materials selection, process simulation, and process optimization are key to virtual manufacturing. Data gathered from manufacturing and materials processing using a variety of sensors can validate and improve design, modeling, simulation, and process control.

MANUFACTURING TOOLS

Manufacturing comprises a wide range of processes, with different emphases in different industries. This section lists those tools that appear generic across industries that make discrete parts products.[41] The tools support several kinds of processes falling into two categories: microscale and macroscale. The microscale category includes individual processes and process steps. The macroscale category comprises the system aspects of designing and operating a manufacturing enterprise.

The following is a list of some of the most common tasks and necessary tools:

- Process planning, including identifying the necessary steps and equipment, and their sequence for part fabrication, for assembly, and for test and inspection
- Process simulation, analyzing capability, cost, time, and yield, e.g., injection molding, casting, machining, and assembly
- Logistics planning, planning factory layout, e.g., equipment location, storage, and material flows
- Factory flow simulation, determining location of bottlenecks and total yield
- Ergonomics analysis for worker safety and effectiveness
- Robotics and material-handling simulations, timing, tooling and workstation layouts, and cost
- Production management of materials requirements planning, manufacturing resource planning, and scheduling
- Economic analysis and justification
- Quality measures, including statistical process control (SPC), six sigma, process capability measurement and analysis

Box 3-5 shows an example of the benefits of using manufacturing software tools. Progress in manufacturing tools has been continuous for decades, driven by advances in basic knowledge about processes and digital representations of this knowledge as well as by improvements in computational power. Commercial industry has taken over a great deal of the effort of converting new knowledge into computer tools. Many of these tools stand alone, but several commercial vendors have linked them together. Interoperability of tools offered by different vendors remains a problem, however, and incentives to make the tools interoperate are few in comparison to the problem of determining which representation to choose.[42] In some

---

[41] R. Brown, Delmia Corp., "Digital Manufacturing Tools," presented to the Committee on Bridging Design and Manufacturing, National Research Council, Washington, D.C., April 29, 2003.

[42] C. Hoffmann, Purdue University, *CAD Tools Evolution and Compatibility,* presented to the Committee on Bridging Design and Manufacturing, National Research Council, Woods Hole, Mass., August 25, 2003.

Box 3-5
Case Study in Manufacturing Software Tools

Baseline

Aerospace parts were programmed for milling by conventional manual programming.

Accomplishments

An expert system was developed to partially automate the programming process. CAD solid models were processed by the new software and geometric features were recognized and noted. Then standard processes for producing those features were found in a feature/process table. Finally, each standard process was expressed in terms of the workpiece size, orientation and position, and machine tool moves were calculated.

The resulting computer numerical control (CNC) program output shown here
was scanned by a programmer and manually edited where necessary.
Reprinted by permission from BobCAD-CAM; available at http://www.bobcadcam.com/.
Note that inclusion as an example is not intended to be an endorsement of any particular product.

Benefits

Benefits included a significant reduction in manual CNC programming time. An average of 83 percent reduction in manual programming time was achieved in a test of five typical aluminum aircraft parts. The total product production process time was reduced by more than one week on average.

Lessons Learned

It is possible to automate much of the manual CNC programming process by using expert system software and feature recognition in connection with a solid model of the part to be machined. Programming time data from the five-part text indicated that conventional processing that took between 45 and 120 hours could be reduced to between 4 and 24 hours using HiThru.[a]

---

[a] P. Zelinski, "Empowering the Programmer," Modern Machine Shop Magazine, April, 2002.

domains, fundamental knowledge is still lacking.

Research is needed to develop efficient scheduling algorithms that permit rapid redirection of resources to meet changing demands or circumstances; models of assembly tasks performed by people to understand fatigue, errors, and injuries; design of factories to permit flexibility and efficient redeployment of large investments; and generalizations of existing design-for-X (DfX) methods and rule bases to include such concerns as product quality, recycling, and environmental friendliness.

Bridging of Design and Manufacturing

The bridging of design and manufacturing is a core issue for this study. It is not represented by an explicit step in conventional definitions of product development, except perhaps in design-for-X (DfX) processes. Instead, ideally, it is a pervasive activity that should occur continuously throughout product development. The committee notes that each identified activity is carried out now, but the degree to which tools exist in automated form varies greatly. Moreover, the lack of understanding of cultural and managerial barriers may be more important than lack of computer tools.

Technical Coordination of Specifications and Procedures

Some of these coordination activities include the following:

- Identification of critical resources such as suppliers, factories, long lead items, and employees' skills needed to manufacture a given design
- Identification of design and materials alternatives or process alternatives needed to manufacture a given design, together with ways of finding the best combination
- Determination of the structure of product families and architectures to coordinate with layout, equipment, and organization of the factory to permit flexibility and efficient redeployment of assets to meet changing requirements
- Alignment of materials properties specifications and production outputs, tolerances on parts and resulting variation, and tolerances on assemblies and resulting variation
- Collection and utilization of lessons learned during product launch
- Collection and utilization of lessons learned during use of the product

There is a race between advancing knowledge and rising expectations regarding product quality and performance. As customers' expectations rise, tolerances that used to be sufficient are now no longer acceptable. Competition drives all players to be as good as the leaders. Better understanding of materials and processing methods will grow incrementally, as it has in the past. Breakthroughs in conventional materials are unlikely, and adoption of new materials in existing industries is notoriously slow. Stand-alone computer tools will emerge when knowledge becomes stable. Adoption of such tools will depend on ease of learning and use and on the relevance of what the tool does and what the company requires its employees to do. Organizational barriers and incorrectly structured incentives may inhibit the adoption of tools and methods.

Many companies outsource the design and construction of manufacturing equipment and systems, often because manufacturers no longer have the capability. But capability was lost when the decision was made to outsource to begin with. Outsourcing of tightly coupled activities adds complexity to an already complex bridging process.[43] This trend is expected to continue, although some companies are trying to regain lost capabilities.

Organizational and Managerial Arrangements, and Enablers of Bridging

There are a number of organizational and managerial arrangements that need to be considered:

- Methods of analyzing design processes to identify inefficiencies such as missing information and unnecessary repetitions of process steps
- Economic models of cost versus value in revising production processes and investments to improve the product
- Skills and training in negotiation
- Definition of roles and responsibilities that bridge conventional organizational boundaries between design and manufacturing

In this domain there is continual flux and reconceptualization of objectives and methods. Lean manufacturing and agile manufacturing are two suggested ways of organizing manufacturing enterprises for the best delivery of value. Within lean manufacturing, one suggested concept is value stream mapping. This technique aims to identify all the steps and actors in creation of an object or a piece of information in order to find inefficiencies and eliminate waste. This is a domain in which enlightened practitioners often lead researchers, who serve to observe, report, and systematize what they observe in order to improve the performance of other companies.

Here, again, there is a race between capabilities and expectations. In particular, companies want to develop products faster. In the car industry, it typically takes about 4 years to go from concept to production. One of the longest steps in car development is evaluation of the manufacturing feasibility of the design, which sometimes takes 2 years. Great improvements in streamlining this process have been achieved by introducing computational tools. At the same time, new requirements for safety, durability, and appearance have made the task harder. Also, much if not most of the value of cars and aircraft is outsourced, requiring coordination of design and manufacturing across many organizational boundaries. This extra set of transactions increases the complexity. The result is that the process is not significantly faster than it was 10 years ago.

However, some aircraft companies using the results of the USAF/MIT Lean Aerospace Initiative with integrated analysis tools have now designed and developed new prototype aircraft such as the X-32, X-45, and X-47 in approximately half the schedule and half the cost of traditional methods. Also, some car companies can bring out new versions of existing cars in as few as 2 years. The reasons appear to be a combination of more astute use of computational tools plus managerial techniques such as coordination of tasks, reuse of existing designs and factories, smart supply chain management, and incentives for design and manufacturing engineers to work more closely together.[44] As another example, the new Boeing 7E7 commercial transport is planned to be in final assembly for only 3 days, reflecting the culmination of the lean enterprise transformation of lean engineering, lean supply chain, and

---

[43] Charles Fine and Daniel Whitney, "Is the Make-Buy Decision a Core Competence?" Moreno Muffatto and Kulwant Pawar (eds.), *Logistics in the Information Age*, Servizi Grafici Editoriali, Padova, Italy, 1999, pp. 31-63.

[44] Durward K. Sobek II, "Principles That Shape Product Development Systems: A Toyota-Chrysler Comparison," PhD Thesis, University of Michigan, 1997; J.M. Morgan, "High Performance Product Development: A Systems Approach to a Lean Product Development Process," PhD Thesis, University of Michigan, 2002.

lean manufacturing.

Improvement in design–manufacturing coordination involves both technical and managerial/organizational actions. Creation of new technical knowledge in this domain will not be sufficient without accompanying improvements in management methods and organizational arrangements. These include how to structure cross-functional teams, how to flow information in a timely manner between team members, how to identify and resolve conflicts and discrepancies, and so on. These are ongoing research topics in business schools and some engineering schools. These activities should be encouraged. Research on outsourcing of key activities to determine how to minimize complexity and maximize coordination is also needed, along with better economic models of outsourcing choices that reflect the strategic impacts on companies and industries. Loss of national capability also needs to be assessed.

Recommendation 4. Manufacturing: The Department of Defense should assess the role and impact of outsourcing on the integration of manufacturing and design functions.

Assessing the impact of outsourcing key activities can help determine how to minimize complexity and maximize coordination in various organizational structures between manufacturing systems. Tools that include efficient algorithms for production scheduling and procedures for flexible factory design can ease the difficulties of outsourcing.

LIFE-CYCLE ASSESSMENT TOOLS

This section deals with the evaluation of the environmental impact of a product over its life cycle from concept to disposal and not with life-cycle design or life-cycle analysis, which is a broader topic that encompasses life-cycle costing, design for reliability, design for maintainability, and life-cycle analysis. Some aspects of life-cycle design are addressed in the earlier sections on systems engineering tools and engineering design tools.

Increasingly stringent environmental regulations are inducing a more holistic approach to environmental problems, shifting the focus from end-of-pipe pollution control to transforming industry to act as ecosystems with closed loops between wastes and resources. This mass balance approach to environmental problems pioneered by Ayers and Kneese[45] and later called industrial ecology (IE) by Frosch and Gallopoulos[46] is attracting considerable interest within the engineering and scientific community. With population pressures, congestion, resource depletion, and other indicators suggesting limitations on the assimilative capacity of the biosphere, source reduction, recycling, and other strategies to reduce waste generation (including emissions) and resource consumption are gaining greater attention.

To devise and implement these strategies, firms must view their environmental impacts in a broad context from input supply and production through product distribution, use, and disposal. For instance, recent efforts by automobile companies to redesign internal combustion engines and to develop hydrogen fuel cell power vehicles are motivated in part by increasingly stringent air emission standards both here and abroad. The net environmental benefits of these technologies over existing transportation systems should be measured broadly to include environmental impacts during energy resource extraction, fuels processing, vehicle utilization,

---

[45] R.U. Ayres and A.V. Kneese, "Production, Consumption, and Externalities," *American Economic Review*, Vol. 59, No. 3, pp. 282-297, 1969.

[46] R.A. Frosch and N.E. Gallopoulos, "Strategies for Manufacturing," *Scientific American*, September, pp. 144-152, 1989.

and product disposal and recovery.

There are several emerging methodologies for tracking environmental impacts within industrial systems. One approach is to quantify mass flows from source to sink for a material, element, chemical compound, or finished product at a point in time for a specific region, which is known as substance or mass flow analysis (MFA). For example, Socolow and Thomas[47] examined flows of lead in the U.S. economy arguing that large-scale use of lead in electric cars should not be precluded because a nearly closed recycling system for lead–acid batteries that exists implies minimal health risks from lead exposure.

Another common IE tool is life-cycle assessment (LCA), which the Society of Environmental Toxicology and Chemistry (SETAC) recommends to address the environmental implications of products and processes.[48] SETAC views LCA as an objective process to evaluate the environmental burdens associated with a product, process, or activity.

Mass balance analysis is employed in the inventory analysis component of an LCA, involving inventories of energy, materials, and wastes in raw material preparation, manufacturing, use, and disposal. For example, an LCA of an automobile involves estimating the resource use and effluents generated in the production of steel, glass, rubber, and other material components of the car. To this are added the resource and emissions inventory of the automobile assembly plant. The focus then shifts to consumers, how much fuel they consume and the emissions generated during the use of a car—that is, to quantify resources consumed and emissions generated in both fuel production and use, and the burdens (consumptions and emissions) associated with vehicle maintenance and repair such as new parts and oil changes. The final phase of the inventory examines the disposal of the vehicle, estimating what proportion is recycled and the composition of that flow.

The inventory provides a more or less quantitative overview of the material and energy flows incurred in the product life cycle. Impact assessment, which follows, attempts to quantify potential impacts of the inventory on environmental and human health through metrics in a series of categories. Aggregating these impacts into metrics for decision making is perhaps one of the greatest challenges facing LCA.[49] From this point, decision makers, such as product design and development teams, identify strategies to improve environmental performance.

Development and implementation of these strategies involve a set of activities known in the industrial ecology community as design for the environment (DfE), for which Allenby[50] identifies two general categories. The first includes generic efforts, such as green accounting systems and environmentally sensitive procurement policies. The second includes technological development, such as computerized DfE design tools integrated with automated design and manufacturing software.

Life-Cycle Assessment

The Society of Environmental Toxicology and Chemistry (SETAC)[51] defines LCA as follows:

---

[47] R. Socolow and V. Thomas, "The Industrial Ecology of Lead and Electric Vehicles," *Journal of Industrial Ecology*, Vol. 1, No. 1, pp. 13-36, 1997.

[48] Society of Environmental Toxicology and Chemistry, *A Technical Framework for Life-Cycle Assessment*, SETAC, Washington, D.C., 1991.

[49] Committee on Material Flows Accounting of Natural Resources, Products, and Residuals, National Research Council, *Materials Count: The Case for Material Flows Analysis*. The National Academies Press, Washington, D.C., 2002.

[50] B.R. Allenby, *Industrial Ecology: Policy Framework and Implementation*, Prentice-Hall, Upper Saddle River, N.J., 1999, pp. 69-95.

[51] Society of Environmental Toxicology and Chemistry, *A Technical Framework for Life-Cycle Assessment*, SETAC, Washington, D.C., 1991, p. 1.

> The life-cycle assessment is an objective process to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and material usage and environmental releases, to assess the impacts of those energy and material uses and releases on the environment, and to evaluate and implement opportunities to effect environmental improvements. The assessment includes the entire life cycle of the product, process or activity, encompassing extracting and processing raw materials; manufacturing, transportation, and distribution; use/reuse/maintenance; recycling; and final disposal.

This definition suggests four steps in LCA: goal and scope definition, resource and emissions inventory, impact assessment, and improvement analysis. The ideal is an objective assessment of the environmental implications of a well-defined production process and the identification of opportunities to improve environmental performance. Owens,[52] however, argues that it is impossible to be entirely objective because most LCAs involve simplifying assumptions and subjective judgments.

As the definition above states, LCA attempts to provide an objective assessment of the environmental implications of a well-defined production process and identifies opportunities to improve environmental performance. LCA studies should clearly define their goals. These goals may serve to improve environmental management and product design within the firm. Other goals include strategic concerns, such as demonstrating that a product or process has environmental attributes that exceed the competition. The definition of "cradle and grave" often varies depending upon the goal and scope of the analysis. In many cases, the cradle includes mining and raw material extraction while the grave is at the plant gate.

One of the key steps in LCA is the emissions inventory. For many industrial processes, detailed inventory data by process are unavailable. In this case, some studies infer the data based upon input–output or mass balance relationships. A considerable number of subjective judgments enter this stage of the assessment, often buried in the details of the data compilation. In some cases, emissions judged to have no impact are not included in the inventory. This practice is misleading, although a mass balance could effectively uncover these emissions, depending of course on their magnitude. Conducting a mass balance requires engineering expertise and a detailed knowledge of the production process.

Once the inventory is complete, the next step of LCA is impact assessment. Many industrial processes generate an array of air, water, and solid-waste emissions. Each of these categories in turn generates an array of impacts. Many studies classify these impacts into several categories, such as human health, air visibility, acid deposition, global climate change, and other impact categories. Since one pollutant can contribute to more than one impact category, LCA studies often develop metrics to measure the effect that each emission has on each impact category.

As envisioned by SETAC, the final step in LCA is an analysis of how to improve the environmental performance of the production process. The analyst has the LCA inventory and estimates of the impacts across several different impact categories. LCA by itself, however, does not provide a framework for improvement analysis. The necessary decision framework should have two features. First, it should consider the cost of existing and alternative production technologies. In most situations, firms will not adopt environmentally beneficial technologies unless they generate significant cost savings over current technology.[53] The second feature of

---

[52] J.W. Owens, "Life-Cycle Assessment: Constraints on Moving from Inventory to Impact Assessment," *Journal of Industrial Ecology*, Vol. 1, No. 1, pp. 37-50, 1997.

[53] It should be noted that the aerospace industry in Southern California, where the regulations of the South Coast Air Quality Management District are perhaps the most stringent in the world, has been very innovative in applying advanced manufacturing technology to develop such technologies as alternative paints, corrosion protection coatings, and adhesives to meet these very stringent requirements and at the same time save weight and reduce unit aircraft cost. For example, Boeing is now using new topcoat paint for the C-17 that has a lower volatile organic compound discharge rate and is lighter, more durable, and less expensive than traditional paints.

the decision framework is that it should include some method to aggregate environmental impacts, which impose indirect costs on the firm, perhaps by inducing onerous regulation, and costs on society. A broader definition of cost would include typical operating and capital costs, costs associated with environmental damage and savings from avoided disposal and regulation. The LCA inventory can provide a good basis to estimate these environmental costs. This last feature requires the development of an environmental metric.

Considerable international effort has been expended to standardize the LCA process. Details of the standards can be found in ISO 14040, 14041, 14042, and 14043. These standards view LCA somewhat differently than SETAC; in fact, the phases of an LCA are goal and scope definition, inventory analysis, impact assessment, and finally interpretation. The ISO process sees LCA as having generally more iteration between the phases and also recommends certain practices pertaining to LCA objectives, public versus private studies, product comparisons, and allocation procedures. However, the basic process and intent of the two methods are the same and use of the SETAC framework here captures, with a little less complication, the essentials of LCA.

The comprehensive nature of LCA is perhaps one of its flaws because the informational requirements can be daunting and expensive to meet. Estimating how these emissions affect human health, global warming, and other environmental problems is even more complex and is fraught with considerable uncertainty. Even with quantification of these uncertainties, impact assessment does not provide policy makers with a clear ranking of alternatives. This task requires an environmental metric that weights various environmental impacts.

Several options exist for developing such metrics. One approach used by environmental economists essentially places a dollar value on impacts. This approach quantifies damage from environmental impacts so that the benefits of pollution reduction are the minimization or elimination of related monetary damages. Like the estimation of impacts, estimating the value of damage introduces another layer of uncertainty. While estimates of health costs associated with environmentally induced illness are easily documented, other impacts, such as ecosystem preservation and biodiversity, are inherently much more difficult to value. Another class of metrics avoids valuation and instead uses a variety of sustainability indices. The main drawback of these approaches is that arbitrary judgments may creep into the quantification of the sustainable standard.

Regardless of what environmental metric or set of metrics is used, the technology adoption problem remains one of optimal choice under uncertainty. Many researchers have used operation research tools, such as linear programming models, to address these problems. For example, Considine et al. use a linear programming model to identify least-cost production and investment strategies for the steel industry under coke oven emission controls.[54] Their model integrates engineering, economic, and environmental information. Other researchers have adopted a similar approach, such as Allen[55] in his study of chlorine minimization strategies in the chemical industry.

Design for the Environment

A firm evaluating new technology must balance cost and strategic concerns with environmental performance. Cost depends upon the unit labor, energy, and material efficiency of the process as well as capital intensity. Cost is important because it ultimately relates to product affordability. Strategic aspects include breaking dependence upon suppliers of essential

---

[54] T.J. Considine, G.A. Davis, and D.M. Marakovits, "Technological Change Under Residual Risk Regulation," *Environmental and Resource Economics,* Vol. 3, pp. 15-33, 1993.

[55] D. Chang and D.T. Allen, "Minimizing Chlorine Use: Assessing the Trade-offs Between Cost and Chlorine Reduction in Chemical Manufacturing," *Journal of Industrial Ecology*, Vol. 1, No. 2, pp. 111-134, 1997.

intermediate materials, expansion into growth markets, and many other considerations. Increasingly, environmental performance is entering technology development and investment decisions.

Evaluating the cost-effectiveness and environmental implications of different process and strategic choices facing a manufacturing plant can be complex. On the environmental side, the main source of complexity is the sheer volume of data from an LCA inventory. Another complication involves the interrelated nature of manufacturing operations. Changes in one unit process can affect the economics and environmental performance of downstream processes. Operations research (OR) tools provide a framework for organizing this information, identifying trade-offs, and making decisions.

One subset of OR tools are engineering–economic process models. As the name suggests, these models integrate engineering detail about the production process with cost information. Environmental data concerning emissions are essentially engineering information. Building an engineering–economic process model typically begins with a definition of the production process at some chosen level of detail dictated by the availability of data about the process. For instance, at a very high level of aggregation, fiber optic production could be modeled to include slurry preparation, glass ingot production, cable extrusion, and product finishing. The level of aggregation depends upon the purpose of the model. If the intent is to understand the economic and environmental trade-offs of a new process, then all that is needed is to determine how that process would alter existing practice. The model of the existing system and its possible reconfigurations would include new technology as a process option.

The next step in developing the model involves quantifying the input–output (IO) relations at each stage of the production process. Inputs include fuels, materials, supplies, maintenance, water, labor, and other inputs that vary with unit production levels. Outputs include the final product, recoverable byproducts, such as heat, steam, or offgases; and air, water, and solid waste emissions (or nonrecoverable byproducts). LCA emissions inventories taken for regulatory purposes are natural databases for estimating these latter components.

In addition to the IO coefficients, constraints are another characteristic of the production process. One common constraint is capacity. For instance, how many tons of iron can a blast furnace produce in 1 year at average capacity utilization? Other constraints include final product demand, environmental emission standards, and material balances. The material balance constraints ensure that supplies of intermediate inputs are at least as large as the demand for them by downstream unit operations.

The IO relations and constraints are essentially engineering information about the production process. The next layer requires economic information, including prices paid for purchased fuels, materials, and supplies. In addition, the analysis requires hourly wage rates on production workers and salaries for managerial and technical staff. Total operating costs equal the product of input requirements and prices paid for these inputs summed across all operations.

The final step of the analysis requires specifying an objective function. There are several approaches available. First, one could specify a multiobjective function that essentially is a weighted function of operating and capital costs and environmental impacts with weights selected by the decision maker. Choosing the weights, however, often involves subjective judgments. Another approach is to specify an environmental damage function, which is the product of the environmental impacts and the dollar-per-kilogram damages. Under this specification, the objective is to minimize the sum of operating, capital, and environmental damage costs. These components—the process activities, their IO coefficients, the production constraints, and the objective function—constitute the engineering–economic process model.

Life-cycle assessment information enters the definition of the process activities and the estimation of the IO coefficients. These coefficients include the indirect environmental impacts from upstream production activities. For example, purchasing a kilowatt of electricity may cost four cents per kilowatt hour and indirectly contribute to global climate change, ground-level ozone impacts, and acid rain problems. In other words, the electricity-purchasing activity costs money and generates environmental impacts that impose costs on society. Subsequent processing activities involve purchasing factor inputs at market prices, using intermediate products that transfer from one process to another, and consuming common property environmental resources with values approximated by the procedures discussed above.

The solution of an engineering–economic process model finds the mix of production activities that satisfies the objective function. Typically one of the first steps is to solve the model using the firm's current objective; for example, by minimizing operating costs and capital charges, and then comparing the optimal solution with current production levels for each unit process. If the constraints, prices, and IO coefficients are correct, then the solution should closely correspond with current practice. In essence, the process model provides a quantitative description of the production process. Some industries use process models for operation management, such as petroleum refiners who optimize their product mix based upon the cost and quality of their hydrocarbon inputs.

Process models for DfE also provide a framework for examining the economics and environmental impacts of process design options. A modification of an existing process or a new process would become a process option in the model. Given market, capacity, and material balance constraints, the model would determine the least-cost mix of processes across different technologies. The challenge for this stage is to develop reliable estimates of the IO coefficients for the new technologies. Box 3-6 illustrates the use of such engineering–economic process models for steel production.[56]

In some cases, the design process is too complex and detailed to perform an overall system optimization. In these cases, process models can be used to optimize system components and less formal methods can be used to arrive at a final design that combines the environment, performance, and cost considerations. Product designers would then apply their own subjective weighting for these criteria, iterating toward a final design.

Tool Development Needs

Despite a mature state of development, life-cycle assessment is a time consuming and costly process. Moreover, the reliability of the results is unknown because the data and the methodology underlying environmental performance metrics are proprietary and, therefore, not subject to rigorous peer review. Although the International Organization for Standardization (ISO) has passed guidelines for conducting life-cycle assessment studies, two areas in need of further development include standardized peer reviewed databases and metrics development. The former is being addressed in North America by the National LCI Database project managed by Athena International. Some insights into the issues pertaining to metrics development can be found in a 1999 National Research Council report.[57]

The development of transparent and reproducible environmental performance metrics is clearly a necessary first step in bridging the gap between design for the environment and manufacturing. Engineers need to know the environmental design criteria. Developing one metric that aggregates many different environmental performance indicators is one approach. Another approach is to consider multiple criteria and subjectively balance them. In practice, however, designers need some notion of what the minimum acceptable environmental standards should be. Government standards, for example, attempt to do this by setting

---

[56] T.J. Considine, C. Jablonowski, and D. Considine, "The Environment and New Technology Adoption in the U.S. Steel Industry," final report to National Science Foundation and Lucent Technologies, BES-9727296, May, 2001.

[57] National Research Council, *Industrial Environmental Performance Metrics: Challenges and Opportunities*, Committee on Industrial Environmental Performance Metrics, National Academy Press, Washington, D.C., 1999.

Box 3-6
Case Study of the Environment and Process Design in Steel Production

Steel mills use one of two types of furnaces to make new steel. Both furnaces recycle old steel into new, but each is used to create different products for varied applications. The first, the basic oxygen furnace, uses about 28 percent steel scrap to make new steel. The other 72 percent is molten iron produced from blast furnaces, which requires iron ore from mines, limestone from quarries, and coke from batteries of ovens. The furnace produces uniform and high-quality flat-rolled steel products used in cans, appliances, and automobiles. The other type of steel-making furnace, the electric arc furnace, melts virtually 100 percent steel scrap to make new steel. Steel minimills using these furnaces now produce nearly 50 percent of total U.S. steel production. This steel is used primarily to make products that have long shapes, such as steel plates, rebars, and structural beams. Steel minimills are far less capital intensive than integrated mills because they do not require blast furnaces and coke ovens. Their reliance on steel scrap also affords them an environmental advantage in lower consumption of energy and virgin material consumption.

Minimills have entered the last domain of integrated steel, employing thin-slab casting that can yield relatively high quality sheet steel. This additional competitive force comes at a time when many integrated steel firms are seriously reevaluating their plants in light of the recent regulations controlling toxic emissions from coke ovens. Most existing methods of producing coke generate fugitive emissions that contain potentially carcinogenic substances, such as benzene soluble organics (BSOs). A variety of strategies, some entailing additional investment and/or higher operating costs, can reduce these emissions. Inland Steel built a large battery of coke ovens using the Thompson nonrecovery process, heralded as a possible clean technology breakthrough. This design allows the controlled burning of coal that destroys the BSOs and other potentially carcinogenic compounds contained in the offgases of the coking process. There are, however, relatively large amounts of sulfur dioxide emissions from the waste heat, which can be recovered via heat exchangers and used to produce steam for electricity generation.

Several other iron- and steel-making technologies could either reduce or eliminate coke consumption. Pulverized coal injection, replacing up to 40 percent of the coke needed in iron making, is widely used in Europe, Asia, and Japan and is now gaining favor in the United States. Natural gas injection is another alternative technology.

There are also two new steel-making technologies that could totally eliminate the need for coke. First, direct reduction, a coal or natural gas-based iron-making process, produces an iron substitute for scrap in electric arc furnaces. Another coke-eliminating option is the Corex process, which does not require coke and produces a large volume of waste heat that can be used to cogenerate electricity. Jewell is a nonpolluting coking technology used in steel making. Another coke steel-making process is Calderon whereby coal feeding and product recovery are employed in a closed process.

To evaluate the economic and environmental performance of these technologies, an engineering–economic model of steel production is used. The model incorporates environmental emissions coefficients from an LCA of steel production from primary resource extraction to the plant gate. The model selects the optimal combination of activities to minimize cost subject to a number of constraints, including mass and energy balances for intermediate products. Substitute activities represent new technologies available for possible adoption. The model is for a specific steel plant with coefficients based upon actual operating performance.

This analysis provides insights into the trade-offs between cost and environmental objectives, such as reducing greenhouse gas emissions, toxic discharges, and acidic residuals. The second application solves the model under two different definitions of cost: private and social cost, which includes private costs and those of the environmental damage, associated with LCA impacts. This approach permits determination of the socially optimal steel production technology mix achieved by internalizing environmental externalities. Following a sensitivity analysis, the third and final application examines the impact of carbon and virgin material taxes on technology choice in the steel industry.

The incremental private and social costs of steel design options are shown below. On the basis of the total quantity of emissions in mass units, scrap-based steel production is environmentally superior to conventional integrated steel production. Using an economic valuation of the life-cycle environmental impacts, however, indicates that these two technology paths are quite similar. In fact, using conventional damage cost estimates, electric arc furnace steel production imposes slightly greater environmental damage than does integrated production due to substantially greater emissions of SO_x and NO_x resulting from the electricity generated to supply these facilities. Hence, adopting a life-cycle perspective for technology assessment can yield some rather surprising conclusions. If producers explicitly minimize social cost, however, scrap-based steel production with natural gas cogeneration of electricity is optimal. This finding suggests that electricity supply decisions are a critical element in assessing the economic and environmental performance of new steel production technologies.

Some of the Incremental Private and Social Costs of Steel Design Options

	Jewell	Corex	Scrap Electric	Scrap-DR Electric	Calderon
New capital expenditures	216.76[a]	575.42	437.41	503.17	246,32
Labor and capital	32.40	90.78	–89.66	–72.73	0.48
Energy	–4.11	30.69	–20.07	–15.10	3.02
Materials	0.00	–35.89	85.57	63.34	0.82
Total operating cost	28.29	85.59	–24.19	–24.49	4.32
(less byproduct sales)	–0.16	–3.07	5.58	5.19	0.00
Net operating cost	28.13	82.51	–18.57	–19.30	4.32
Environmental damage	2.34	132.84	57.39	63.34	–16.58
Total social cost	30.63	218.43	33.23	38.85	–12.26

[a] Millions of 1998 dollars.

standards for emissions of air pollutants, such as sulfur dioxide, nitrous oxides, and particulate matter. Standards, however, are often considered an inefficient way to improve the environment because they stifle technological innovation.

There is also a need for integrating life-cycle assessment tools with operations-research-based decision science models so that cost, technical, and environmental performance can be optimized. For this to occur, however, environmental performance metrics must be specified and measured. Decision makers need a measure of the environmental bottom line, not an array of different environmental impacts that are difficult to value individually, much less collectively. Balancing various technical performance measures in design is a similar problem. In this case, establishing minimum acceptable standards helps simplify the decision problem in which the choice becomes a constraint or requirement. Unfortunately, the societal consensus reflected in environmental standards is often at odds with companies' attempts to maintain their fiduciary responsibility to stockholders for company profitability.

Another need for life-cycle assessment is to simplify and standardize its application. A modular approach could be one possibility to simplify and reduce LCA cost in which industry has off-the-shelf modules that provide LCA impacts for a material or transformation process under consideration.

Recommendation 5. Life-Cycle Assessment: The Department of Defense should develop tools and databases that enable life-cycle costs and environmental impact to be quantified and integrated into design and manufacturing processes.

Establishing and maintaining peer-reviewed databases for environmental emissions and impacts of various materials and manufacturing processes will be critical for the government to integrate these factors into acquisition processes. Environmental performance metrics that combine multiple impacts are most useful for design *decisions. The development of high-level optimization methods can allow analysis of the trade-offs between cost, performance, schedule, and environmental impact.*

COMMON THEMES

Different disciplinary areas are directly involved in the design and manufacturing process—systems engineering, engineering design, materials science, manufacturing, and life-cycle assessment. Other supporting infrastructures are involved indirectly and affect all of these specific fields in an overarching way.

As outsourcing becomes more prevalent, and as many of these tasks are sent overseas, maintaining design and manufacturing capability in the United States is a real concern. It is essential that the United States continue to produce students who are trained for design, manufacturing, and systems engineering. It must also maintain a manufacturing capability in this country that employs these graduates.

Engineering Education

The availability of an educated domestic workforce is crucial to the quality of life, to the national defense, and to the economic security and competitiveness of the nation, and a key part of this workforce is in the manufacturing sector. The education and training of tomorrow's workforce become even more critical when one considers that the entire design and manufacturing field has expanded greatly in knowledge in recent years and will continue to do so, most likely at an even faster pace, in the foreseeable future.

Information technology is rapidly enhancing the process of communication between customers, engineers, and manufacturers. The broadening of the arena requires an integrated and well-balanced science and engineering education that covers systems, design, materials, and manufacturing. An integrated approach for traditional educational institutions as well as for certification programs for practitioners will ensure that the workforce is able to use the new tools and strategies for efficient product realization.

Recommendation 6. Engineering Education: The Department of Defense should invest in the education and training of future generations of engineers who will have a thorough understanding of the concepts and tools necessary to bridge design and manufacturing.

Integrating knowledge of virtual manufacturing into university curricula to train new engineers can help them use tools to bridge design and manufacturing. To ensure an adequate supply of such trained engineers, the DoD can help to develop programs to increase the quality and the number of graduating engineers available to work in these fields. It is also critical to retain U.S. capability in contributing disciplines, such as materials science and engineering.

4

Economic Dimension of Bridging Design and Manufacturing

There is a general consensus that since the mid-1990s the United States has enjoyed an acceleration of productivity growth from the rapid creation and widespread utilization of new information technology. Oliner and Sichel[1] found that the use of information technology and the production of computers accounted for about two-thirds of the 1 percentage-point increase in annual U.S. productivity growth between the first and second halves of the 1990s. These gains in productivity are continuing despite the slowdown in growth in gross domestic product from 2000 to 2002.[2] Whether productivity growth will remain high in the future is a critical question facing economic policy makers. Productivity growth is a key factor affecting the accumulation of income and wealth.

Understanding the dimensions and challenges associated with bridging design and manufacturing could generate insights into how application of information technology enhances productivity growth. Most importantly, in laying out an agenda for basic research and development that enhances the integration of many engineering tools, that report could chart a path toward continued and perhaps even faster productivity growth in the future.

The challenge from a social science perspective is to identify the incentives and organizational structures affecting the adoption of technologies that bridge the gap between design and manufacturing. These behavioral dimensions may rise to the level of the engineering and scientific challenges that lie ahead.

Several fundamental economic questions surround the goal of bridging design and manufacturing:

- What are the costs of tool integration and how do they vary by industry?
- What are the expected benefits in terms of cost reduction and strategic advantage?
- What are the impacts for productivity growth?
- Is government-sponsored research and development necessary?
- How do organizational and management structures affect development and adoption?

The following sections address these questions and raise a number of economic issues

---

[1] Stephen D. Oliner and Daniel E. Sichel, "The Resurgence of Growth in the Late 1990s: Is Information Technology the Story," *Journal of Economic Perspectives*, Vol. 14, No. 4, pp. 3-22, 2000.

[2] National Research Council, *New Directions in Manufacturing*, Committee on New Directions in Manufacturing, The National Academies Press, Washington, D.C., 2004.

that arise when contemplating the incentives and barriers to bridging design and manufacturing. These issues involve questions of how firms are organized and managed and how government agencies write and manage contracts. Economic models can estimate the private and social rate of return for investments in virtual design and manufacturing tools and help understand how incentives and organizational structures affect the adoption of virtual design and manufacturing tools.

THE COST OF BRIDGING

Developing virtual computer simulation of the production process from design conception to product life and disposal would enable a firm to quickly examine multiple designs and the trade-offs between various goals, including performance, cost, and environmental impacts. However, developing this capability in some cases may be very costly.

These capabilities can be achieved either by contracting with an outside vendor to produce the system or by developing the integrated set of design tools in-house. Both choices involve opportunity costs. While the outside vendor may deliver at a lower cost, the firm or government agency loses the ability to retain any strategic benefits from integration, such as more comprehensive knowledge of the design process and how it can be developed for new systems. Developing these capabilities within the firm involves a reallocation of engineering and software development teams that may involve adjustment costs in the form of reduced output or reduced productivity as the system is developed.

Another consideration is whether firms consider tool integration as an investment activity amortized over time or whether they treat these activities as regular production activity. As illustrated in the case of integrated design for the unmanned underwater vehicle (UUV), (see Box 3-2), the development cost of the ARL design tools was funded under a defense contract with the U.S. Navy. In this case, the integrated design tool, which is essentially a capital good because it can be reused to generate services over time, was developed as the design services were delivered. Private firms may view the cost of tool development and integration somewhat differently, placing these efforts in competition with other capital investment projects. Of course, costs are only one side of the equation.

IDENTIFYING THE EXPECTED BENEFITS

Bridging design and manufacturing requires the integration of various engineering tools developed for several key elements of the overall process as shown in Figure 3-1. This integration is an investment that involves up-front expenditures on computer resources and labor that generates a flow of expected benefits over time.

These benefits, however, may be highly uncertain due to the rapidly evolving nature of systems integration software technology. This uncertainty may induce firms to highly value the option of adopting a wait-and-see approach, holding off on investing until this uncertainty is reduced or until the expected benefits are substantially larger than expected project costs. On the other hand, early adopters of systems integration technology may be able to exercise valuable options in the future, such as the ability to apply the new methods to gain competitive advantage in the marketplace. Linking various engineering tools may enable the firm to more quickly develop products at lower cost. Identifying these real options associated with investments to bridge design and manufacturing is a key challenge.

Another issue is whether there are substantial degrees of freedom in the design process or whether regulatory or industry standards lock companies into a rather narrowly confined design set. If so, firms in certain industries may have little incentive to develop a sophisticated design process that utilizes computer simulation. These constraints may contribute to a reluctance of firms to standardize and integrate design tools because the returns from such efforts are diminished.

Where the returns are high, development of integrated tool sets is already taking place. The aerospace and automotive industries invest heavily in design tools, both commercial and homegrown, because of the increased speed and accuracy of the resulting designs, the ability to design manufacturing systems faster, and the huge cost of a mistake. Here cost avoidance, such as redoing a factory, being late to market, or having high warranty costs, is the issue.

IMPACTS ON PRODUCTIVITY GROWTH

Scholars are just beginning to understand how information technology affects productivity growth. Feldstein[3] observes that U.S. productivity gains made possible by information technology have been concentrated in white-collar jobs, including management, sales, purchasing, design, accounting, and other nonproduction activities that collectively account for most jobs, even in manufacturing. In contrast, Europe and Japan have not witnessed a similar surge in productivity. Feldstein speculates that incentives, work rules, and other institutional constraints may have slowed the adoption and flexible, innovative application of information technology in Europe and Japan. Well-defined case studies are needed in order to examine how incentives affect the creation and adoption of technologies that lead to a more integrated design process.

STRATEGIC ISSUES

Technologies that bridge design and manufacturing will no doubt require highly trained engineers who possess knowledge from several different areas. Attracting people to this emerging field will be an important challenge, especially in light of declining enrollments among domestic students in engineering schools across the nation. This diminished supply of domestic engineers to develop bridging technologies could have national security implications. In recent years, an influx of foreign students has filled this shortage, but with this development comes the risk that these professionals will transfer this knowledge to their home countries. This erosion of the manufacturing base could have a negative impact on innovation and on national competitiveness.

UNDERSTANDING THE ROLE OF GOVERNMENT

Bridging the gap between design and manufacturing may be too complex and costly for any lone firm to accomplish. The benefits of integration may be difficult to identify, much less quantify. Moreover, if the methods and technologies for bridging design and manufacturing are shared or intended to be made widely available in an open environment, firms may be unwilling to invest because they cannot benefit from these investments in the marketplace. The responsibility for the development and advocacy of such an approach comes to rest on a central entity, such as government or an industry trade association, that is willing to develop institutional arrangements to foster this development. Of course, this assumes that the development track is known.

INSTITUTIONAL STRUCTURES

Firms deal with complex problems that often defy highly integrated centralized control. Instead, firms often establish certain overall design parameters and then work on specific

---

[3] Martin S. Feldstein "Why Is Productivity Growing Faster?" *Journal of Policy Modeling*, Vol. 25, No. 4, pp. 445-451, 2003.

optimization problems, such as selection of materials, control systems, and manufacturing methods. This is the strategy that has influenced how firms have developed their organizational structures for product design. The premise of this report suggests that current organizational structures need to be made more efficient.

The design process to date almost invariably involves sequential optimization within units. For example, materials selection is not fully integrated into the design process. The shape of a product may restrict material choices. Multiattribute optimization that involves many design choices, constraints, materials, and choices may be possible given advances in computer technology. Another fundamental problem is the choice of the objective function. What is the goal? Minimize cost given certain performance constraints? What is the utility function of the design process in terms of trade-offs between cost, fatigue life, flexibility, and other attributes? There are management science tools available to optimize systems with many process and product choices given constraints, technical parameters, and multiple objectives. Ultimately the objective function involves an articulation of the functionality of the product. After all of these individual and often uncoordinated decisions are made, the overall system still may not be optimized.

The gains from more integrated optimization strategies need to be identified and quantified in order to encourage firms to rethink their organizational structures.

5

Barriers to Virtual Design and Manufacturing in DoD Acquisition

The DoD acquisition process is designed to support the programmatic and operational needs for a broad and rapidly evolving material infrastructure, which in turn supports national defense and the warfighter. The DoD acquisition programs cover platforms, weapons, and command, control, communications, computers, intelligence, surveillance, and reconnaissance (C4ISR). Utilization of modeling and simulation (M&S) through all phases of the acquisition process can:

- enhance the DoD's ability to field transformational capabilities;
- reduce concept to product cycle time to field a military capacity;
- archive technology investments for support of current programs and facilitate rapid response to new application requirements;
- enable broad component, system, and system-of-system optimization via large design parameter space during technology exploration and concept development.

NEED FOR DEFINITION AND MANAGEMENT OF REQUIREMENTS

In April of 2003 Secretary of Defense Rumsfeld issued the "Transformation Planning Guidance" document describing the goals of transforming the DoD into a faster and more flexible force capable of meeting the challenges of fighting new enemies and engaging new targets in new ways.[1] Transformation of capabilities within the DoD therefore requires a faster and more flexible capability-based acquisition system. Modeling and simulation provide a key enabler to integrating the research and development community, defense contractors, DoD acquisition offices, and the testing community to achieve the transformational changes envisioned in Secretary Rumsfeld's future DoD.

Therefore, effective utilization of modeling and simulation through all phases of the DoD acquisition process encompasses a compelling opportunity to embrace the simulation-based acquisition (SBA) policy, adopted by the DoD since its articulation by the Acquisition Council of the Executive Council on Modeling and Simulation in 1997, and the Simulation Test and Evaluation Program (STEP) program issued by the DoD Director of Test, System Engineering and Evaluation in the same year.[2] The various phases of acquisition are:

---

[1] U.S. Department of Defense, Donald H. Rumsfeld, Secretary of Defense, "Transformational Planning Guidance," April, 2003. Available at: http://www.oft.osd.mil/index.cfm. Accessed May 2004.

[2] A.L. Hillegas and J.F. O'Bryon, "Modeling and Simulation in the Acquisition Process," *ITEA Journal*, March/April,

- preconcept design and technology development;
- manufacturing and supply system design;
- requirement definition and analysis;
- system development and demonstration (including system integration);
- live-fire test and evaluation (LFT&E);
- effectiveness testing and analysis;
- system logistics;
- system interoperability;
- production;
- deployment;
- sustainment;
- upgrades and refitting;
- end of life—decommissioning and disposal.

The multiple steps of the acquisition process are schematically shown in Figure 5-1. Several DoD-sponsored studies within the last few years have examined these factors that limit more effective and timely utilization of modeling and simulation in defense acquisition. The 2002 NRC study *Modeling and Simulation in Manufacturing and Defense Systems Acquisition—Pathways to Success* shares a particularly significant synergy with the focus of this report.[3] The recommendations of that study in regard to modeling and simulation in acquisition identified the importance of (1) "building the right thing," (2) development of guidelines concerning model, simulation, algorithm, and data ownership to enhance collaboration and facilitate reuse, (3) effort to define how modeling and simulation is to be integrated into DoD acquisition including use of simulation support plans, (4) incentives for managers to adopt best practices for the use of modeling and simulation, and (5) development of pilot efforts sponsored by the OSD to advance the use of modeling and simulation.

The findings of the current report are based upon extensive insights from DoD programmatic experts and industrial leaders[4-7] and show a strong correlation with the recommendations of the 2002 NRC study.[8] Several of the topics identified in the current study directly mirror those of the 2002 NRC study, specifically the importance of developing and implementing simulation support plans (SSPs) to assist requirement definition. The development of incentives for program managers to adopt SBA, SSPs, and utilization of

---

pp. 25-29, 2001; E.A. Seglie, "The Future of Test and Evaluation," *ITEA Journal*, September/October, pp. 21-28, 2002.

[3] National Research Council, *Modeling and Simulation in Manufacturing and Defense Systems Acquisition—Pathways to Success*, Committee on Modeling and Simulation Enhancements for 21st Century Manufacturing and Acquisition, National Academy Press, Washington, D.C., 2002.

[4] Martin R. Sambur, Assistant Secretary of the Air Force for Acquisition, *Air Force Print News*, April 14, 2003, Washington, D.C., 2003.

[5] J.W. Hollenbach, Simulation Strategies, Inc., "Modeling and Simulation in Aerospace," presented to the Committee on Bridging Design and Manufacturing, National Research Council, Washington, D.C., February 24, 2003.

[6] W.H. Lunceford, Jr., Director, Army Model and Simulation Office, "The Institutionalization of Modeling and Simulation or Making M&S All It Can Be," presented to the Committee on Bridging Design and Manufacturing, National Research Council, Washington, D.C., April 29, 2003.

[7] R.K. Garrett, Jr., TCG-I Coordinator, Naval Surface Warfare Center, "Opportunities in Modeling and Simulation to Enable Dramatic Improvements in Ordnance Design," presented to the Committee on Bridging Design and Manufacturing, National Research Council, Washington, D.C., April 29, 2003.

[8] NRC, 2002. See note 3 above.

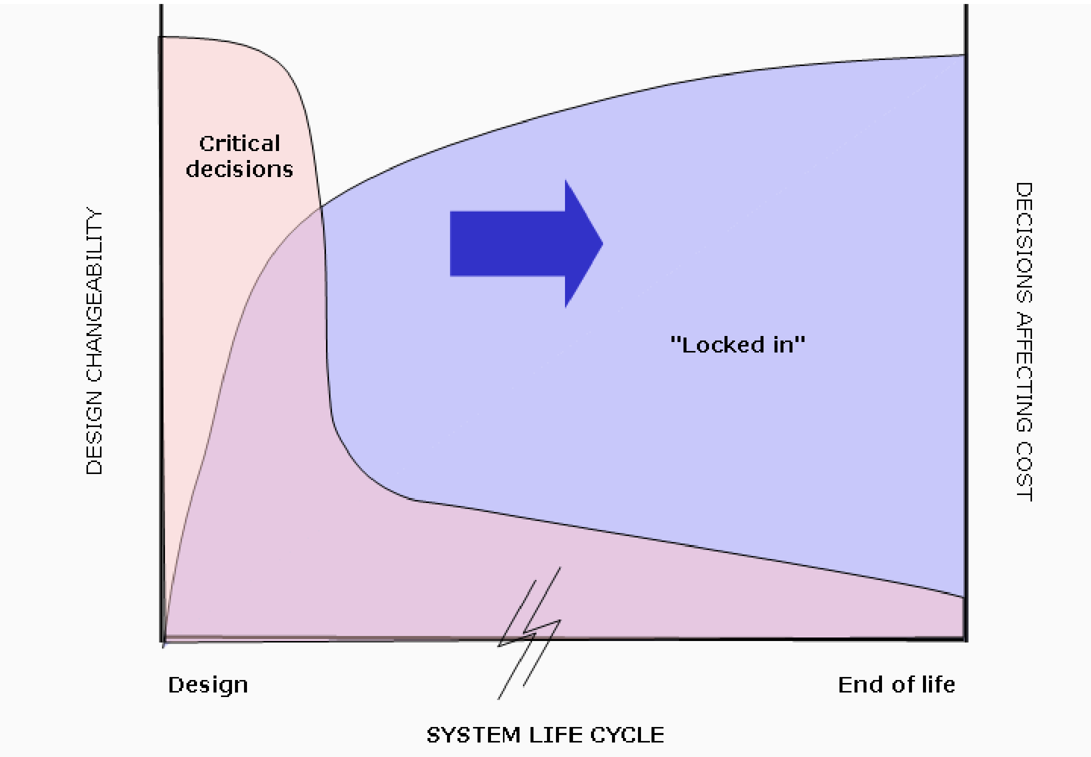


FIGURE 5-1 Phases of the DoD acquisition process and the associated trends in design flexibility and decisions affecting cost as a function of system life cycle. This schematic illustrates the dominant role of design and requirements definition in the acquisition process as they determine cost, performance, and quality. Source: R. Garrett, "Opportunities in Modeling and Simulation to Enable Dramatic Improvements in Ordnance Design," presented to the Committee on Bridging Design and Manufacturing, National Research Council, Washington, D.C., April 29, 2003; and M. Lilienthal, "Observations on the Uses of Modeling and Simulation," presented to the Committee on Bridging Design and Manufacturing, National Research Council, Washington, DC, February 24, 2003.

modeling and simulation throughout the acquisition life-cycle process remains a recommendation that the current study also strongly endorses.

The rapidly evolving field of virtual modeling and simulation has the potential to improve the DoD acquisition process significantly. Performance, cost, and product quality are identified in this report as central to any design, manufacture, and life-cycle support dominated by early program requirement definition and analysis. Timely establishment of firm technical program scope and mission requirements not only is crucial to avoiding unnecessary acquisition costs and reducing risk, but also is the crucial step preceding the follow-on nested stages of design, testing, and manufacturing necessary to effectively address all the phases of acquisition. The importance of timely requirements definition cannot be overstated. The use of modeling and simulation to guide the establishment of realistic requirements that all the relevant communities—design, manufacturing, performance—can agree on is essential to minimizing requirements drift and reducing both production cost and time to deployment. A recent example of the effects of failure to establish firm requirements definitions was given by the Assistant Secretary of the Air Force for Acquisition, Marvin R. Sambur, in regard to the F/A-22 Raptor

Program Review.[9] He stated regarding the review that "unstable requirements, faulty cost estimates, lack of test community buy-in, inadequate systems engineering, and unstable funding" were linked to the Raptor program's problems with meeting cost and schedule targets.

NEED FOR BUILDING LINKAGES ACROSS ALL PHASES OF DOD ACQUISITION

Realization of a new acquisition paradigm for future DoD procurements that will optimize performance, cost-effectiveness, and time to actual military capability (which is not the same as a formal declaration of an initial operational capability or deployment) requires the use of modeling and simulation in each of the sequential phases of acquisition. These must encompass concept initiation, technology demonstration, subsystem design, manufacture and supply chain design trade-offs, subsystem performance analysis, subsystem performance assessment, system integration and logistics, live-fire test and evaluation (LFT&E), interoperability, manufacture, system deployment, maintenance, upgrading and refitting, and finally, decommissioning and disposal. Each stage in this sequence plays a key role in enabling military systems to meet performance goals, cost and schedule goals, and, therefore, the warfighters' needs. Each acquisition stage builds on and is dependent on the foundation of the acquisition step and technical analysis and risk assessment of the stage directly preceding it to expand design options while simultaneously decreasing time to field capability and to reduce the risk of implementation. Figure 5-2 reflects this hierarchy and the additive nature of the types of modeling and simulation critical to making the technical decisions to support development and thereafter acquisition.

As reflected in this schematic pyramid diagram, modeling and simulation tools utilized in the development of a new military system span many levels of fidelity. At one end are the physics-based codes used to design trade-off studies and CADCAM tools for assessing the manufacturability of the proposed designs. At the top of the pyramid are simulation tools essential to establishment of military worth (system effectiveness) and determination of how the system will be used by the warfighter (concept of operations). Across the range of modeling and simulation embodied in the pyramid structure are not only different tools but also different communities that develop each level's tools. Traditional barriers between levels and lack of transmissibility of data between levels remain one of the chief barriers to more robust utilization of modeling and simulation to positively affect DoD acquisition. While there are natural linkages between each of these levels, two principal barriers exist. First, fundamental modeling requirements are often lost in enthusiasm over information technology (IT) advances; i.e., you cannot develop and implement predictive models of processes and physics if you don't understand the fundamentals at the lowest level of representation in the pyramid scheme. Second, realization of SBA relies on efficient and timely connectivity between each of the hierarchical levels of the total DoD life-cycle process; a missing linkage between any of the levels represents a "bridge-to-nowhere" situation, which must be crossed. Herein lies a chief barrier to more effective utilization of modeling and simulation in all the steps of the acquisition process (see Figure 5-1).

Virtual modeling and simulation possesses a unique ability to integrate the technical decision points up this pyramid to establish the military worth of the technology under development and thereafter assess impact logistics and examine system-level interactions.

Lack of Modeling and Simulation Plans in DoD Acquisition Programs

Early implementation of modeling and simulation support plans has positively impacted

---

[9] Sambur, 2003. See note 4 above.

acquisition and has helped the program managers (PMs) who use them to better justify the funding for program execution.[10] Nevertheless, these support plans are not widely used. Planning for a project's modeling and simulation needs can provide a more realistic assessment of development costs for the necessary resources; can foster more accurate quantification of the benefits of modeling and simulation; and can provide a timely vision of which tools, databases, and validation, verification, and accreditation (VV&A) are needed during each portion of the acquisition process.

Effective plans for modeling and simulation, and timely returns from their utilization, are not free, however. Focused emphasis on these plans is best achieved through integrated product teams (IPTs) and dedicated staff assigned to the acquisition program.[11] The benefits of adopting modeling and simulation plans can impact programs in both the short term and the long term, as well as having a broader effect on the DoD. Development of proactive plans allows the PM to engage the DoD service laboratories to leverage existing expertise within the DoD, as well as that available through the Department of Energy (DOE), and also to engage the academic science and technology base. Planning that looks beyond the end of the immediate program can also facilitate reuse of modeling and simulation tools, whether these tools were developed by the prime contractor, within the DoD or DOE technology laboratories, or at universities. Reuse of the data and tools developed for a particular project could provide strong growth of simulation-based acquisition within the DoD.

Lack of Ownership of Models, Simulations, Data, and Databases

In DoD acquisition programs surveyed during the "meet MASTER" exercise, over half of the models and databases in use were developed by industry, and industry retained 40 percent of this total following program completion.[12] The high rate of retention was directly linked to industry viewing these models, data, and databases as proprietary. This opinion is in part a reflection of corporate investments in internal research and development (IR&D) in a spectrum of design, performance, manufacturing, and life-cycle areas including the following:

- CADCAM coupled models
- Manufacturing automation and control models
- Performance models and simulations
- Physics-based performance models and their associated databases
- Subsystem integration and assembly models
- Verification and validation test problems
- System analysis and performance models
- Hardware-in-the-loop (HITL)
- Man-in-the-loop (MITL)
- System interoperability

Need for an Integrated Perspective on Modeling and Simulation

As illustrated in Figure 5-2, a nested set of modeling and simulation capabilities is required to accomplish SBA from concept, to manufacture, to system performance, to

---

[10] Hillegas and O'Bryon, 2001. See note 2 above; and Sambur, 2003. See note 4 above.

[11] Hillegas and O'Bryon, 2001. See note 2 above; and Hollenback, 2003. See note 5 above.

[12] Hillegas and O'Bryon, 2001. See note 2 above.

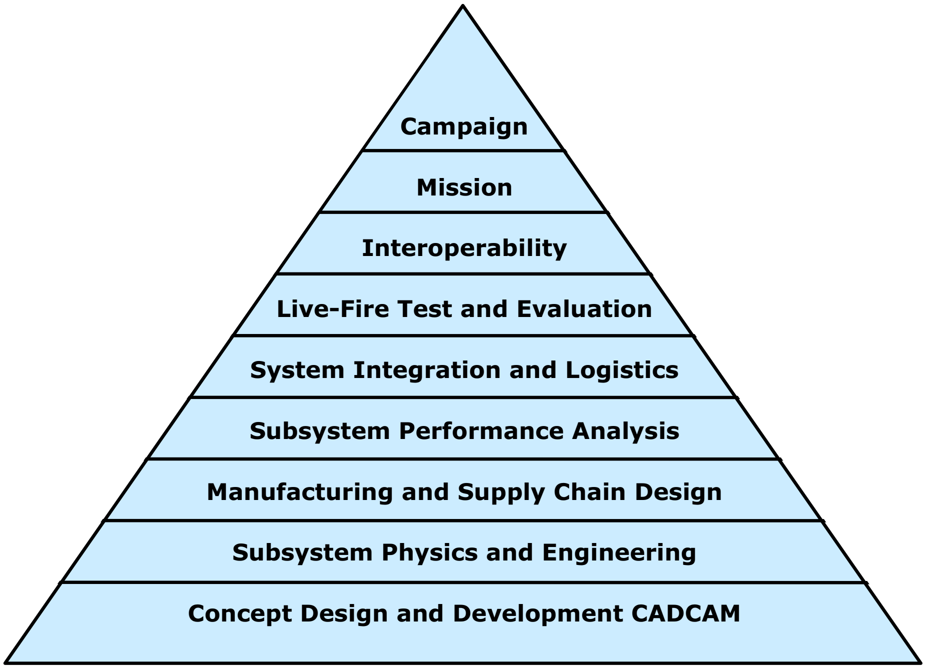


FIGURE 5-2 Hierarchy of modeling and simulation to support total DoD life-cycle process. Source: M. Lilienthal, "Observations on the Uses of Modeling and Simulation," presented to the Committee on Bridging Design and Manufacturing, National Research Council, Washington, D.C., February 24, 2003.

deployment. As the level of complexity of a program increases, modeling and simulation offer a practical means to examine, quantify, and exercise all portions of a system in an organized manner and allow assessment of its capabilities to meet mission objectives. Assessment of the system of systems and the interoperability of systems deployed is an area that particularly benefits from using virtual modeling and simulation due to the severe financial and operational issues of live testing and validation of these two issues in actual battlefield situations. Nevertheless, integration of modeling and simulation tools to allow bridges from one stage of acquisition to the next remains one of the largest challenges of SBA.

As an illustration, let us examine the development of a munitions system. Physics-based tools, including CAD and CAM, used to examine the design trade-offs in concert with the ability to manufacture the components, reflect in many cases state of the art technology readily available to the DoD contractor infrastructure. Emerging physics and phenomenological modeling approaches are pushing abilities to integrate the previous design and manufacturing knowledge at the subsystem level with subsystem performance metrics in some instances. However, weaponization through buildup of the subsystems to produce a full system with the performance capability to meet field objectives now rests at the fringes of a contractor's modeling and simulation capability in many instances due to the lack of interoperability among tools for creating models and simulations, and the insufficiency of the physics-based tools to accurately assess system integration, analysis, and logistics.[13] Due to this limited connectivity and lack of robust, validated tools and databases, further promulgation of the design tools to the

---

[13] Garrett, 2003. See note 7 above.

level of accurate assessment of system lethality, collateral damage, and mission planning is greatly hindered if not impossible.

Interoperability is one of the "Grand Challenges" of the DoD acquisition requirements. With ever increasingly sophisticated programs and complex platforms deployed within a mission scenario, use of models and simulations offers one of the few avenues, barring full theater testing and evaluation, to assess program interoperability and performance. Interoperability will continue to increase in importance as connectivity is extended beyond system-of-systems considerations. For example, since September 11, 2001, evolving DoD requirements embrace fully functional interoperability with civilian police and indigenous military personnel as demonstrated in the war in Iraq.

Recommendation 7. Defense Acquisition Processes: The Department of Defense should define best practices for government ownership rights to models, simulations, and data developed during system acquisitions.

Formal guidelines and best practices for transferring models, simulations, and data between the government and its contractors are essential for competitive procurement. Instituting common model access, common model databases, and common document controls will ensure that information generated under government funding is available to multiple program managers.

Incentives for program managers to develop integrated design and manufacturing tools can make simulation-based acquisition become a reality for DoD programs. Well-defined metrics for integration of design and manufacturing can help the program managers use simulation-based acquisition. Metrics that are compatible with different acquisition programs will allow these investments to be leveraged in the future. Also, specifying the modeling and simulation techniques that will be used in the proposal evaluation process, especially the cost structure analysis and affordability models, will facilitate simulation-based acquisition. Integrating the concept-of-operations definition into the modeling and simulation program plans can bring end users into the acquisition process and thus foster a more successful transition to military capability.

6

Summary, Recommendations, and Research Needs

The design and manufacturing enterprise can be interpreted using the flow diagram presented in Figure 2-2, which seeks to capture series and parallel activities at several levels of detail over time during the development of a product. At the lowest level (the bottom of the "V"), individual components are designed and manufactured for integration into subsystems. In an automotive context, components might include brake rotors, suspension parts, or engine control computers. At the next level (the middle of the V), these components are assembled into subsystems—the brake subsystem, the suspension subsystem, or the engine. The subsystems are then integrated into a platform, in this example, an automobile. Finally, at the enterprise level (the tips of the V), such matters as marketing, distribution, and life-cycle management are considered.

Bridging design and manufacturing requires the ability to conceptualize, analyze, and make decisions at all levels of the V in Figure 2-2. Using this framework, knowledge and information from several disciplines can be integrated to make intelligent decisions at all levels. New tools (Chapter 3) can enable the effective application of this process. As depicted in the colors in Figure 2-2, software tools are not available (red) for many of the required product development activities. For other activities, software tools may be emerging (yellow) or common (green) but are not interoperable and so are not used together, or are used inefficiently. When tools are fully interoperable, designers and engineers can use and link various data and models for a given activity as well as across different activities required for product realization. For example, tools that allow data to be easily shared instead of being regenerated or re-entered are more efficient, as are tools that allow information at all levels to be viewed with an appropriate amount of abstraction.

New collaborative environments will also be necessary to bridge design and manufacturing. These environments will use modeling and simulation tools to enable collaborations between different disciplines. Realization of integrated engineering design with manufacturing, variously referred to as design for manufacturing, design for six sigma, or concurrent design and manufacturing, further requires implementation of an up-front series of program planning steps within the DoD acquisition process, as discussed in Chapter 5, to achieve measurable savings in the cost and time to first deployment. Such savings in cost and time in commercial industry are discussed in Chapter 4.

In the process of developing recommendations in various disciplinary areas, described in Chapter 3, some common themes emerged regarding the flow of information and knowledge between the different areas. These themes—system requirements, geometric information, and material properties and process data—form the fabric of the entire design and manufacturing system in commercial industry and in the DoD acquisition process. This chapter collects the recommendations made by the committee in different disciplinary areas, identifies common themes, and also provides recommendations on bridging design and manufacturing in DoD acquisition as well as in engineering education.

SYSTEMS ENGINEERING

Recommendation 1. Systems Engineering: The Department of Defense should develop tools to facilitate the definition of high-level mission requirements and systems-level decision making.

Tools to create, visualize, and analyze design and manufacturing alternatives can facilitate systems-level decision making. A specific opportunity is to develop tools for converting customer needs into engineering specifications, and for decomposing and distributing those specifications to subsystems and components.

The design and manufacturing process leading to product realization is essentially a system of systems. Performance requirements are set at the highest level. For example, in an automotive system, the vehicle capacity, performance, weight, and cost are specified. In weapons systems, range, power, and cost are specified. These requirements come from analysis of the needs of the customer and from estimates of funding and other resources.

Performance requirements, set at the highest level, flow down to the other levels in the form of system and interoperability specifications. Conceptual designs are broken down into subsystem and component designs. Decisions are then made about materials, assembly, and manufacturing processes. Information may also flow back up this chain to modify the design.

Such a sequential approach, however, can lead to inefficiencies. Decisions may be made at one level without full consideration of the implications for other levels. For example, parts may be designed that cannot be manufactured or parts can be manufactured that are difficult to assemble. Simple manufacturing processes may be impossible to use because of an arbitrary design specification. A systems engineering approach can avoid these consequences by requiring collaboration at different levels and collective decision making.

Moving from a linear approach to an integrated systems-level approach will require substantial cultural and organizational changes. In order for such an approach to work, all of the participants require access to sufficient and timely information. Designers need to be able to work with a multidimensional trade space, where design alternatives can be effectively compared. Software tools can make important contributions to this effort. The systems approach requires that analyses and decisions be made in multiple disciplines and that global optimization be performed. Further, since it is likely that several different analyses will be done, functional interoperability between the various computer codes is essential. Finally, the integration of such tools will require significant training.

Research is needed on improved techniques to derive and elicit mission needs, and to translate those needs into model-based requirements and executable specifications. The current process for this step is largely experiential and tends to force designers to think within the constraints of previously developed products, discouraging innovation in favor of incremental improvement.

So that designers can link system requirements and full component specifications, better tools and techniques are needed to create, visualize, and analyze the design trade space. These tools will include fully interoperable codes, where data do not have to be recreated for different analyses. They will also support automated abstraction of the data at different levels.

The DoD can foster the growth of this systems approach in two ways. Funding can be provided for demonstrations and benchmarks of existing tools. This funding would also encourage improved interoperability. The DoD can also support systems engineering curricula at both the graduate and undergraduate levels. Further, programs can be developed, along the lines of the NSF Grant Opportunities for Academic Liaison with Industry (GOALI) program, to disseminate these methods into industry and government laboratories.

ENGINEERING DESIGN

> **Recommendation 2. Engineering Design: The Department of Defense should develop interoperable and composable tools that span multiple technical domains to evaluate and prioritize design alternatives early in the design process.**
>
> *Improving interoperability, composability, and integration of design and manufacturing software is a complex problem that can be addressed with near-, mid-, and long-term objectives. In the near term, developing translators between existing engineering design environments and simulation tools can solve problems with minimum effort. In the mid term, a common data architecture can improve interoperability among engineering design environments and simulation tools. Key long-term research goals include (1) the development of interoperable modeling and simulation of product performance, manufacturability, and cost; (2) the creation of tools for automated analysis of design alternatives; and (3) the application of iterative optimization using both new and legacy codes.*

Almost 70 percent of the cost of a product is set by decisions made early in the engineering design process. If system integrators have the ability to see and work with a large design space, they can better analyze trade-offs between alternatives. Designers need to be able to work within a multidimensional space where design alternatives can be effectively compared. While adequate design tools exist for making decisions within a narrow framework, mature tools do not exist for making decisions over the broad range of design and manufacturing shown in Figure 6-1.

The ability to integrate modeling and simulations across multiple domains is yet to be demonstrated. Domains may include geometric modeling, performance analysis, life-cycle analysis, cost analysis, and manufacturing. If such simulations were able to integrate system behavior and performance in multiple domains, performance, manufacturability, and cost information could be considered and optimized early in the design process. Such integration will require giant leaps in interoperability among various software packages and databases.

Designers also need tools that allow them to explore a wider design space. Such an approach encourages innovation. However, the designer must be able to adequately assess the feasibility of radical designs by supported behavior, manufacturability, and cost analyses. An important challenge lies in the fact that many performance metrics conflict and require careful trade-off analyses. These problems can be extremely complex. In the absence of tools for exploring trade spaces, people argue or rely on their opinions.

The efficiency and productivity of the engineering design process are affected by the tools that are available to designers, the degree to which these tools (often deriving from different disciplines) are integrated, and the culture that supports the use of these tools. Integration among the various tools used during the engineering design (geometric modeling tools, performance analysis tools, control system development tools, life-cycle analysis tools, cost-estimating tools, and manufacturing simulation tools) was clearly identified as a critical shortcoming of existing software. It is critical that this issue be addressed in order for bridging of design and manufacturing to become a reality. The committee identified both short-term and longer-term approaches to address this issue, starting with translators between existing codes and advancing to complete data architectures developed for this purpose.

Organizational culture changes are essential to produce gains in productivity and efficiency. These issues are also the most difficult to address. However, a new generation of engineers trained to accept, and indeed to expect, integration of design and manufacturing is the best long-term solution.

MATERIALS SCIENCE

> **Recommendation 3. Materials Science: The Department of Defense should create, manage, and maintain open-source, accessible, and peer-reviewed tools and databases of material properties to be used in product and process design simulations.**
>
> *Integrated tools and databases for materials design, materials selection, process simulation, and process optimization are key to virtual manufacturing. Data gathered from manufacturing and materials processing using a variety of sensors can validate and improve design, modeling, simulation, and process control.*

Materials play a key role in any product. These materials are selected based on their ability to meet the product specifications, availability, and cost. While new materials with enhanced capabilities are constantly being developed, the greatest impact on the design and manufacturing enterprise may come from more effective use of existing materials. The time scale for development, characterization, and acceptance of new materials may be too long to have a significant impact on manufacturing in the near term.

Effective use of today's materials can be greatly enhanced by using software tools. In particular, databases of accurate and well-characterized material properties would have a significant impact on the quality and speed of product design and manufacturing. Validation by peer review of such databases is essential for their acceptance.

Conventional materials such as monolithic metals, ceramics, and polymers will continue to be the most important ones used in production. However, the relationships between structure and properties in these materials are yet to be fully understood and their potential is not realized. Thus, continued funding of fundamental research intended to delineate the relationships between processing, structure, properties, and performance in these materials is warranted. Both experimental investigations and fundamental simulations are necessary to understand these relationships.

The variety of forming processes by which materials are converted into products (e.g., casting, forging, stamping, cutting, molding, and welding) can all be simulated by modeling and analysis. However, the fidelity of these analyses depends strongly on the properties of the material in a variety of states and under different external conditions. In addition, even when databases exist, many analysis codes suffer from a lack of interoperability with each other and with specific databases. This makes a strong case for an extended database of materials properties.

Most processing simulations require a mesh of the volume of the product, and often the tool that is used to manufacture it, as well. Generating these volumetric representations from the surface models used in other design processes remains a time-consuming and expensive task.

Optimization tools can be used effectively to improve product designs. However, their use in process simulations is relatively rare because the simulations themselves are slow and expensive, and this precludes adequate exploration of the design space. Research on more efficient optimization methods and on coupling these methods to legacy codes is needed.

Any simulated process is only valid within prescribed boundary conditions. Often, the boundary conditions are not well characterized or are unnecessarily limited, and this limits use of the generated data. Sensors can be deployed in both research and manufacturing environments to improve the fidelity of the simulations of various manufacturing processes. As an example, solidification processing is an area where sensors are used effectively. Because the interfacial heat transfer characteristics cannot be completely predicted, temperature sensors embedded in the mold are used to "tune" the simulation parameters. The use of such sensor data in conjunction with modeling can provide process control for many other manufacturing processes as well.

Validated data can also be used to develop methods to predict material properties from fundamental physics and to develop constitutive models that predict material behavior for a wide range of materials and conditions that are outside measured boundary conditions. Success in this area will greatly enhance the next generation of virtual manufacturing. The DoD should create, manage, and maintain a database of material properties to be used in product and process design simulations. Entries in this database should be validated and peer-reviewed by the community at large. Further, the DoD must assert ownership of material property data generated under its auspices.

Process simulation should become a required component of DoD system development. Methods for design optimization and sensitivity analysis should be developed, and standards for integrating codes into design environments should be implemented.

MANUFACTURING

Recommendation 4. Manufacturing: The Department of Defense should assess the role and impact of outsourcing on the integration of manufacturing and design functions.

Assessing the impact of outsourcing key activities can help determine how to minimize complexity and maximize coordination in various organizational structures between manufacturing systems. Tools that include efficient algorithms for production scheduling and procedures for flexible factory design can ease the difficulties of outsourcing.

Improvement in the coordination of design and manufacturing involves both technical and organizational actions. Within a single company, coordination between design, materials supply, production scheduling, and process control can be difficult; outsourcing of tightly coupled design and manufacturing activities adds complexity to an already complex bridging process. For example, software tools in use across many organizational boundaries may not communicate without substantial effort.

Creation of new technical knowledge in this domain will not be sufficient without accompanying improvements in management methods and organizational arrangements used for outsourcing. These include how to structure cross-functional teams, how to transfer information in a timely manner between team members, and how to identify and resolve conflicts and discrepancies. Implementing the results of research in this area from both business and engineering schools will help improve design–manufacturing coordination. Organizational and managerial structures that facilitate teamwork can make manufacturing efficient and can overcome the tendency toward decentralization that is magnified by outsourcing.

Economic models can estimate the private and public rate of return for investments in virtual design and manufacturing tools and help characterize how incentives and organizational structures affect the adoption of those tools. Economic models of outsourcing choices can also help to assess the strategic impacts on companies, industries, and national defense. The loss of national capability due to outsourcing to offshore companies may become clearer with more appropriate models. Outsourcing of software development, in particular to offshore companies, may represent a substantial barrier to interoperability.

LIFE-CYCLE ASSESSMENT

Recommendation 5. Life-Cycle Assessment: The Department of Defense should develop tools and databases that enable life-cycle costs and environmental impact to be quantified and integrated into design and manufacturing processes.

Establishing and maintaining peer-reviewed databases for environmental emissions and impacts of various materials and manufacturing processes will be critical for the government to integrate these factors into acquisition processes. Environmental performance metrics that combine multiple impacts are most useful for design decisions. The development of high-level optimization methods can allow analysis of the trade-offs between cost, performance, schedule, and environmental impact.

In a systems approach to design and manufacturing, the cost of a product over its entire life is considered. Cost can be viewed from several dimensions. First, there is the acquisition cost of a product that includes design, development, and manufacturing. After acquisition, operating or ownership cost is incurred by operators of the product, which is particularly relevant for defense systems that may last generations. In this case, design decisions can have a profound impact on the adaptability of defense systems to modification or retrofits. Third, there is the environmental impact of manufacturing processes and end-of-life recycling or disposal.

The metrics for quantifying all of these assessments are challenging. Accurate assessment is difficult because gathering the necessary data is expensive and also may be subjective or arbitrary. One reason is that recycling is often done by widely distributed small businesses that operate with a variety of business models, making the economics of the industry opaque.

There is also a need for tools that can integrate life-cycle assessment metrics into design environments for performance and manufacturability. This would enable "design for environment" approaches to also be considered early in the design cycle.

COMMON THEMES

Different disciplinary areas are directly involved in the design and manufacturing process—systems engineering, engineering design, materials science, manufacturing, and life-cycle assessment. Other supporting infrastructures are involved indirectly and affect all of these specific fields in an overarching way.

System Integration

Bridging is inherently integrative and requires tools and methods that are holistic. The committee's assessment of current information technology (IT) tools indicates that few provide significant integration. Models and simulations thrive at the component level or in one phase of the product creation process. At higher levels of subsystems and systems or across phases of the product creation process, the existence and use of these virtual tools drop off sharply. Among the reasons is that components operate in one phenomenological domain or in a relatively simple system, whereas subsystems and systems involve many phenomena and are big and complex. Similarly, each phase of the product creation process involves a narrow set of disciplines with its own vocabulary and methods, whereas across many levels, a number of cultures, methods, and processes have to be merged. Major advances will require integration of disparate databases, representations of phenomena, mathematical models, methods, communication networks, and organizations.

Data Management

Success in bridging design and manufacturing depends on the successful management of data. At the component level, designers need extensive and reliable material property data. Robust tools are needed to efficiently translate geometric design data for use with the various analysis codes. Also needed are effective tools for projecting total life-cycle cost using these data. The DoD should establish guidelines and procedures for the sharing of data, models, and simulations that still protect proprietary and security concerns.

Materials selection and process design require reliable databases for material properties, and reliable constitutive models to predict material behavior over a wide range of conditions. The DoD should establish and maintain open material property databases. Public validation and verification of these databases must be organized to ensure their reliability. A central organization could help to eliminate redundant efforts and to consolidate and leverage expenditures by DoD and other government agencies. Some of these data may be obtained through improved fundamental physics simulations. The DoD should continue to support these efforts. The most immediate benefit will derive from studies of conventional materials.

Effective bridging of design and manufacturing will require better ability to seamlessly pass design data between the different levels. A phased approach is recommended to improve this situation:

- A short-range recommendation is to develop translators between existing engineering design environments and simulation tools.
- An intermediate-range recommendation is to develop a database or architecture available to all engineering design environments and simulation tools.
- A long-range research topic is to develop fully interoperable, multiple-resolution, multiple-domain modeling and simulation of product behavior, performance, manufacturability, and cost.

Design and Analysis Methodologies

Improved design and analysis methods are critical to the successful bridging of design and manufacturing. These methods must be capable of resolving multiple length and time scales and be coupled to multiple domains. There are critical needs in three areas:

- Product behavior and performance
- System behavior and performance
- Manufacturability and cost

Tools are needed for the automated synthesis of design alternatives and for improved exploration of engineering design spaces. Research is needed to develop optimal design tools that effectively consider multiple objectives, particularly those arising in different domains. These tools should identify areas of high sensitivity to normal process and product variations, leading to improved monitoring and sensing for product and process control.

Organizational Issues

Improvement in design–manufacturing coordination involves both technical and managerial/organizational actions. Creation of new technical knowledge in this domain will not be sufficient without accompanying improvements in management methods and organizational arrangements. These include how to structure cross-functional teams, how to flow information in a timely manner between team members, how to identify and resolve conflicts and discrepancies, and so on. These are ongoing research topics in business schools and some engineering schools. These activities should be encouraged.

Research on outsourcing of key activities to determine how to minimize complexity and maximize coordination is also needed, along with better economic models of outsourcing choices that reflect the strategic impacts on companies and industries. Loss of national capability also needs to be addressed. The DoD must ensure that U.S. engineering graduates are capable of performing the analysis and design discussed in this report.

Modeling and simulation plans should be made a required component for all DoD acquisition programs. The DoD should institute incentives for program managers to develop new tools and databases that contribute to the general infrastructure, including an annual competition for the best infrastructure contributions. Other creative means should be sought to provide incentives for adoption of modeling and simulation.

Infrastructure

As outsourcing becomes more prevalent, and with it a certain amount of offshoring, maintaining design and manufacturing capability in the United States is a real concern. It is essential that the United States continue to produce students who are trained for design, manufacturing, and systems engineering. We must also maintain a manufacturing capability in the United States that employs these graduates.

Engineering Education

> **Recommendation 6. Engineering Education: The Department of Defense should invest in the education and training of future generations of engineers who will have a thorough understanding of the concepts and tools necessary to bridge design and manufacturing.**
>
> *Integrating knowledge of virtual manufacturing into university curricula to train new engineers can help them use tools to bridge design and manufacturing. To ensure an adequate supply of such trained engineers, the DoD can help to develop programs to increase the quality and the number of graduating engineers available to work in these fields. It is also critical to retain U.S. capability in contributing disciplines, such as materials science and engineering.*

The availability of an educated domestic workforce is crucial to the quality of life, to the national defense, and to the economic security and competitiveness of the nation, and a key part of this workforce is in the manufacturing sector. The education and training of tomorrow's workforce become even more critical when one considers that the entire design and manufacturing field has expanded greatly in knowledge in recent years and will continue to do so, most likely at an even faster pace, in the foreseeable future.

Information technology is rapidly enhancing the process of communication between customers, engineers, and manufacturers. The broadening of the arena requires an integrated and well-balanced science and engineering curriculum that covers systems, design, materials, and manufacturing. An integrated approach for traditional educational institutions as well as for certification programs for practitioners will ensure that the workforce is able to use the new tools and strategies for efficient product realization.

LEVERAGING DESIGN AND MANUFACTURING IN THE DOD ACQUISITION PROCESS

Recommendation 7. Defense Acquisition Processes: The Department of Defense should define best practices for government ownership rights to models, simulations, and data developed during system acquisitions.

Formal guidelines and best practices for transferring models, simulations, and data between the government and its contractors are essential for competitive procurement. Instituting common model access, common model databases, and common document controls will ensure that information generated under government funding is available to multiple program managers.

Incentives for program managers to develop integrated design and manufacturing tools can make simulation-based acquisition become a reality for DoD programs. Well-defined metrics for integration of design and manufacturing can help the program managers use simulation-based acquisition. Metrics that are compatible with different acquisition programs will allow these investments to be leveraged in the future. Also, specifying the modeling and simulation techniques that will be used in the proposal evaluation process, especially the cost structure analysis and affordability models, will facilitate simulation-based acquisition. Integrating the concept-of-operations definition into the modeling and simulation program plans can bring end users into the acquisition process and thus foster a more successful transition to military capability.

Given the formal support of simulation-based acquisition by the DoD, modeling and simulation plans could become a central requirement in all defense acquisition programs. Common tools and plans will naturally emerge, and these can be reused to ensure real growth and progress in acquisition. As the quality, accuracy and applicability of modeling and simulation tools grow, the simulation-based acquisition policy will be realized. Instituting incentives for program managers to use modeling and simulation tools can help this vision become a reality.

Collaborative environments support the integration and interoperability of models, simulations, and data through an overarching structure that facilitates the secure linkage of modeling and simulation across distributed locations and organizations. The establishment of such collaborative environments can link modeling and simulation between phases in the product realization process (such as requirements definition, design, manufacturing, live-fire testing, and acquisition), as well as connect distributed locations and organizations, thus facilitating the sharing of models, simulations, and data.

Modeling and simulation tools used in the acquisition process will also be able to be integrated into increasingly complex performance simulations. As the Department of Defense builds capabilities to support an agile and evolving warfighter, this agility can be supported by transformations in defense acquisition.[1] Establishing strong connections between the levels of existing expertise and capabilities already available within the DoD's modeling and simulation infrastructure is a critical step that includes establishing the role of the government research and development service laboratories in this process.

Modeling and simulation will become more valuable and widespread when the tools and data developed in one DoD program can be reused in others. The modeling and simulation

---

[1] Donald H. Rumsfeld, Secretary of Defense, U.S. Department of Defense, "Transformational Planning Guidance," 2003. Available at: http://www.oft.osd.mil/index.cfm. Accessed May 2004.

tools include not just codes, but also supporting data, databases, environments, and the associated validation and verification test results. Negotiating incentives to provide models, simulations, and data as contract deliverables will provide program managers and their integrated product team staff with insight into the design, engineering, manufacturing, and performance trade-offs in a way that is not available in current procurement schemes. It also provides a starting point on the path to establishing modeling and simulation as a method for ensuring that design requirements are met. These deliverables would lead to a reduced amount of validation testing, and thus lower overall cost and faster product delivery times.

Appendixes

Appendix A

Biographical Sketches of Committee Members

R. Byron Pipes (Chair), NAE, is Goodyear Tire and Rubber Professor of Polymer Engineering at the University of Akron. He was elected to the NAE for interdisciplinary leadership in composite materials research and for development of an exemplary model of university, industrial, and governmental interactions in research and education. He served as the president, Rensselaer Polytechnic Institute from 1993 to 1998. As Distinguished Visiting Scholar at the College of William and Mary, he pursued research at the NASA Langley Research Center in the field of carbon nanotechnology during 1999 to 2001. He was provost and vice president for academic affairs at the University of Delaware from 1991 to 1993 and served as dean of the College of Engineering and director of the Center for Composite Materials during 1977 to 1991 at the same institution. Dr. Pipes was elected to the Royal Swedish Academy of Engineering Sciences in 1993. He is the author of more than 100 archival publications, including four books, and has served on the editorial boards of four journals in his field. Dr. Pipes has served on a number of National Research Council committees as both member and chair and served two terms on the National Materials Advisory Board.

Reza Abbaschian is Vladimir A. Grodsky Professor of the Department of Materials Science and Engineering at the University of Florida. He has been at the university since 1981 and served as chairman of the department from 1986 to 2003. Prior to this, he was chairman and served on the faculty at the Pahlavi University, Shiraz, Iran, and was a visiting associate professor at the University of Illinois and a visiting scientist at the Massachusetts Institute of Technology. He has more than 200 scientific publications on subjects such as metals processing, crystal growth, solidification, intermetallic matrix composites, and phase diagrams. He also has four patents and five books to his credit, and he coauthored the third edition of *Physical Metallurgy Principles*. Dr. Abbaschian has been active in several regional and national educational and professional organizations, including the National Materials Advisory Board, NASA's Space Station Users Advisory Committee, the Minerals, Metals and Materials Society Board of Directors, trustee of the Federation of Materials Societies, National Science Foundation Materials Research Advisory Committee, and chairman of the University Materials Council.

Erik Antonsson is currently chief technologist at NASA's Jet Propulsion Laboratory and is also a professor in the Department of Mechanical Engineering at the California Institute of Technology (Caltech). He has been at Caltech since 1984 where he organized the Engineering Design Research Laboratory and has conducted research and taught. His research interests include the areas of formal methods for engineering design, rapid assessment of early designs, and structured microelectromechanical systems design. His research accomplishments include the development of formal methods for engineering decisions and trade-offs and for representing and manipulating imprecision in engineering design, automated methods for synthesis of engineering design, structured design synthesis of microelectromechanical systems, and the invention and development of digital micropropulsion microthrusters. Dr. Antonsson is currently on the editorial board of the international journals *Research in Engineering Design* and *Fuzzy Sets and Systems*, and from 1989 to 1993 served as an associate technical editor of the *ASME Journal of Mechanical Design* (formerly the *Journal of Mechanisms, Transmissions and Automation in Design*), with responsibility for the design research and the design theory and methodology areas. He has published more than 100 scholarly papers in engineering design research literature, has edited two books, and holds five U.S. patents.

Thomas S. Babin is the director of the Virtual Design and Manufacturing Group at Motorola Advanced Technology Center. He has been with Motorola since 1987 and is involved in projects related to virtual prototyping, manufacturing, and reliability. Prior to joining Motorola he worked as a consultant with General Motors, Ford Motor Company, General Electric, and others in the area of statistical methods for the improvement of quality and productivity. Dr. Babin has been involved in the design of software and the design and delivery of several internal short courses related to statistical experimental design, process characterization and optimization, and electronic assembly line throughput estimation. He is a member of Alpha Pi Mu, Phi Kappa Phi, the Institute of Industrial Engineers, the American Society for Quality, the American Society of Mechanical Engineers, the Society of Manufacturing Engineers, and the Institute of Electrical and Electronic Engineers.

Bruce Boardman has been the manager for metals research at the John Deere Technology Center since 1986. From 1968 to 1986 he was a metallurgist at John Deere. Before that, he was a metallurgist at Republic Steel Corp. Mr. Boardman is past chair and a current member of the ASM International Database Committee and the Federal Affairs Committee. His expertise is primarily in ferrous metallurgy (steel and cast iron) as well as powder metallurgy and aluminum (wrought and cast), including heat treatment, welding, forming, machining, plating, and other processes involved in the making of ferrous parts for the ground and heavy equipment industries. He has supervised and managed metallurgy, ceramic, failure analysis, heat treatment, wear test, and lubrication laboratories and research since 1972. He is a member of several ASM International, Society of Automotive Engineers, and American Society of Mechanical Engineers committees. He is a fellow of the ASM International.

Timothy J. Considine is a professor of energy, environmental, and mineral economics at the Pennsylvania State University. He is also the current Gilbert F. White Postdoctoral Fellow at Resources for the Future. His research focuses on energy and materials markets, as well as how those industries interact with the environment. Another area is risk management, such as valuation of weather derivatives for use in decision making. He has published in prestigious journals, including *Review of Economics and Statistics*, *Journal of Business and Economic Statistics*, and *Journal of Environmental Economics and Management*. He has conducted research on the industrial ecology of steel; the impact of sales from the U.S. strategic petroleum reserves on global crude oil markets; commodity price and inventory dynamics; electricity deregulation in California and Pennsylvania; and the value of improved forecasts of hurricanes to oil and gas producers in the Gulf of Mexico. Prior to joining Penn State in 1986, he worked at Bank of America and at the U.S. Congressional Budget Office as an applied economist. He also held visiting positions in economics at American University in Washington, D.C., as well as at the University of Newcastle, Australia.

Jonathan Dantzig is a professor of mechanical engineering at the University of Illinois at Urbana-Champaign. He worked on casting process development at Olin Metals Research Laboratories from 1977 to 1982. While there, he was principal inventor of a process to produce "rheocast" microstructures in continuously cast aluminum alloys. He moved to the University of Illinois, Department of Mechanical and Industrial Engineering, in 1982, where he is currently a professor of mechanical engineering. His area of specialization is the modeling of casting processes, including foundry and continuous casting. Professor Dantzig is co-holder of 20 U.S. patents deriving from his work at Olin and has authored numerous publications in the field of casting process modeling, including a recently published textbook, *Modeling in Materials Processing*, coauthored with Charles Tucker III. His current research interests include studies of microstructure development, residual stresses in casting and quenching, and optimization applied to process design.

Mark Gersh is currently manager of the Lockheed Martin Advanced Technology Center's Modeling, Simulation and Information Sciences Department responsible for pursuing destabilizing information technologies critical to the success of the Lockheed Martin Space Systems Company. He also serves as the Lockheed Martin program manager for an effort with the Advanced Systems and Technology arm of the National Reconnaissance Office exploring constructs for agile design and development of space systems. Previously, Mr. Gersh was the Lockheed Martin program manager for the Defense Advanced Research Projects Agency's (DARPA) simulation-based design effort. This program pioneered the use of virtual prototyping technology in the form of advanced integration frameworks, product modeling techniques, software agent-based services, and multidisciplinary optimization. Prior to joining Lockheed Martin, Mr. Gersh was director of research for the Vanguard Information Technology Strategy Program within Computer Sciences Corporation's subsidiary Index. Before holding this position, Mr. Gersh was a program manager for the Information Technology Office at DARPA and actively managed a portfolio of research and advanced technology development that focused on experimental information systems architectures, engineering, and integration.

George T. "Rusty" Gray III is a laboratory fellow and team leader of the dynamic properties and constitutive modeling team within the Materials Science Division of Los Alamos National Laboratory. His research is focused on experimental and modeling studies of substructure evolution and mechanical response of materials. These constitutive and damage models are utilized in engineering computer codes to support large-scale finite element modeling simulations of structures in such areas as national defense (Department of Energy and DoD), industry (crashworthiness work with General Motors, Ford, and Chrysler), foreign object damage (General Electric Aircraft engines), and manufacturing (International Nickel Company, Ford). The constitutive models are utilized by the U.S. Navy, Air Force, and Army for both platform and munitions simulations related to performance and for manufacturing simulations. He is the project leader for a DoD Office of Munitions program on materials modeling and validation. He co-chaired the Physical Metallurgy Gordon Conference in 2000 and served on the board of directors of the Minerals, Metals and Materials Society as the chair of the Structural Materials Division from 2001 to 2003. He is a fellow of ASM International and serves on the International Scientific Advisory Board of the European DYMAT Association. He has authored or co-authored over 220 technical publications.

Elizabeth A. Holm is a Distinguished Member of the Technical Staff, Materials and Process Modeling, at the Sandia National Laboratories. She is a computational materials scientist with a long-standing interest in bringing materials modeling to industrial practice. Over her 10 years at Sandia, she has worked on simulations to improve processes for lighting manufacture, microcircuit aging and reliability, and the processing of advanced bearing steels. Her research areas include the theory and modeling of microstructural evolution in complex polycrystals, the physical and mechanical response of microstructures, and the wetting and spreading of liquid metals. She works with team members from industry, government, and academia to develop materials and process models. She develops, integrates, and parallelizes computational materials models at all length scales. Dr. Holm has several professional honors and awards. She has authored or co-authored over 100 publications.

David A. Koshiba is the deputy director for the Phantom Works Lean and Efficient Thrust of The Boeing Company. He has 25 years of experience successfully leading multidisciplinary engineering and integrated product design teams. Previously, he was program manager for Lean Engineering/Design, Manufacturing, and Producibility Simulations Group responsible for leading a team to develop, enhance, and integrate modeling and simulation processes and supporting tools. Before that he was the forebody define manager for the Joint Strike Fighter (JSF) program responsible for leading a team to develop and mature the JSF forebody structures and systems using advanced design tools and processes. He was responsible for developing a JSF virtual prototype, including implementation of three-dimensional solid models of structures and subsystems, assembly simulations, finite element modeling, and external loads development in an integrated digital environment. He was responsible for evaluation of the manufacturing organizations within McDonnell Douglas Corporation. Mr. Koshiba is a member of Sigma Gamma Tau—the National Honor Society for Aeronautical Engineers—and a senior member of the American Institute of Aeronautics and Astronautics.

Morris H. Morgan III is professor of chemical engineering and dean of the School of Engineering and Technology at Hampton University. He was development engineer at Inland Manufacturing Division of GMC, Dayton, Ohio, where he worked on the development of polyurethane foams for Pontiac's "Enduro" bumper by formulating and testing the effectiveness of different polymeric compounds. He was a system safety engineer for the Mound Laboratory, run by Monsanto Company in Miamisburg, Ohio, where he analyzed the safety and reliability of various manufacturing processes. After that, he was a staff scientist at the GE Corporate Research and Development Center, where he conducted research on the direct process for manufacturing of silicones. He went on to the position of associate professor of chemical engineering at Rensselaer Polytechnic Institute, Troy, New York, before his current position at Hampton University, where he conducts research on statistical modeling of environmental and combustion systems. Dr. Morgan has published more than 70 scientific engineering papers.

Daniel E. Whitney is a senior research scientist at the Center for Technology, Policy and Industrial Development and a senior lecturer in the Engineering Systems Division at MIT. His interests include the use of computers in product design, understanding the role of assembly in the design and manufacturing process, and understanding how companies decide what design and manufacturing skills are core competencies. He conducts research on product development, automation, CAD, mechanical assembly, outsourcing strategy, and comparisons of product development processes in U.S. and foreign companies. He teaches mechanical assembly and product development in the MIT Engineering and Business Schools. He consults for major corporations in product development, supplier relations, and technology strategy. Prior to joining MIT, Dr. Whitney spent 19 years at the Charles Stark Draper Laboratory, Inc., where he conducted research and consulting on robotics, assembly automation, design for assembly, and CAD tools for assembly processes. He has published over 80 technical articles, has co-authored a book on concurrent engineering, and holds a number of patents. In 2003, his book *Mechanical Assemblies: Their Design, Manufacture, and Role in Product Development* was published by Oxford University Press.

Appendix B

Meeting Agendas

Meeting One
February 24-25, 2003
Keck Center of the National Academies

Acquisition-Focused Basic Research: Context and Initial Thoughts
John H. Hopps, Jr., Department of Defense

Materials and Processing Models
Peter Angelini, Oak Ridge National Laboratory

Predictive Product Realization—Bridging Design and Manufacturing Through Modeling and Simulation
Delcie R. Durham, National Science Foundation

Models of Products and Processes
Daniel E. Whitney, Massachusetts Institute of Technology

Observations on the Uses of Modeling and Simulation
Michael Lilienthal, Defense Modeling and Simulation Office (retired)

Computational Engineering Sciences for Design to Manufacturing
Thomas C. Bickel, Sandia National Laboratories

Modeling and Simulation
in Aerospace Industry
James W. Hollenbach, Simulation Strategies

Modeling and Simulation in the U.S. Automotive Industry
Jack F. White, Altarum

Bridging Design and Manufacturing: Electronics Industry View
Thomas S. Babin, Motorola Advanced Technology Center

Meeting Two
April 29-30, 2003
Keck Center of the National Academies

Tools for Accelerated Insertion of Materials into Systems
Leo Christodoulou, Defense Advanced Research Projects Agency

Life Cycle Behavior Models and Tools
John L. Sullivan, Ford Motor Company

Digital Manufacturing Tools
Robert Brown, Delmia Corporation

Model-Based Development of Embedded Systems
Hans-Peter Hoffmann, I-Logix

Interoperability Considerations for Manufacturing Simulation and Visualization Tools
Chuck McLean, National Institute of Standards and Technology

Use of Models in the Development of Implantable Devices
Jonathan Krueger, Guidant Corporation

Simulation and Modeling for Acquisition, Requirements, and Training
W.H. (Dell) Lunceford, Jr., Army Model and Simulation Office

Design by Simulation for Mars Entry Descent and Landing Systems
Adam D. Steltzner, Jet Propulsion Laboratory

Development of Uninhabited Combat Aerial Vehicles
Allen Haggerty, Vice President—General Manager Engineering (ret.), Boeing Military Aircraft and Missiles

Opportunities in Modeling and Simulation to Enable Dramatic Improvements in Ordnance Design
Robert K. Garrett, Jr., Naval Surface Warfare Center

Virtual Aluminum Castings
John Allison, Ford Motor Company

Meeting Three
June 25-26, 2003
Ford Motor Company

Overview of the Ford Product Development System
Chris Minger, Ford Motor Company

Analytical Powertrain: Product Development Process
Agus Sudjianto, Ford Motor Company

Virtual Product Creation and Virtual Manufacturing Engineering
Shuh-Yuan Liou, Ford Motor Company

Virtual Manufacturing—Rough Parts Forming
Alan Lecz, Ford Motor Company

Roundtable on Automotive Industry (Discussion of best practices, identification of gaps and what is needed to bridge the design to manufacturing gap)
Will Guerra, DaimlerChrysler Corporation
Alan N. Baumgartner, Ford Motor Company
Steven W. Holland, General Motors
Arthur H. Adlam, Jr., U.S. Army TACOM
Mohammad Usman, Visteon
Prasad Mangalaramanan, Dana Corporation
Ray Quatrochi, Federal Mogul Corporation
Joseph A. Spiegel, Intermet Corporation
Bryan Froese, Meridian Castings

Translating Design to Manufacturing: Army Trucks
Arthur H. Adlam, Jr., U.S. Army TACOM

Sheet Metal Process Modeling and Its Use on the Manufacturing Shop Floor
Edmund Chu, Alcoa Inc.

Advanced Engineering Environments for Small Manufacturing Enterprises
Joseph P. Elm, Software Engineering Institute, Carnegie Mellon University

Integration of Nanotechnology Manufacturing Processes into Microsystems
Gregory W. Auner, Wayne State University

Real Time NDE to Validate Product Designs and Manufacturing
Connie Philips, National Center for Manufacturing Sciences

Meeting Four
August 25-26, 2003
J. Erik Johnson Center

CAD Tools Evolution and Compatibility
Chris Hoffmann, Purdue University

Trends Associated with Data Representation and Integration
Fred Waskiewicz, Object Management Group

Appendix C

Current Engineering Design Tools

Tools for simulating manufacturing encompass various levels of CAD, CAM, CAE, PDM, and PLM tools. Solutions are usually tightly integrated vertically within the vendor's own environment, with different levels of "openness" within their architectures allowing integration or interoperability with other vendors' products. Some of the first-tier vendors for these types of product suites include the following:

- EDS: Unigraphics/TeamCenter/I-deas/Vis-Mockup
- Dassault Systemes: CATIA/ENOVIA/DELMIA
- PTC: Pro-Engineer/Windchill/Product Vision

There are other vendors that also supply integrated solutions that do not encompass the full product life cycle. An example of one of these second-tier vendors is MSC Software, which provides an engineering analysis focused suite of products (including NASTRAN and PATRAN).

Many engineering tools for modeling and simulation of particular aspects of the performance of engineered devices and systems are in common use but are usually not well linked to other tools. These engineering design and analysis tools are grouped below by several of the categories shown in Figure 3-1. Each software tool is described briefly in terms of the design or analysis function it performs, and in some cases the underlying technology or technical assumptions.

ENGINEERING MODELING—SIMULATION AND VISUALIZATION

Multidisciplinary Optimization

Product (or vehicle) synthesis tools typically are used to explore a product's design space by bringing together multiple design and analysis disciplines (e.g., structural, electrical, performance) and trying to understand how a product will best meet the design requirements. The input used to support these synthesis tools typically comes from simplified physics models or from trend analyses sourced from detailed design and analysis tools. The earlier and better the design team understands the product's design space—including the interplay of variables, constraints, and requirements—the better the resulting product design will meet the customer's needs. The result is not only a product design but also analysis to show why one design is preferred over another and how the designs could be improved by changing variable limits, constraints, and requirements.

COMPUTER-AIDED ENGINEERING

Aerodynamics / Fluid Dynamics

CFD (computational fluid dynamics) tools are generally used to evaluate the performance of a product in gas or fluid atmospheres (e.g., aircraft wing design). CFD provides an understanding of key fluid dynamic interactions with a three-dimensional description of flow. Various methodologies are available, including partial Navier-Stokes, full Navier-Stokes, and hybrid approaches.

Panel methods solve a linear partial differential equation numerically by approximating the configuration surface by a set of panels. Various methodologies are available to the analyst.

Propulsion

CFD (computational fluid dynamics) tools—see "Aerodynamics / Fluid Dynamics" section.

Thermal Modeling

Aeroheating analysis tools are typically used to define the thermal environments that a product's structure will be exposed to and in which it must perform its function. Various technologies are employed, including finite difference, finite element, and CFD.

EMP (electromagnetic pulse) / lightning strike analysis tools are used to assess the survivability of a product to these phenomena—whether natural or human-induced.

Environmental analysis tools are used to describe the environments to which a product is subjected, including temperature, pressure, humidity, and others.

Reentry analysis tools are used to analyze the aerothermal environments specific to vehicle reentry.

TPS (thermal protection system) analysis tools are used to design and analyze the performance of the systems that are used to protect or insulate a product from the thermal environments to which it is exposed.

Structural Analysis

Ballistics damage tools are used to assess the effect of load path loss on dynamic response and aeroelastic margins. Local damage can be predicted with high-fidelity nonlinear finite element tools. The overall changes to dynamic response and aeroelastic margins are then evaluated relative to their effect on aircraft performance.

Damage tolerance tools are used to predict residual strength in the presence of flaws and the remaining service life given crack growth arising from such flaws. The flaws could be inherent material discontinuities or a result of fatigue, corrosion, or accidental damage. Various methods are used to calculate the stress intensity and crack growth retardation and acceleration.

Durability analysis tools are used to predict the economic life of a structure based on the expected usage, material, and stress concentrations. Local stress and strain excursions are calculated using a variety of methods, and life predictions are based on stress-displacement curves.

Fatigue analysis tools (see Durability analysis tools)

FEA (finite element analysis) tools use numerical methods to idealize a structure and then solve for the displacements and internal loads due to a general loading condition. The types of analysis can vary from simple linear-static to complex nonlinear geometry and material.

FEM (finite element modeling) tools typically have a graphical user interface (GUI) to rapidly create the finite element models for the finite element analysis (FEA) code of choice. The FEM tool, typically with a GUI, is then used to process the FEA results.

Fracture mechanics analysis tools (see Damage tolerance tools)

Subsystems Design and Analysis

Environmental control design and analysis tools are used to define onboard environmental control systems and simulate their performance. This covers the total design process from a logical, functional, and physical viewpoint. Examples include onboard oxygen generation systems.

Fluid flow design and analysis tools are used to design and analyze fluid systems for platforms. Included in these analyses are fault generation and failure scenarios.

Fuels design and analysis tools are used to define onboard fuel systems and simulate their performance. This covers the total design process from a logical, functional, and physical viewpoint.

Hydraulic systems design and analysis tools are used to define onboard hydraulic systems and simulate their performance. This covers the total design process from a logical, functional, and physical viewpoint.

ELECTRONIC DESIGN AUTOMATION

Electrical System Design / Analysis

Circuit design tools provide the layout design for circuit boards and electronics.

E/CAD (electrical and electronics computer-aided design) tools are utilized to perform circuit design, systems and wiring design, and analysis.

Electrical installations design tools orient the electrical components (equipment and wiring) in three-dimensional (3D) geometric space. Deliverables generally include installation drawings, manufacturing plans for equipment and wiring, support provisions, protection mechanisms, and support structure. Generally, this environment is utilized to integrate the systems and wiring requirements (functional and logical requirements) with the physical requirements (3D structure and manufacturing and supportability requirements).

EMI (electromagnetic interference) analysis tools evaluate an electrical system to determine if any electromagnetic disturbance, phenomenon, signal, or emission could cause undesired response, malfunction, degradation, or performance of electrical and electronic equipment. Analysis tools utilize information from the 3D physical design or the circuit board layout and the signal requirements / systems operation to conduct the analysis / modeling activities.

Logical design and analysis tools are typically employed after the definition of the level-three wiring schematic. The pin-to-pin signal requirements between the components in a system are finalized via inputs from analysis activities such as wiring length requirements received from the physical 3D CAD tools and electrical load analysis tools (which assist in finalizing the wiring gage required) and an analysis of electromagnetic compatibility/interference, which assists the designer in the grouping of compatible signals into wire bundles/harnesses and the definition of separation requirements for dissimilar and incompatible signals.

Wiring schematic design and analysis tools are used to generate the design and analyze the performance of schematic diagrams. Schematic diagrams are utilized to describe the functionality of a system. A level-one schematic describes the top-level systems-to-system interactions. A level-two schematic is a block diagram for component- and function-level interactions. A level-three schematic, sometimes called a wiring schematic, is a detailed view of all equipment, connectors, wiring, and pins. During the design process, feedback from the logical design and manufacturing analysis process results in an update of the level-three schematic to include production disconnects or inline connectors that facilitate the manufacturing process.

COMPUTER-AIDED GEOMETRIC DESIGN

Mechanical Design and Analysis

Kinematics and dynamics tools are used to analyze or simulate mechanical systems in motion based on the Newtonian physics of rigid bodies.

M/CAD (mechanical computer-aided design) tools are typically used to generate the three-dimensional geometric representations of products and their constituent component parts and pieces. These geometric representations are often the starting point for other engineering design and analysis tools. Technologies that are often applied to these CAD systems include Boolean process, 3D wire-frame processes, 3D surfaced representations, 3D solid models, parametric design processes, relational design processes, and knowledge-driven (or intelligent) design processes.

Manufacturing Modeling—Simulation and Visualization

3D factory definition and analysis (factory analysis and simulation) consists of modeling the physical layout and the assembly of defined processes in an existing, new, or reconfigured facility. This process is used to analyze and validate work flow, space requirements, tooling concepts, methods of part and assembly movement, staging requirements, and supplier flow, and to identify resource requirements. This process is also used to validate new lean initiatives prior to incorporation. Product teams use this process to determine factory design viability and to explore and validate new facility concepts.

3D PFA (process flow analysis, or discrete event analysis and simulation and fabrication and assembly flow) is the process of determining the performance of the build plan, given a limited set of resources. This analysis helps to determine the resource levels and cycle times needed to produce a given configuration of a product. PFA can be performed on an individual control station or groups of control stations within the build plan for a single cycle or several years. PFA is one of many enablers that allow us to predict cost and cycle times without having to produce a single unit.

Assembly analyses describe, visualize, analyze, and communicate the proposed build process as it matures during a program. Assembly simulations are created using an iterative process that enables them to be concurrently developed as the product, process, and resources mature. Simulation provides a three-dimensional graphical visualization of the assembly process that includes engineering parts, design tools, hand tools, human models, and other resources. Assembly simulations are used to perform analysis of engineering data to determine interference checks and assembly variations to create an efficient repeatable process.

Casting and molding analysis consists of modeling and simulation of the flow of molten materials into molds, as well as the thermal aspects of cooling and solidification.

Machining and forming analysis consists of modeling of material removal by cutting operations and forming of metals by forging and sheet-metal forming.

PROCESS PLANNING

Classes of engineering design and analysis tools are grouped by discipline, skill, or function:

- Avionics design / analysis
- Guidance, navigation, and control design and analysis
- Mass properties analysis
- Affordability and cost-estimating analysis
- Physics-based performance models

Appendix D

Selected Computer-Based Tools Vendors

Name	Function	Web Site
@RISK	Risk and Decision Analysis	www.atriskinc.com/
ABAQUS	Finite Element Analysis	www.hks.com/
ABC	Cost Modeling	www.sim2k.com/New/consulting.htm
Abinitio	Data Processing	www.abinitio.com
ACIS	3D Modeling	www.spatial.com/
ADAMS	Virtual Product Development	www.mscsoftware.com/products/products_detail.cfm?PI=413
Alloy Finder	Materials Properties	www.chemtec.org/cd/pdlcd_19.html
Amira	3D Visualization	www.amiravis.com/
AML	Multilevel Modeling	www.applied-ml.com/
AMPTIAC	Materials Properties	amptiac.alionscience.com/
ANSoft,	Electronic Design	www.ansoft.com/
ANSYS	Computer-Aided Engineering	www.ansys.com/
Arena PLM	Life-Cycle Management	www.arenasolutions.com
AutoCAD	Computer-Aided Drafting	www.autodesk.com
AVL	Powertrain Simulation	www.avl.com/
Cadence	Electronic Design	www.cadence.com
CaliberRM	Software Design	community.borland.com/caliberrm/0,1419,11,00.html
CAMPUS Web View	Materials Properties	plastics.about.com/cs/datasheets/
CASRE	CADCAM Optimization	www.openchannelfoundation.org/discipline/CAD_CAM_CAE/
CATIA	Product Life-Cycle Management	www.3ds.com/en/home.asp
CES Selector 4.0	Material and Process Selection	www.grantadesign.com
CIMBridge	CADCAM Optimization	www.tecnomatix.com/
CINDAS	Materials Properties	https://engineering.purdue.edu/IIES/CINDAS/
CimStation	Manufacturing Simulation	www.acel.co.uk/

Name	Function	Web Site
Cognition	Process Flow Cost Modeling	web.mit.edu/cmse/
Crystal Ball	Management Simulation and Optimization	www.decisioneering.com/
DADS	Virtual Prototyping, Testing, Evaluation	www.lmsintl.com/
Dante	Heat Treat Simulation	deformationcontrol.com/dct_products.htm
Dassault	CAD, CAM	www.3ds.com/en/
DEFORM	Metal-Forming Simulation	www.deform.com/
Delmia V5	Product Life-Cycle Management	www.3ds.com/en/home.asp
DFMA	Manufacturing and Assembly	www.dfma.com
DICTRA	Alloy Design	www.thermocalc.com/
DisCom2	Integrated Computing Environment	www.cs.sandia.gov/discom/about.html
DOORS 7.0	Requirements Management	www.telelogic.com
DSM	Integrated Circuit Design	www.mentor.com/dsm/
DYNA3D	Finite Element Analysis	www.llnl.gov/eng/mdg/Codes/DYNA3D/body_dyna3d.html
Dynasty	Virtual Prototyping	www.caterpillar.com/products/
EASA	Enterprise Software Front-End	www.easa.aeat.com/
Eclipse CRM	Distribution Management	www.eclipseinc.com
Eclipse ERP	Enterprise Management	www.acs-australia.com.au/
EDS	Enterprise IT Management	www.eds.com
Engineous	Design Exploration and Optimization	www.engineous.com/index.htm
Enovia V5	Product Life-Cycle Management	www.3ds.com/en/home.asp
EnSight	Enterprise Software Front-End	www.easa.aeat.com/
Envision/Igrip	Robot Instructions	www.delmia.com
Excel	Spreadsheet	office.microsoft.com/home/
Extend	Extendable Simulation Tool	www.imaginethatinc.com/prods_overview.html
FakeSpace	Virtual Reality	www.fakespace.com/
FiPER	Process Integration and Optimization	www.engineous.com/FIPERPartners.htm
FleXsim	Manufacturing Simulation and Visualization	www.taylor-ed.com
Fluent	CFD Flow Modeling	www.fluent.com/
Functional Prototyping	Product Synthesizing	www.centricsoftware.com/fp/
Galorath	Life-Cycle Management Costing	www.galorath.com/

continues

Name	Function	Web Site
Geac	Performance Management, Enterprise Resources Planning (ERP)	www.geac.com/
HMS-CAPP	Computer-Aided Manufacturing	www.hmssoftware.com/pages/prodcapp.html
i2	Value Chain Management, Supply Chain Management	www.geac.com/
IBIS	Technical Cost Modeling	www.ibisassociates.com/
ICEM CFD	CFD Analysis	www.icemcfd.com/
IDEAS	Computer-Aided Engineering	www.eds.com/products/plm/ideas/
I-Logix	Embedded Design and Implementation	www.ilogix.com/
Innovation Mgmt	IT Tracking	www.innovate.com/
Innovation Mgmt RDD-SD	IT Tracking	www.holagent.com/
Integrated Analysis	CFD Thermal Analysis	www.crtech.com
Invensys	Production Management	www.invensys.com/
iSIGHT	Network Publishing for Engineering	www.engineous.com/images/isightextract.swf
Jack	Human Factors	www.eds.com/products/plm/efactory/jack/
JD Edwards	Supply Chain Management	www.peoplesoft.com/corp/en/public_index.jsp
JMP	Statistical Data Analysis	www.jmp.com/
Key to Metals	Nonferrous Metals Properties	www.key-to-metals.com/
Key to Steel	Steel Properties	www.key-to-steel.com/
KIVA	Thermal Stress	deformationcontrol.com/dct_products.htm
LabVIEW	Virtual Instrumentation	www.ni.com/labview/
LMS	Virtual Prototyping, Testing, Evaluation	www.lmsintl.com/
Logistics	Supply Chain Management	
MAGMA	Casting Modeling	www.magmasoft.com
Manugistics	Supply Chain Management	www.manugistics.com/
MatLab	Computing Environment, Graphics, Visualization	www.mathworks.com/
MatWeb	Materials Properties	www.matweb.com/index.asp?ckck=1
Minitab	Statistical Data Analysis	www.minitab.com/
ModelCenter	Optimization Analysis	www.phoenix-int.com
MSC	Simulation	www.mscsoftware.com/
MySAP PLM	Product Life-Cycle Management	www.sap.com/solutions/plm/index.asp
NASTRAN	Product Development	www.mscsoftware.com/
OpenDX	Visualization Software	www.opendx.org/

Name	Function	Web Site
Opnet	Networking Modeling and Simulation	www.opnet.com
Oracle	Internet Database	www.oracle.com/
PADS	Programming Language	www.mentor.com/pads/
Pandat	Phase Diagrams	www.computherm.com/
PeopleSoft	Supply Chain Management	www.peoplesoft.com/corp/en/public_index.jsp
Phoenix	Optimization Analysis	www.phoenix-int.com/
PLM Vis	Digital Prototyping	http://www.ugs.com/products/open/vis/index.shtml
Preforms	Forging Process Design	deformationcontrol.com/dct_products.htm
Price Systems	Life-Cycle Management Costing	www.pricesystems.com/
Prismark	Manufacturing Cost Modeling	www.prismark.com/home.html
ProCast	Casting Modeling	www.esi-group.com
ProE	Design Exploration and Optimization	www.ptc.com
Project	Project Management	office.microsoft.com/home/
ProModel	Business Process Optimization	www.promodel.com/
PTC	Product Life-Cycle Management	www.ptc.com
Purchasing plus	Purchasing Management	www.samco.com/products/samco_pa.pdf
QFD/Capture	Quality Function Deployment	www.qfdcapture.com/
Quest	Management Solutions	www.quest.com/
RDD-DVF	IT Tracking	www.holagent.com/
RDD-IDTC	IT Tracking	www.holagent.com/
RDD-OM	IT Tracking	www.holagent.com/
RDD-RM	IT Tracking	www.holagent.com/
RDD-SA	IT Tracking	www.holagent.com/
RDD-SD	IT Tracking	www.holagent.com/
Rhnio	3D Modeling	www.rhino3d.com/
SABRE	IT Software	www.sabresys.com/history.asp
SAP	Enterprise Business Integration	www.sap.com
SavanSys	Conceptual Design Cost Modeling	www.savantage.com/
Siebel	Customer Relationship Management	www.siebel.com
Simul8	PC Simulation	www.simul8.com
Simulink	Systems Simulation	www.mathworks.com/products/simulink/
Slate	Systems Engineering	www.sdrc.com/slate/

continues

Name	Function	Web Site
STAR-CD	CFD Plug-In	www.cd-adapco.com
Statemate	Modeling and Simulation	www.ilogix.com/products/magnum/index.cfm
Stella/Ithink	Systems Modeling and Simulation	www.hps-inc.com
System Vision	Virtual Prototyping	www.mentor.com/systemvision/overview.html
SysWeld	Welding and Heat Treating Simulation	www.esi-group.com/Products/Welding/
Taylor ED	Enterprise Simulation	www.enterprisedynamics.com/
Tecnomatix	Virtual Manufacturing	www.tecnomatix.com/
Thermo-Calc	Thermodynamics and Diffusion	www.thermocalc.com/
TRIZ	Technical Innovation	www.triz.org/triz.htm
Unigraphics	Product Life-Cycle Management	www.eds.com/products/plm/unigraphics_nx/
Verilog-XL	Timing Simulation	www.deneb.com/products/virtualnc.html
Virtual NC	Virtual Machining	www.deneb.com/products/virtualnc.html
Windchill	Product Life-Cycle Management (PLM)	www.ptc.com/appserver/it/icm/cda/icm01_list.jsp?group=201&num=1&show=y&keyword=37
WinSMITH	Weibull Plotting	www.barringer1.com/wins.htm
Working Model	2D Visual NASTRAN	www.krev.com/
Wright Williams & Kelly	Cost of Ownership Modeling	www.wwk.com/

Appendix E

Acronyms

2D	two-dimensional
3D	three-dimensional
ABC	activity based costing
AEE	advanced engineering environment
AIM	accelerated insertion of materials
ARL	Applied Research Laboratory (Pennsylvania State University)
ASM	American Society for Metals
ASME	American Society of Manufacturing Engineers
AWACS	Airborne Warning and Control System
BOF	basic oxygen furnace
BOM	bill of materials
BSO	benzene soluble organic
C4ISR	command, control, communications, computers, intelligence, surveillance, and reconnaissance
CAD	computer-aided design
CAD	component advanced development
CADCAE	computer-aided design and engineering
CADCAM	computer-aided design and manufacturing
CAE	computer-aided engineering
CAIV	cost as an independent variable
CAM	computer-aided manufacturing
CAPP	computer-aided process planning
CASE	computer-aided software engineering
CFD	computational fluid dynamics
CM	configuration management
CNC	computer numerical control
COO	cost of ownership
DARPA	Defense Advanced Research Projects Agency
DfE	design for environment
DfX	design for X
DoD	Department of Defense
DOE	Department of Energy
DR	direct reduction
EAM	embedded atom method

ECA	environmental control systems
ECU	electronic control unit
EMC	electromagnetic compatibility
EMI	electromagnetic interference
EMP	electromagnetic pulse
EPA	environmental protection agency
EPS	environmental priorities system
ERP	enterprise resources planning
E/CAD	electrical / electric computer-aided design
FEA	finite element analysis
FEM	finite element method; finite element modeling
GOALI	Grant Opportunities for Academic Liaison with Industry
GUI	graphical user interface
GNC	Guidance, Navigation, and Control
HITL	hardware-in-the-loop
IE	industrial ecology
IEEE	Institute of Electrical and Electronics Engineers
INCOSE	International Council on Systems Engineering
IO	input-output
IPT	integrated product teams
IR&D	internal research and development
ISO	International Organization for Standardization
IT	information technology
JSF	Joint Strike Fighter
LCA	life-cycle assessment
LCI	life-cycle inventory
LFT&E	live-fire test and evaluation
LRIP	low-rate initial production
MDO	multidisciplinary optimization
MES	manufacturing execution system
MITL	man-in-the-loop
M&S	modeling and simulation
MFA	mass flow analysis
M/CAD	mechanical computer-aided design
NAE	National Academy of Engineering
NASA	National Aeronautics and Space Administration
NAVSEA	Naval Air–Sea Systems Command
NDE	nondestructive evaluation
NRC	National Research Council
OEM	original equipment manufacturer
OR	operations research
OSD	Office of the Secretary of Defense

PDAT	propulsor design and analysis tool
PDM	product data manager
PFA	process flow analysis
PLM	product life-cycle management
PM	program manager
RaDEO	Rapid Design Exploration and Optimization
RANS	Reynolds-averaged Navier-Stokes
RM	risk management
SBA	simulation-based acquisition
SCM	supply chain management
SE	system engineering
SEI	Software Engineering Institute (Carnegie Mellon University)
SETAC	Society of Environmental Toxicology and Chemistry
SME	subject matter expert
SPC	statistical process capability
SSP	simulation support plan
STEP	simulation test and evaluation program
STEP	standard for the exchange of product model data
TPS	thermal protection system
USAF	United States Air Force
UUV	unmanned undersea vehicle
VV&A	verification, validation, and accreditation