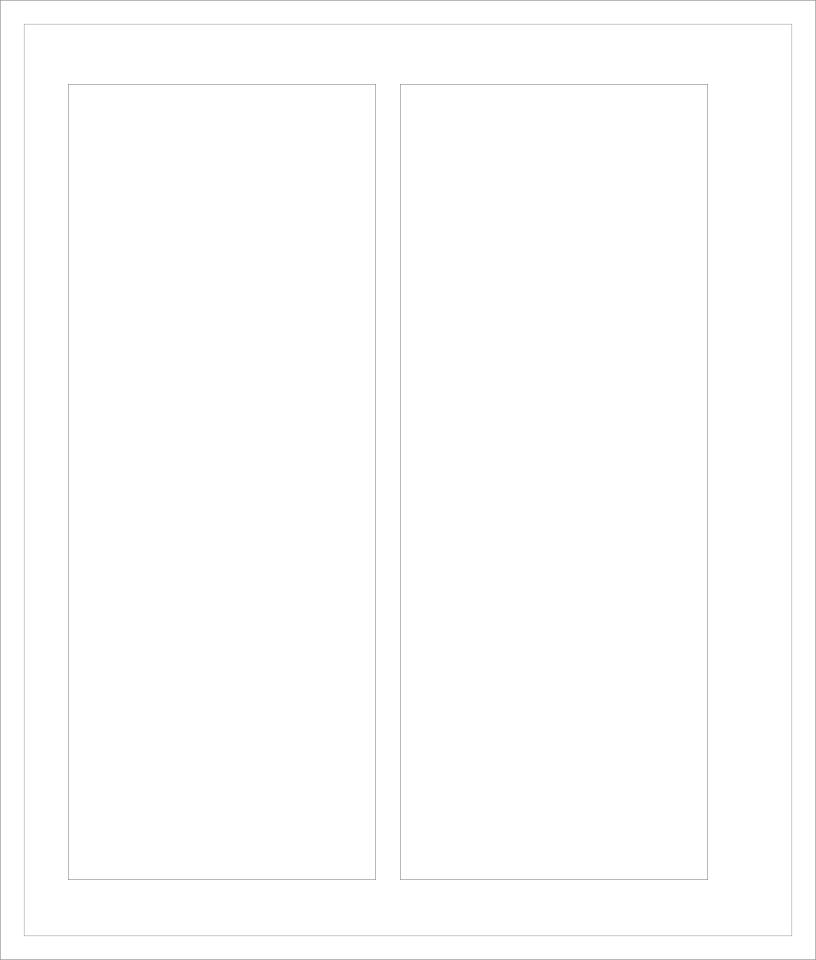
Fundamentals of Solid Modeling and Graphic Communication



FUNDAMENTALS of SOLID MODELING AND GRAPHIC COMMUNICATION



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SEVENTH EDITION

Gary R. Bertoline

Purdue University

Nathan W. Hartman

Purdue University

William A. Ross

Purdue University, Emeritus

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North Carolina State University





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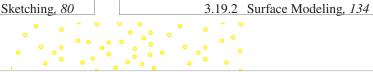
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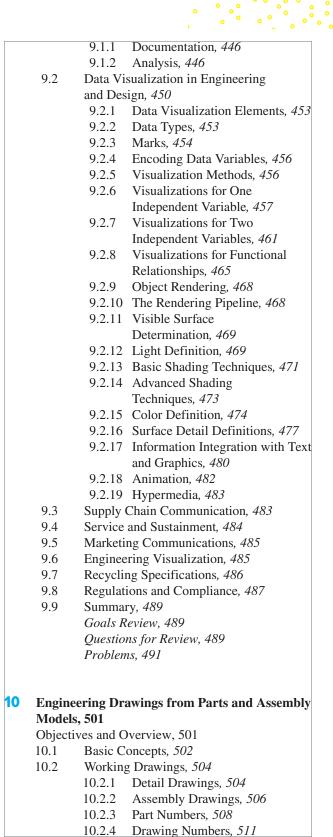
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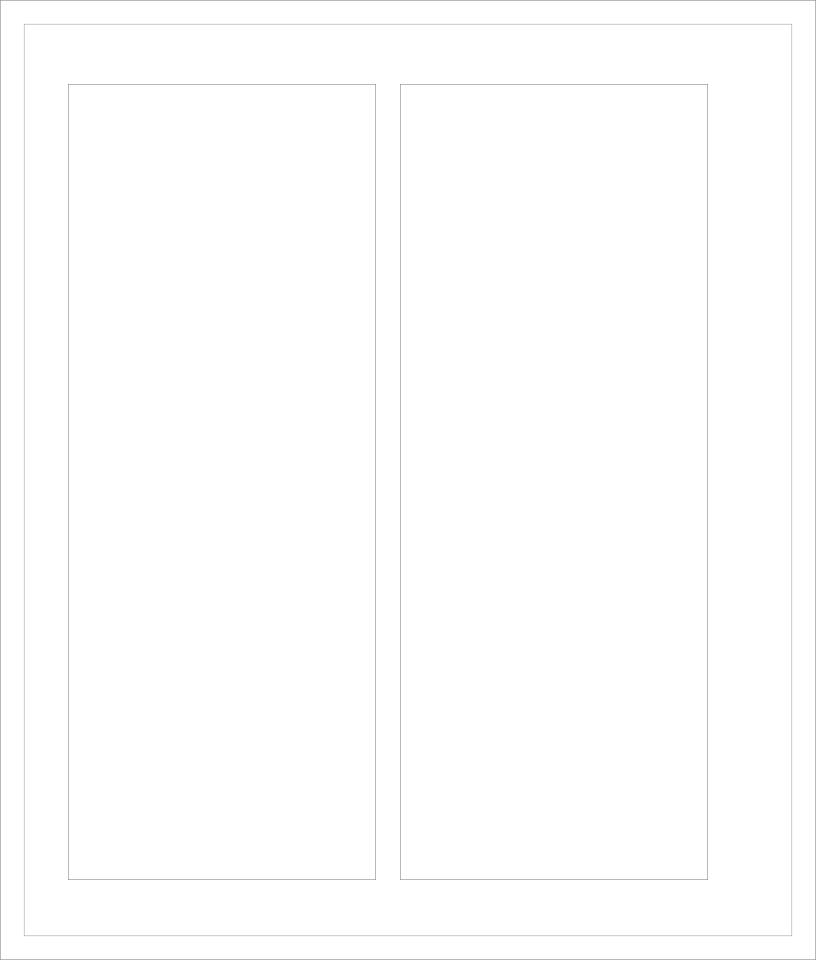
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Preface

Engineering and technical graphics have gone through significant changes in the last four decades, due to the use of computers and CAD software. Advances in digital technologies, information science, and modern manufacturing and materials have fundamentally altered the role of engineering and technical graphics communication in the 21st century. Gone are the days of creating 2-D drawings using manual methods and tools. Quickly fading are the days of using 2-D drawings to design and manufacture modern products and systems. Engineers and technologists still find it necessary to communicate and interpret designs, but they will do it by creating highfidelity 3-D models and digital representations of the products they are developing, and those models will be reused and repurposed by numerous other people (and likely machines as well) over the course of the product lifecycle. As powerful as today's computers and design software have become, they are of little use to engineers and technologists who do not fully understand fundamental graphics principles and 3-D modeling strategies or do not possess a high-level visualization ability.

In addition to the evolution of CAD technologies, there has been a corresponding shift in the role of 2-D drawings. No longer are drawings made with manual drawing tools by hand. In fact, few people use 2-D CAD tools today. At one time, drawings were considered the document of record for products as they were manufactured and put into use. Even today, some companies still consider drawings to be the document of record. However, that is rapidly changing. Drawings are no longer constructed from scratch in most cases; they are extracted as derivatives from the 3-D model, with their driving dimensional information coming from the dimensional and geometric constraints used to create the 3-D CAD model. The central role of the 3-D model as the driving artifact of digital product definition information is the fundamental theme in this edition of the book, which is reflected in the new title and a more streamlined table of contents.

To the authors of this text, teaching graphics is not a job; it is a "life mission." We feel that teaching is an important profession, and that the education of our engineers is critical to the future of our country. Further, we believe that technical graphics is an essential, fundamental part of a technologist's education. We also believe that many topics in graphics and the visualization process can be very difficult for some students to understand and learn. For these and other reasons, we have developed this text, which addresses both traditional and modern elements of technical graphics, using what we believe to be an interesting and straightforward approach.

In Chapter 1, you will learn about the "team" concept for solving design problems. The authors of this text used this concept, putting together a team of authors, reviewers, industry representatives, focus groups, and illustrators, and combining that team with the publishing expertise at McGraw-Hill to develop a modern approach to the teaching of technical graphics.

This new-generation graphics text therefore is based on the premise that there must be some fundamental changes in the content and process of graphics instruction. Although many graphics concepts remain the same, the fields of engineering and technical graphics are in a transition phase away from 2-D media and 2-D drawings towards the adoption of 3-D digital product definitions and models that possess the properties and characteristics and mimic the physical products and the environments in which they operate. We realize that hand sketching will continue to be an important part of engineering and technical graphics for some time to come. Therefore, the text contains an appropriate mix of hand sketching and CAD instruction.

Goals of the Text

The primary goal of this text is to help the engineering and technology student learn the techniques and standard practices of technical graphics, solid modeling, and the role of the 3-D model within the lifecycle of the product. So that design ideas can be adequately communicated and produced. The text concentrates on the concepts and skills necessary for sketching, 3-D CAD modeling, and the concept of a model-based product definition. The primary goals of the text are to show how to:

- 1. Clearly represent and control mental images.
- 2. Graphically represent technical designs, using accepted standard practices.
- 3. Use plane and solid geometric forms to create and communicate design solutions.
- Understand the role of the 3-D CAD model as a communications mechanism within a digital enterprise.
- Solve technical design problems using 3-D modeling techniques.
- Communicate graphically, using sketches, and CAD.
- Apply technical graphics principles to many engineering disciplines.

What Is Different and Why

A major shift in this edition of the text is toward a strong emphasis on the 3-D model as the focal point for graphics communication with technical drawings as an intelligent by-product of the model. As such, there is a very strong emphasis on 3-D **solid modeling** exercises and problems in this edition. Extensive attention has been given to making 3-D solid modeling a primary method for creating technical and engineering graphics for design, documentation, manufacturing, and product management. Looking toward the future role of computer graphics in product design and development, new solid modeling exercises and problems in Chapters 3, 4, 5, 6, 7, 9, and 10 have been designed that focus on the following:

- 1. The creation of intelligent constraint based 3-D solid models based on their design intent.
- Placing a strong emphasis on creating 3-D models based on the assembly and operability of mechanisms viewed as products as opposed to individual pieces and parts.
- 3. Making 3-D models that can become the core of the data pipeline for design, manufacturing, marketing, documentation, maintenance, and general communication concerning that product.

When developing the latest edition of this book, the author team has called upon many years of industry practice and engagement with companies and the standards communities alike to create a book that captures the fundamental elements of 21st-century engineering graphics communication. Historically, this textbook series has focused on the techniques, technology, and educational content necessary to teach students how to develop engineering graphics to support the design process and to enhance their personal visualization skills. Included were topics such as orthographic projection, auxiliary views, dimensioning techniques for drawings, sketching, and many others. These topics were presented in the context of creating a technical drawing to be used to communicate product information as part of the engineering design process and the production processes used to create the product.

However, as the technologies used to create and disseminate engineering graphics have evolved over the last three decades, many traditional instructional resources and techniques for use in classrooms have not. In that period of time, the educational community surrounding engineering graphics communication has continued to embrace the tools and techniques used in the creation of 2-D drawings as the centerpiece of instruction on engineering graphics communication, while treating the use of 3-D CAD as simply a related technique. In that same period of time, many industry sectors have made the transition to 3-D CAD as a staple for communicating product information through the enterprise; have eliminated many of the employment positions traditionally reserved for people skilled in drafting techniques and standards; and are currently on the precipice of eliminating the use of 2-D drawings in many aspects of their business. So why not prepare students to meet this new environment in which they will design and make products?

The seventh edition of *Fundamentals of Solid Modeling Graphics Communication* is intended to start the transition of engineering graphics instructional content and techniques away from the focus on 2-D drawing techniques and standards towards the creation and use of 3-D models as a primary communications mechanism within an enterprise. This book is intended to promote the idea that people within a manufacturing organization are authors and consumers of information alike, and that much of that information can be distributed between them using the content within the digital product model and tools used to create it. Students in engineering and technical graphics courses, modeling courses, CAD courses, and introductory manufacturing courses at the university, community and technical college, and high

school levels would benefit from the use of this book. Fundamentally, this book will not change one of the primary pillars on which engineering graphics is based—the need to communicate product information between people—however, it will begin to explore and support the trend towards the possibility of including machines in the communications loop where only humans had existed before. If that is to be done, 3-D models must include clear, complete, and unambiguous information, and the techniques illustrated in this book will support that change.

The seventh edition of *Fundamentals* fully embraces digital age graphics communication as a dynamic, interactive, and geometric process. Communication in the manufacturing enterprise using 3-D solid modeling with associated drawings, and the related uses of spread sheets and engineering math-related products, is presented as the intelligent core of the engineering design graphics process. Emphasis is on the shared 3-D database as the basis for disseminating product data used for designing, manufacturing, and sustaining products and systems over their projected lifetime (Product Lifecycle Management). When possible, case studies and industrial examples have been incorporated.

The seventh edition of *Fundamentals of Solid Modeling* and *Graphics Communication* contains a more focused look at leveraging the 3-D model as a communications mechanism throughout the product lifecycle. It includes the following items:

- A discussion of neutral file formats for data exchange
- A focus on model-based practice problems
- An overview of product lifecycle management, with the 3-D model playing a central role
- An initial review of current 3-D lightweight file formats used for displaying product model information.

Fundamentals of Solid Modeling and Graphics Communication presents a modern approach to engineering graphics, providing students with a strong foundation in 3-D solid modeling techniques and graphics communication in the engineering design process. The goal of this text is to help students learn the techniques and practices of technical graphics, enabling them to create and communicate successful design ideas. Design concepts are well integrated, including team design exercises and current design examples from industry.

Features of This Edition Include

- NEW!!! The seventh edition features new 3-D solid modeling problems for each chapter. Solid modeling creation and editing techniques are presented with new learning activities, as well as discussions of standards and CAD data exchange. The 3-D solid modeling activities focus on the assembly, design, and function of products through the inclusion of new assembly modeling projects. New exercises also emphasize visualization, graphical and spatial problem solving through the use of interactive solid modeling, sketching, and related documentation.
- The emphasis on 2-D drawings has been removed, along with many of the references for topics related to traditional drawings, such as auxiliary views, section views, and orthographic projection as stand-alone topics.
- Precise, full-color illustrations allow students to actually SEE the power of graphics and bring important concepts to life.
- Topics tied to industrial practice, such as product lifecycle management, digital enterprise, and model-based definition, are illuminated throughout the text.
- Visualization techniques are discussed throughout the text with an emphasis on 3-D model data re-use. Many exercises reinforce the importance of developing good visualization skills.
- Design in Industry boxes are presented to illustrate how graphics and design are being used in industry today.
- Dream High Tech Jobs explain how engineers and technologists have found interesting jobs after completing their education. You will read about how they are using their knowledge and skills to design products, devices, and systems.
- Many examples that use step-by-step procedures with illustrations are used to demonstrate how to create graphics elements or to solve problems. These step-by-step procedures show the student in simple terms how a model or drawing is produced.
- Discussion of file formats used in current model data exchange and archival practices.

Chapter Features

Every chapter has been planned carefully and written with a consistent writing, illustration, and design style and pedagogy. Students and instructors will learn quickly where to find information within chapters. The book was written as part of a more global instructional approach to engineering and technical graphics and will serve as a starting point for instructor and student.

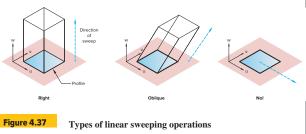
Here is a sampling of the features inside *Fundamentals*:

Objectives Each chapter has a list of measurable objectives that can be used as a guide when studying the material presented in the text. Instructors also can use the objectives as a guide when writing tests and quizzes. The tests and quizzes included on the website for the text include questions for each objective in every chapter. This feature allows instructors to make sure that students learn and are tested based on the listed objectives.

Color as a Learning Tool This textbook uses four-color illustrations throughout to better present the material and improve learning. The selection and use of color in the text are consistent to enhance learning and teaching. Many of the color illustrations also are available to the instructor in the image library found on the website to supplement lectures, as explained in detail later in this Preface.

The use of color in the text was used specifically to enhance teaching, learning, and visualization. Workplanes are represented as a light pink (Figure 4.37). Projection and picture planes are a light purple color (Figure 10.39).

Important information in a figure is shown in red to highlight the feature and draw the attention of the reader (Figure 3.40). Color shading is often used on pictorial illustrations so the user can better visualize the three-dimensional form of the object (Figure 10.67). This is especially important for most students who are being asked to use their visual mode to think and create. Color shading highlights important features, more clearly shows different sides of objects, and adds more realism to the object being viewed.



In some systems, linear sweeps are restricted to being perpendicular to the sketch plane.

Some texts use two colors, which are adequate for some illustrations, but our research with students clearly demonstrates that having the ability to display objects and text illustrations in many different colors is a huge advantage when teaching engineering and technical graphics.

Photographs and grabs of computer screens are much more interesting and show much more detail when in color (Figure 1.44). Many texts use four-color inserts to supplement the lack of color in the text. This forces

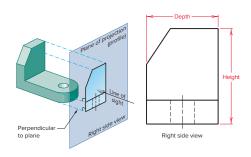


Figure 10.39 Profile view

A right side view of the pbject is created by projecting onto the profile plane of projection

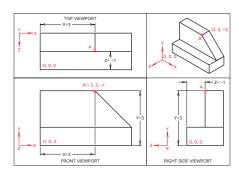


Figure 3.40 Display of coordinate axes in a multiview CAD drawing

Only two of the three coordinates can be seen in each view

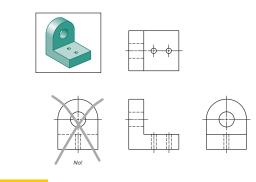


Figure 10.67 Most descriptive views

Select those views that are the most descriptive and have the fewest hidden lines. In this example, the right side view has fewer hidden lines than the left side view.



Figure 1.44 A computer-rendered image created by the technical illustrator using the CAD model

The technical illustrator can import the 3-D CAD model into a rendering program, where surface textures and light sources are applied.

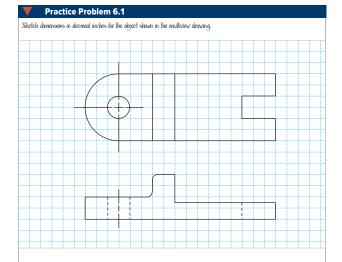
(Courtesy of Robert McNeel & Associates.)

students to search the color insert section or look at the insert out of context of the readings. In some aspects of engineering design, such as finite element analysis, color is the method used to communicate or highlight areas of stress or temperature.

Design in Industry Every chapter includes a special feature covering some aspect of design as practiced in industry. This Design in Industry feature covers design in many types of industries so that students with varied engineering interests can see how design is used to solve problems. Many feature quotes from engineers working in industry explaining how they solved problems or used CAD tools to enhance the design process. All the Design in Industry items include figures to supplement the information presented.

Practice Problems This feature gives students drawing practice as they learn new concepts. Through immediate hands-on practice, students more readily can grasp the chapter material. To illustrate, in Chapter 6, "Product Manufacturing Information (PMI)," Practice Problem 6.1 provides a grid for students to sketch dimensions in a multiview drawing.

Practice Exercises A unique feature of the text is the use of practice exercises, which cause the student to pause and actively engage in some activity that immediately reinforces their learning. For example, Practice Exercise 7.2 in Chapter 7, "Standard Parts," asks the student to find a few familiar objects and begin making isometric sketches. This exercise allows a student to experience and try making isometric sketches without the pressure of



graded assignments. Students have the opportunity to try to sketch isometric features, such as ellipses, and practice before having a formal assignment. They also are working with known objects that they can pick up and move, which is important in the visualization process. Being able to pick up objects is especially important for that segment of the population who are haptic learners and learn best when able to manipulate objects to be visualized.

Step-by-Step Illustrated Procedures Most chapters include many drawing examples that use step-by-step procedures with illustrations to demonstrate how to create graphics elements or to solve problems (Figure 4.39).

Integration of CAD Modeling The entire text has been edited (and in some cases, rewritten) to reflect the importance of solid modeling and the role of the 3-D CAD model as a mechanism for communication in modern digital enterprises. The role and necessity of the 2-D drawing as a document of record is diminishing, and as such, it is important to strike the proper balance between coverage of 2-D techniques and 3-D techniques in this book.

Dream High Tech Jobs This feature is included in many chapters and explains how engineers and technologists have found interesting jobs after completing their education. You will read about how they are using their knowledge and skills to design precuts, devices, and systems.

Questions for Review Each chapter includes an extensive list of questions for review. Included are questions meant to measure whether students learned the objective listed at the start of each chapter. Other questions are used to

reinforce the most important information presented in the chapter. The types of questions used require students to answer through writing or through sketching and drawing. Answers to questions are included in the instructor material included with the text.

Further Reading Many of the chapters include a list of books or articles from periodicals relevant to the content covered in the text

Problems Every chapter in the text includes an extensive number and variety of problem assignments. Most chapters include text-based problems that describe a problem to solve or drawing to create. The figure-based problems are very extensive and range from the very simple to complex. This arrangement allows the instructor to carefully increase the complexity of the problems as students learn and progress. The most complex drawings can be used to supplement assignments given to the most talented students or for group-based projects.

Most of the problems are of real parts made of plastic or light metals, materials commonly found in industry today.

The wide range and number of problems allow the instructor to frequently change assignments so that fresh problems are used from semester to semester. Additional problems are available on the website and through our workbooks. Most problems' solutions are provided to the instructor. Instructors may receive access to these password-protected solutions by contacting their local McGraw-Hill sales representative.

Classic Problems Many chapters include Classic Problems, which are additional problems that can be assigned. They have been taken from the seminal technical graphics textbooks by Thomas E. French, published by McGraw-Hill. Many of the problems are castings with machined surfaces, giving the student experience with additional materials and machining processes.

Glossary, Appendixes, and Index

At the end of the text is an extensive glossary containing the definitions of key terms shown in bold in the text. This glossary contains over 600 terms related to engineering and technical drawing, engineering design, CAD, and manufacturing.

Fundamentals of Solid Modeling and Graphic Communication, 7th Edition, contains supplementary information in the Appendixes useful to students, such as metric equivalents, trigonometry functions, ANSI standard tables, welding symbols, and more.

An extensive index is included at the end of the text to assist the reader in finding topics quickly. This index is carefully cross-referenced so related terms easily can be found by the user.

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xxi

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The authors also would like to thank the publisher, McGraw-Hill, for its support of this project. This has been an expensive and time-consuming process for the authors and the publisher. Few publishers are willing to make the investment necessary to produce a comprehensive, modern graphics text from scratch. The technical graphics profession is indebted to McGraw-Hill for taking the risk of defining a discipline in transition.

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Finally, we would like to know if this book fulfills your needs. We have assembled a "team" of authors and curriculum specialists to develop graphics instructional material. As a user of this textbook, you are a part of this "team," and we value your comments and suggestions. Please let us know if there are any misstatements, which we can then correct, or if you have any ideas for improving the material presented. Write in care of the publisher, McGraw-Hill, or e-mail Gary R. Bertoline at bertoline@purdue.edu.

Gary R. Bertoline Nathan W. Hartman William A. Ross



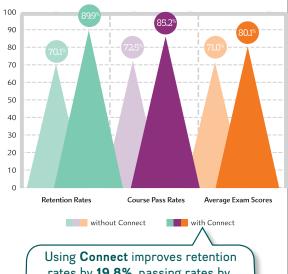
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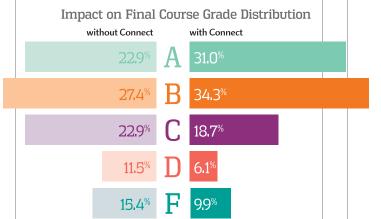
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- If you're looking for some guidance on how to use Connect, or want to learn tips and tricks from super users, you can find tutorials as you work. Our Digital Faculty Consultants and Student Ambassadors offer insight into how to achieve the results you want with Connect.

CHAPTER

Introduction to Engineering Graphics Communication and the Product Lifecycle

A drawing is the reflection of the visible mind. On its surface we can probe, test, and develop the workings of our peculiar vision.

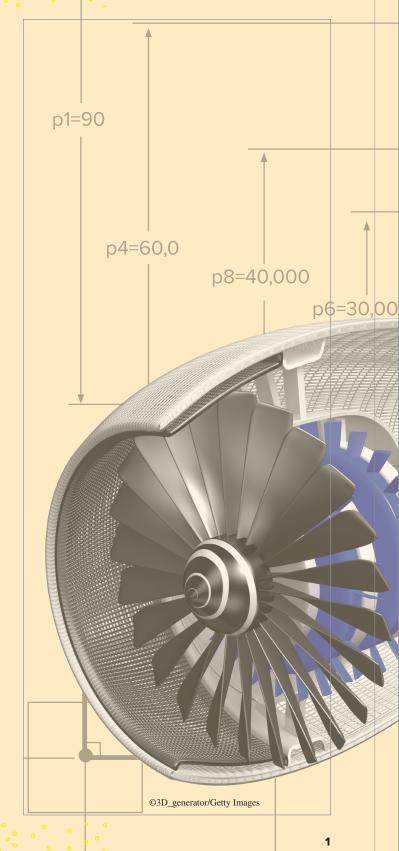
-Edward Hill

Objectives and Overview

After completing this chapter, you will be able to:

- 1. Describe why the use of graphics is an effective means of communicating during the design process and throughout the product lifecycle.
- 2. Describe the model-centered design process.
- **3.** Explain the role 3-D modeling plays in the engineering design process and the entire product lifecycle.
- **4.** Describe the role of PLM and PDM in the engineering enterprise.
- **5.** List and describe the modeling techniques used in design.
- **6.** List and describe the analysis techniques used in design.
- 7. Describe additional technologies used to capture data, output, and visualize 3-D models.

Chapter 1 is an introduction to the graphics language and tools of the engineer and technologist.



∢p3=30.000

This chapter explains the role and importance of graphics communications in engineering design, and in the context of the greater product lifecycle. It explains why drawing and modeling are an effective way to communicate engineering concepts, relating past developments to modern practices. Current industry trends are also introduced, showing why engineers and technologists today have an even greater need to master graphics communication. The concept of visualization is introduced so students can begin to relate its importance to design graphics. There is a strong emphasis on communications and teamwork for solving design problems, as well as the communications artifacts used in the process. It is the authors' primary intent that students begin to understand that graphics is a powerful form of human communications that is enabled by a model-based enterprise (MBE) environment in the context of the product's lifecycle. Concepts and terms important to understanding modern graphics communication and its relationship to the model-based engineering design process are explained and defined.

1.1 Introduction

What is graphics communication? For one thing, it is an effective means of communicating technical ideas and problem solutions. Humans have historically used drawings, paintings, sculpture, models, and other graphical and visual forms of expression to share and document their ideas. Modern graphics communication, especially that which is used for the design and creation of products for humankind, are no different. What is different today is the manner in which those graphical forms of expression are created—usually in a visual form rather than a physical form—to support the design and creation of a product.

Look at what happens in engineering design. The process starts with the ability to visualize an idea in one's mind, to see the problem and the possible solutions. Then, sketches are often made to record and evaluate initial ideas. The next steps are where the modern processes of engineering graphics communication differ from those done historically. Geometric models are created from the sketches and are used as input for analysis, production, communicating with customers, maintenance, and many other activities related to the product. Detail and assembly drawings are only made if the consumer of the product information needs them for a specific task or if the terms and conditions under which the product is made and delivered require drawings to be made. Visualizing, sketching, modeling, and detailing are how engineers and technologists communicate as they design new products and structures for our technological world.

Graphics communication using engineering models and drawings is a language; a clear, precise language with definite rules that must be mastered if you are to be successful in engineering design. Once you know the language of graphics communication, it will influence the way you think, the way you approach problems. Why? Because humans tend to think using the languages they know. Thinking in the language of graphics, you will visualize problems more clearly and will use graphic images to find solutions with greater ease.

In engineering, 92 percent of the design process is graphically based. The other 8 percent is divided between mathematics and written and verbal communications. Why? Because graphics serves as the primary means of communication for the design process. Figure 1.1 shows a breakdown of how engineers spend their time. 3-D modeling and documentation comprise over 50 percent of the engineer's time and are purely visual and graphical activities. Engineering analysis depends largely on understanding the results of computer simulations that use the 3-D design model as an input to determine the product's or structure's performance in certain physical conditions, and manufacturing engineering and functional design also require the creation and reading of graphics in order to fully define and make the product or structure.

Why do graphics come into every phase of the engineer's job? To illustrate, look at the jet aircraft in Figure 1.2. Like any new product, it was designed for a specific task and within specified parameters; however, before the parts of the jet aircraft could be manufactured, a three-dimensional

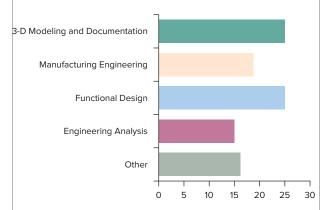


Figure 1.1 A total view of engineering divided into its major activities

Graphics plays a very important role in all areas of engineering, for documentation, communications, design, analysis, and modeling. Each of the activities listed is so heavily slanted toward graphics communication that engineering is 92 percent graphically based.

(3-D) model like that shown in Figure 1.3 had to be produced. Just imagine trying to communicate all the necessary details for designing and producing the aircraft verbally or in writing. It would be impossible!

A designer has to think about the many features of an object that cannot be communicated with verbal descriptions (Figure 1.4). These thoughts are dealt with in the mind of the designer using a visual, nonverbal process. This "visual image in the mind" can be reviewed and modified to test different solutions before it is ever communicated to someone else.



Figure 1.2

This jet aircraft would be impossible to create without computer graphics models and drawings. Drawings are the road maps that show how to manufacture or build products and structures.

©John Foxx/Getty Images RF

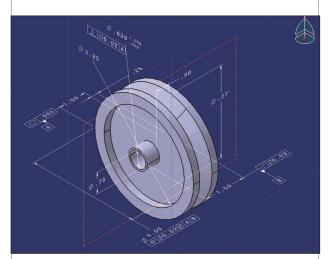


Figure 1.3 Model with dimensional controls

Computer models such as this one are used to produce manufactured parts. The 3-D model is also used to inspect parts after production.



Figure 1.4 Technical drawings used for communications

Technical drawings are a nonverbal method of communicating information. Descriptions of complex products or structures must be communicated with drawings. A designer uses a visual, nonverbal process. A visual image is formed in the mind, reviewed, modified, and ultimately communicated to someone else, all using visual and graphics processes.

©Charles Thatcher/Stone/Getty Images

As the designer draws a line on paper or creates a 3-D model representation with a computer, he or she is translating the mental picture into a model or other graphical representation that will produce a similar picture in the mind of anyone who sees the drawing. This drawing or graphic representation is the medium through which visual images in the mind of the designer are converted into the real object.

Technical graphics can also communicate solutions to technical problems. Such technical graphics are produced according to certain standards and conventions so they can be read and accurately interpreted by anyone who has learned those standards and conventions.

The precision of technical graphics is aided by tools; some are thousands of years old and still in use today, and others are as new and rapidly changing as computeraided design (CAD). This book will introduce you to the standards, conventions, techniques, and tools of technical graphics and will help you develop your technical skills so that your design ideas become a reality.

Engineers are creative people who use technical means to solve problems. They design products, systems, devices, and structures to improve our living conditions. Although problem solutions begin with thoughts or images in the mind of the designer, presentation devices and computer

CHAPTER 1

graphics hardware and software are powerful tools for communicating those images to others. They also can aid the visualization process in the mind of the designer. As computer graphics have a greater impact in the field of engineering, engineers will need an ever-growing understanding of and facility in graphics communications.

Technologists work with engineers and are concerned with the practical aspects of engineering in the designing, planning, and production of a product, process, or structure and in the development and implementation of tools to aid in the creation of the product, process, or structure. Technologists must be able to communicate quickly and accurately using graphics, by sketching and modeling design problems and solutions, analyzing design solutions, and specifying production procedures.

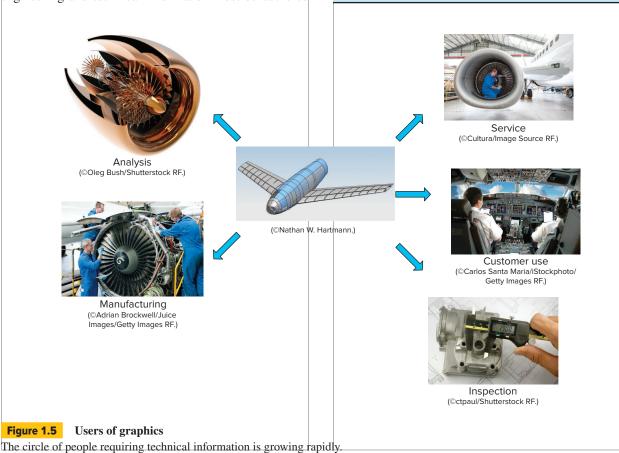
Both engineers and technologists are finding that sharing technical information through graphical means is becoming more important as more nontechnical people become involved in the design/manufacturing/sustainment process. As Figure 1.5 illustrates, the circle of people requiring technical information is widening rapidly, and engineering and technical information must be authored

and delivered effectively to many other people who are not engineers or technologists, such as marketing, sales, and service personnel. Computer graphics can assist in the process. It can be the tool used to draw together many individuals with a wide range of visual needs and abilities.

Practice Exercise 1.1

- 1. Try to describe the part shown in Figure 1.44 using written instructions. The instructions must be of such detail that another person can make a sketch of the part.
- Now try verbally describing the part to another person. Have the person make a sketch from your instructions.

These two examples will help you appreciate the difficulty in trying to use written or verbal means to describe even simple mechanical parts. Refer to Figure 1.6 and others in this text to get an idea of how complicated some parts are compared to this example. It is also important to note that air- and watercraft have thousands of parts. For example, the nuclear-powered Sea Wolf class submarine has over two million parts. Try using verbal or written instructions to describe that!



1.2 The Importance of Graphics in the Design Process

Technical graphics is a real and complete language used in the design process for:

- 1. Visualization
- 2. Communication
- 3. Documentation

Graphical representations are used by individual engineers and designers to problem-solve about a technical problem they are working on (Figure 1.6). For an engineer, this problem can often be a 3-D object that is either being modified from an initial design or created from scratch. Part of this problem-solving process can be the use of informal drawings or sketches. While these types of drawings were historically done with pencil and paper, increasingly computer-based sketching and modeling tools are used to rapidly create multiple ideas for solutions to the problem.

Graphic representations are useful as a permanent record of ideas as they are being mentally worked through by an engineer or designer. Later on in the design process, more refined graphic representations in the form of models or drawings can be used to communicate problem solutions to other members of the larger team working on the design problem (Figure 1.7). The permanent, visible record of ideas means that they can be shared with others to work with at a later time (asynchronously) or used as part of a shared meeting time (synchronously) when ideas and problems are worked through collectively.

While informal sketches can be done by anyone, practice and instruction help one to quickly and accurately express ideas. When computer tools are used, more training is often needed so that the engineer/designer can appropriately represent his or her design solutions. As the designs become more refined, specialized knowledge is needed to use the agreed-upon standardized language of **technical drawing** and **modeling**. These standards, developed by organizations like the American National Standards Institute (ANSI) and the American Society of Mechanical Engineers (ASME), ensure accurate and precise communication of engineered design specifications (Figure 1.8).

1.2.1 Visualization

A powerful tool for design engineers is the ability to see in their minds the solution to problems. **Visualization** is the ability to mentally picture things that do not exist



Figure 1.6 Technical drawing of an electric motor

Only experienced users of technical drawings can interpret the various lines, arcs, and circles sufficiently to get a clear mental picture of what this part looks like three-dimensionally.

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Figure 1.7 3-D computer model of the interior of an automobile

This computer rendering of a 3-D computer model is more easily understood because more detail is given through the use of colors, lights, and shades and shadows.

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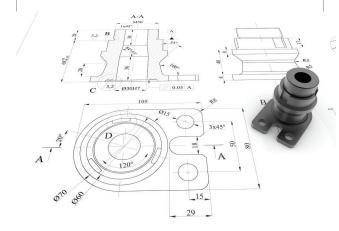


Figure 1.8

Technical drawings are used to communicate complex technical information.

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and to understand the interaction between them. Design engineers with good visualization ability can not only picture things in their minds, they can also control that mental image, allowing them to move around the image, change the form, look inside, and make other movements as if they were holding the object in their hands. Some of the greatest engineers and scientists throughout history have had powerful visualization ability, such as Albert Einstein, James Clerk Maxwell, Leonardo da Vinci, and Thomas Edison.

In his book titled *Engineering and the Mind's Eye*, Eugene Ferguson summarizes the importance of visualization to the design process. "It has been nonverbal

thinking, by and large, that has fixed the outlines and filled in the details of our material surroundings for, in their innumerable choices and decisions, technologists have determined the kind of world we live in, in a physical sense. Pyramids, cathedrals, and rockets exist not because of geometry, theory of structures, or thermodynamics, but because they were first a picture—literally a vision—in the minds of those who built them."

Most designers will initially capture their mental images by sketching them on paper. Sometimes these sketches are very rough and quickly done to capture some fleeting detail in the mind of the designer. When communicating one's sketch to others, the sketches must be refined (Figure 1.9).

Your ability to visualize should improve as you solve the problems located at the end of every chapter in this book. Visualization and the resulting sketch is the first phase in the whole process of graphics being used in the design process. You will find that as a professional engineer, the ability to visualize problem solutions and communicate them through your sketches will be one of your most important skills.

1.2.2 Communication

The second phase in the graphics produced to support the design process is **communication** models and drawings. In this phase your goal is to refine your initial sketches so your design solution can be communicated to others without ambiguity. In other words, you must be able to improve the clarity of your graphics to such an extent that others can visualize your design. This is done by adding more detail to your sketches, then creating a 3-D model

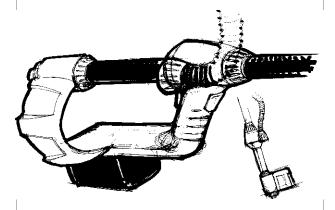


Figure 1.9 Design sketch of a hand digitizing system
These sketches allowed the designers to quickly explore and communicate design ideas.

Courtesy of Priority Designs (www.prioritydesigns.com)

using CAD software (Figure 1.10). The 3-D model is modified and changed as the design is refined. In the past, real models of the design were created for activities like product testing or production planning; however, many industries now use 3-D digital models to replace real models. Sometimes it is necessary to have real models, which can be produced from the 3-D model through a process called rapid prototyping, which will be explained later.

1.2.3 Documentation

After the design solution is finalized, graphics is the most effective way to permanently record that solution. Before 3-D modeling, **documentation** drawings were 2-D detail drawings that were copied through a process called blueprinting. Although many companies still create drawings,

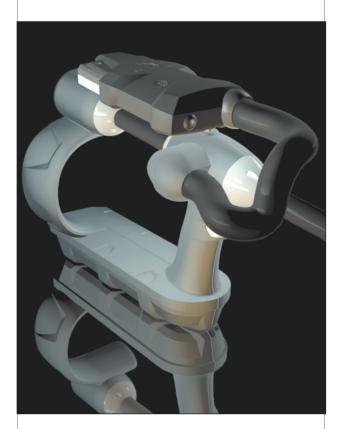


Figure 1.10 A refined 3-D model of the digitizing system used to communicate the design without ambiguity

With a CAD model, it is possible to test fit parts, analyze tolerances, and check interferences before making the actual components. It is also possible to locate the center of gravity and distribute the internal components to achieve perfect ergonomic weight and balance.

Courtesy of Priority Designs (www.prioritydesigns.com)

the trend is for companies to refine the 3-D model, which then is used directly by machine tools to create the design; measuring machines to inspect the design; and by sophisticated robots to help with the assembly of the design. Detail drawings still may be created, but the emphasis placed on their creation and use is shifting. Modern manufacturing organizations are moving toward the use of the 3-D model as the primary communication and documentation artifact of the design process, and drawings (when not used during production) are being used for things like meeting contractual obligations for legal and archival purposes (Figure 1.11). Two-dimensional documentation drawings follow very strict standard practices so everyone in the engineering field can "read" the drawing, and as 3-D modeling tools and processes have evolved, they are beginning to follow strict standard practices and techniques as well. These standards are the "language" used to communicate graphically. Advances in networking computer tools and storage, and the distribution of manufacturing organizations across the globe, means that electronic copies of 3-D models and 2-D drawings are increasingly being stored and accessed over the Internet to design, produce, and maintain products, processes, and structures.

1.3 The Engineering Design Process

Engineering design is one of the processes normally associated with the entire business or enterprise, from receipt of the order or product idea, to maintenance of the product, and all stages in between (Figure 1.12). The design process requires input about such areas as customer needs, materials, capital, energy, time requirements, and human knowledge and skills.

Two important societal concerns that an engineer must take into account are legal and environmental issues. Every business must operate within the law that governs their business. When designing, it is important that the engineer understand that legal issues may affect the designed product. Safety laws related to automobiles are an example of how government legislation can affect a design. Government regulations related to the environment may also have a bearing on the final outcome of the design. For example, the emission requirements on an automobile engine have a great effect on the final design.

Human knowledge input, such as an engineer's knowledge of graphics, mathematics, and the sciences, will also have a great effect on the outcome of a finished product. Such knowledge is used by the engineer to analyze and solve problems, which ultimately make a product better by meeting more of the customer's requirements.

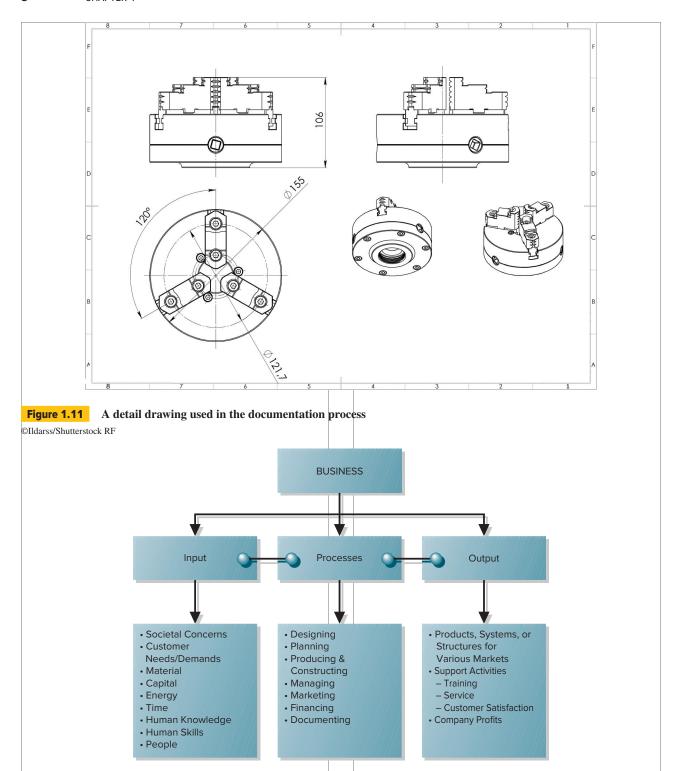


Figure 1.12 The business process

A manufacturing business or enterprise includes all the inputs, processes, and outputs necessary to produce a product or construct a structure. Designing is one of the major processes in such a business.

Design in Industry

Arc Second

This case study describes the design of a 3-D digitizing system. In this case study, you will see examples of how sketching is used and the importance of sketching in the design process to create this new product.

What Vulcan Does

The digitizing system consists of two laser transmitters and a wand receiver. The transmitters emit overlapping signals which create a digital grid, and the wand receiver picks up the signal and triangulates the position of the tip relative to the transmitters. In plain English, it means a person can walk around—free from wires—and simply click off precise measurements or navigate to a predetermined coordinate with ease.

The data is collected and saved to the CE box, and it can be downloaded directly into a CAD system via proprietary software. This allows for inspection, navigation, and modeling directly in CAD.

Brainstorm Sketching

To achieve our goals, we first brought all of our internal design staff together and created fast, rough brainstorm sketches. These sketches allow us to quickly explore and communicate our ideas with each other and the client. During the first week, work began in earnest to create a platform which would incorporate all of the features and functionality that Arc Second needed. It also was important to establish a language of aesthetics that would differentiate Arc Second from its competitors.

Presentation Model

After a final direction was chosen by the client, the design was transformed into a three-dimensional model, which allowed all team members on the project to see and touch it. This ensures that everybody involved is on the same page. At this point, the final aesthetic direction can be evaluated, as well as sizing and component packaging. Although many details will change, the overall look was locked in. Molded in solid foam, it was realistic enough to be shown at trade shows to determine consumer acceptance.

CAD Modeling

After the final design and graphics were chosen by the client, the foam model was digitized. This allowed our engineers to electronically model all of the components using Pro-Engineer (now known as Creo). We were now able to test-fit parts, analyze tolerances, and check interfaces before making the actual components. Additionally, our engineers were able to locate the center of gravity and

distribute the internal components to achieve a perfect ergonomic weight balance.

Engineering

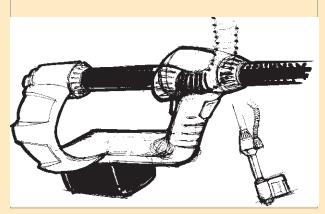
Our designers and engineers collaborated to streamline the engineering process. Whenever possible, "off the shelf" parts were utilized to reduce time to market. An accurate and fully detailed computer model was crucial for this project to come together on schedule.

Knowing that changes would likely be made, the Pro-E models were carefully constructed to best facilitate downstream modifications. This database allowed us to check clearance and interference, leave room for cables and fasteners, and give accurate, functional assembly drawings to the client.

Production Parts

Pleased with our work thus far. Arc Second was anxious to field-test these units. Our prototype staff was contracted to create functional prototypes before committing to costly hard tooling. Utilizing our engineer's Pro-E data, we created RTV silicone molds from SLA masters. With these molds, we produced copies using two-part polyurethane. The units were then sprayed with a soft polyurethane coating which looked, felt, and performed like production injection molded parts. The coating also sealed the original material and protected it from UV rays. In addition, we cast the soft rubber "boots" that protected the handheld computer interface. All parts were test fitted in our shop before shipping to Arc Second for final assembly.

Ultimately, Priority Designs was contracted to produce 90 fully functioning Beta production units, which have been, and continue to be used and evaluated by consumers.



Courtesy of Priority Designs (www.prioritydesigns.com)

An engineering design involves both a process and a product. A **process** is a series of continuous actions ending in a particular result. A **product** is anything produced as a result of some process. As the design of a product or process is developed, the design team applies engineering principles, follows budgetary constraints, and takes into account legal and social issues. For example, when a building is designed, engineering principles are used to analyze the structure for loads; determine the structure's cost, based on the materials to be used, the size of the structure, and aesthetic considerations; and create a design that adheres to the local laws.

Graphics is an extremely important part of the engineering design process, which uses graphics as a tool to visualize possible solutions and to document the design for communications purposes. The geometric model, or graphics derived from it, are used to visualize, analyze, document, and produce a product or process. In fact, geometric modeling itself could be considered both a process and a product. As a process, geometric modeling produces final design solutions, as well as inputs to the production process, in the form of computer databases. As a product, geometric modeling is a result of the engineering design process, capturing the shape, behavioral, and contextual information of a product or process.

1.3.1 Linear Engineering Design

The linear engineering design process is a design approach divided into a number of steps. For example, a six-step process might be divided into problem identification, preliminary ideas, refinement, analysis, documentation, and implementation. (See Figure 1.13.) The design process moves through each step in a sequential manner; however, if problems are encountered, the process may return to a previous step. This repetitive action is called iteration. Many industries are incorporating a new process that combines some features of the traditional process with a team approach that involves all segments of a business. The process was linear due in large part to the limitations of older paper-based communication tools. New computer and network-based design and production tools, along with the use of 3-D CAD models to communicate, allow more flexibility in how information is accessed and used.

1.3.2 Model-Centered Engineering Design

The production process executes the final results of the design process to produce a product or system. In the past, the creative design process was separated from the

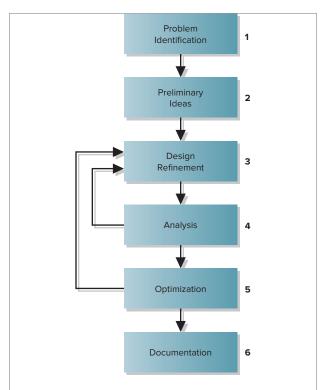


Figure 1.13 Traditional engineering design sequence

The traditional design process is a sequential process that can be grouped into six major activities, beginning with identification of the problem and ending with documentation of the design. Technical graphics is used throughout this process to document design solutions.

production process. With the advent of 3-D CAD and product data management systems, this separation is no longer necessary, and the modern engineering design approach brings both processes together.

The model-centered engineering design process is a nonlinear team approach to design that brings together the input, processes, and output elements necessary to produce a product. The people and processes are brought together at the very beginning, which normally is not done in the linear approach. The team consists of design and production engineers, technicians, marketing and finance personnel, planners, and managers, who work together to solve a problem and produce a product. Many companies are finding that concurrent engineering practices result in a better, higher-quality product, more satisfied customers, fewer manufacturing problems, and a shorter cycle time between design initiation and final production. However, this approach works best when each person accesses product information from a complete, unambiguous, wellstructured digital product representation.

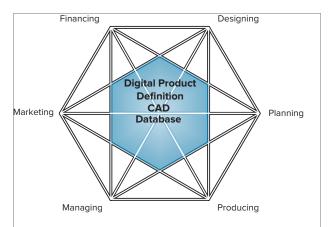


Figure 1.14 Sharing the Digital Product Model

The model-centered engineering diagram shows how every area in an enterprise is related, and the digital product model is the common thread of information between areas.

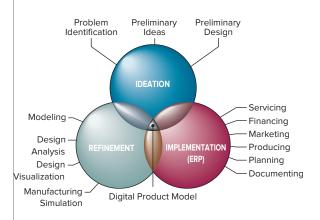


Figure 1.15 Model-centered engineering design

The engineering design process consists of three overlapping areas: ideation, refinement, and implementation, which all share the same 3-D CAD database.

Figures 1.14 and 1.15 represent the model-centered approach to collaborative engineering design based on 3-D modeling. The three intersecting circles represent the interrelated nature of this design approach. For example, in the ideation phase, design engineers interact with service technicians to ensure that the product can be serviced easily by the consumer or a technician. This type of interaction results in a better product for the consumer. The three intersecting circles also represent the three activities that are a major part of a collaborative, model-based design process: ideation, refinement, and implementation. These three activities are divided further into smaller segments, as shown by the items surrounding the three circles.

Design for manufacturability (DFM) and design for assembly (DFA) practices developed out of the concurrent engineering paradigm as an effort to capture manufacturing and assembly knowledge up front in the conceptual and detailed design process. This allowed engineering and manufacturing professionals to speak a common language that results in an optimized product design. DFM and DFA eventually expanded to include other practices, such as design for serviceability and design for reliability. This led to the realization that it is important to include others in the design process, such as marketing, sales, field service, finance, purchasing, and quality control.

The center area in Figure 1.15 represents the 3-D computer model and reflects the central importance of 3-D modeling and graphics knowledge in engineering design and production. With the use of a modeling approach, everyone on the team can have access to the current design through a computer terminal. This data sharing is critically important to the success of the design process.

Through the sharing of information, often in the form of a database, it is possible for all areas of the enterprise to work simultaneously on their particular needs as the product is being developed. For example, a preliminary 3-D model could be created by the design engineers early in the ideation phase. A mechanical engineer could use the same 3-D model to analyze its thermal properties. The information gained from this preliminary analysis then could be given to the design engineers, who then could make any necessary changes early in the ideation phase, minimizing costly changes later in the design process.

1.3.3 Collaborative Engineering

Collaborative engineering has evolved from domainspecific, process-centered engineering into a true enterprise-wide integrated product development process. Model-centered engineering and design seeks to establish well-defined organizational structures for digital product definition, as well as the accompanying structured business processes. This complete and unambiguous digital product definition enables collaborative engineering. Collaborative engineering creates the infrastructure and best environment for highly effective team collaboration using computers to store and share information. The development of such tools as e-mail, groupware, video conferencing, and chat rooms was important in the adoption of collaborative engineering in industry. Concurrent engineering is fundamentally process-centric through the creation of well-defined, documented, and executed business processes for the development of products. Collaborative engineering is fundamentally a productcentric process that builds onto the concurrent engineering practices a mindset of highly effective collaboration about the product and its manufacturing and support processes. The product becomes the central focus instead of the process.

Collaborative engineering is based on empowered, cross-functional teams and low-level decision making. Figure 1.16 shows the basic structure of collaborative engineering where cross-functional teams share a common goal through the sharing of information using computer networks. This information has an impact on the product as it is being designed and manufactured for eventual distribution to consumers.

1.3.4 Digital Product Representation

Collaborative engineering is highly dependent on computer-based tools to create a digital product representation that can be shared throughout an enterprise. Tools used to support the design process include CAD, CAM, CAE, and office applications. From there, the digital product representations are communicated through the enterprise via product lifecycle management (PLM) systems, manufacturing execution systems (MES), and enterprise resource

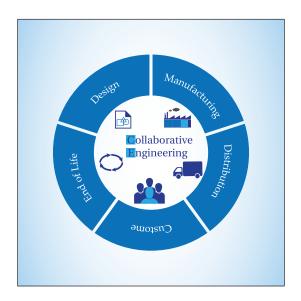


Figure 1.16 Collaborative engineering

This diagram shows the major functions involved in the design, manufacture, and distribution of a product. The information produced by each function is shared through a highly sophisticated network of computers and software tools.

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planning (ERP) systems. The following tools are used to create a digital representation of a product design through:

- 1. 3-D CAD models
- 2. Product data management
- 3. Large assembly visualizations
- 4. Packaging analysis
- 5. Tolerance analysis
- 6. Structural, thermal, and flow analyses
- 7. Dynamic simulations for design and manufacturing
- 8. Virtual reality
- 9. Collaborative Web technology

1.3.5 Prototyping

One step closer to reality is gained by using physical prototyping through either rapid prototyping or 3-D printing to quickly create a physical model of a part, or functional prototypes to create mockups of the part using traditional means, such as machine tools. A printed prototype is typically limited in its functional usage due to the materials that are used to created it, such as plastic, wax, or organic powders. While 3-D printing machines are capable today of printing objects from metal powders, they are prohibitively expensive for all but the largest companies to implement. Printed prototypes are primarily used for creating geometric and topological representations of a part. A functional prototype includes geometric and topological representations of a part in addition to functional representation in terms of mechanical, structural, thermal, fluid, and electrical behaviors. Functional prototypes are expensive to create, but they are often the most realistic in depicting the finished product for the purposes of testing. An emerging form of prototyping is the creation of virtual prototypes. A virtual prototype uses 3-D CAD models combined with analysis tools to simulate the behavioral and contextual conditions in which the product will operate.

1.3.6 Productivity Tools

There are a number of tools used to enhance overall productivity and the sharing of design and manufacturing information. These are used by engineers and technicians on a daily basis to support the overall design process but are not viewed as engineering tools as CAD software is. Tools to share the output of the design process include e-mail, word processing, spreadsheet, groupware, file transfer, file translation, videoconferencing, and workflow.

1.3.7 PDM/Configuration Management

Tools to manage the long-term overall design/manufacture process include product data management (PDM) and configuration management (CM) software programs. CM and PDM are used to track and manage all the electronic documents and product data associated with the design and manufacture of products. Product data management always has been important in manufacturing and design, but it was done traditionally using paper-based filing systems. Configuration management was done the same way, or more recently with spreadsheets and databases, as a way to manage the various options and specific configurations a product may have. This is especially relevant to any company that makes variations of its products for different customers or applications. However, these paperbased systems are being replaced with a digital, relational, object-oriented database system using CM and PDM software. One element of CM and PDM software that makes them particularly useful to nontechnical people throughout the enterprise for accessing digital product data is that they typically incorporate Internet browser interfaces, which are easy for most people to use across operations around the world.

1.3.8 Internet, Intranet, and Extranet

Most of the software tools just described are used within the context of a computer network to provide the interconnectivity necessary to share information. Recently the **Internet** has become the network most capable of providing the interconnectivity for collaborative engineering. Intranets are used as the backbone for internal corporate information sharing. An **intranet** is a private internal network that uses web browsers and servers to connect users in an organization in order to share information. **Extranets** are private and secure networks that allow access to a company's internal intranet by outside sources, such as supply vendors, through the Internet. Extranets are a part of a rapidly expanding area of *business-to-business* (B-to-B) information technology that includes the Internet, extranet, and intranet.

1.3.9 Product Lifecycle Management (PLM)

The manufacture of a new product now calls for the involvement of all the company's departments: engineering, strategy, marketing and sales, planning and production, procurement, finance, and human resources. **PLM** is a methodology that facilitates the simultaneous working of all these functional groups within an organization. It promotes

the ability for a company to create, manage, simulate, share, and communicate digitally all the information related to the company's products, processes, and resources, thereby optimizing its overall performance (Figure 1.17). A fundamental element of PLM is the use of the digital thread—the interconnected digital product representation that includes the shape, behavioral, and contextual attributes of a product—to enable product data sharing between authors and consumers of information across an enterprise.

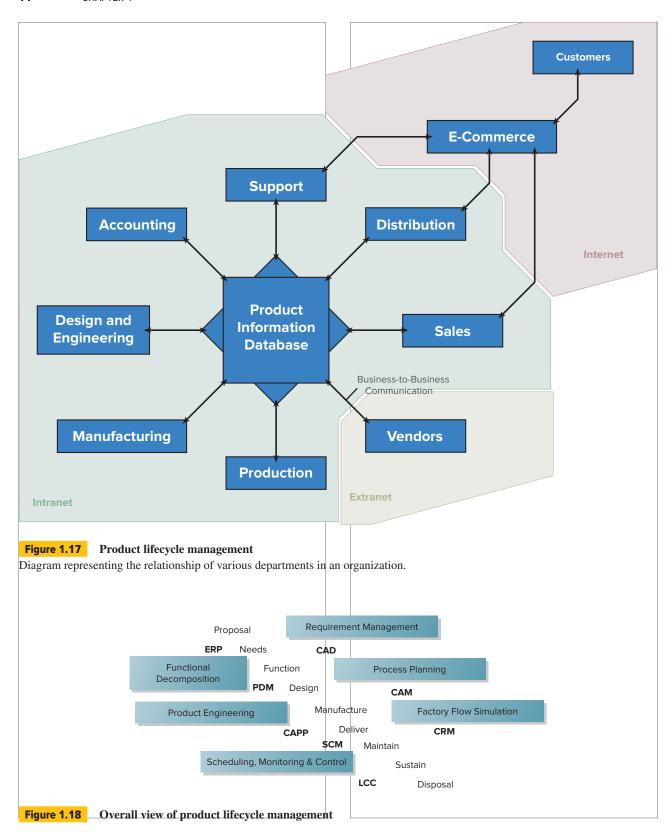
In addition to CAD software used to design, specialized software is required to focus on product data management and tools for sharing product data across the enterprise. It is possible through the use of computer simulation that problems can be discovered early in the product definition when changes are less costly. Being able to move this information across an enterprise so multiple people can view it and check it encourages errors to be caught early in the process. Companies are using different processes and systems to manage the product data from conceptual design to in-the-field service, and they are looking at ways to improve data flow and streamline processes to increase their competitiveness.

A clear, complete, and unambiguous digital product definition is critical for modern PLM technology to be successful. The overall objective is to provide the capability for companies to design and simulate products "virtually" across an integrated enterprise, covering the entire lifecycle of a product, all without ever having to build a real prototype. This is achieved through advances in CAD, digital mockup, digital manufacturing simulation, web access, and other key technologies. As a result, companies are dramatically changing the way they do product design and management, including the integration of functions within an enterprise that, until recently, have been either "outside" or at the end of the product development process.

Manufacturers using CAD systems produce a tremendous amount of digital information and knowledge that remains buried in digital form on hard drives and file servers. The PLM environment leverages the knowledge found in these digital files by making that information available in various forms to the whole organization.

PLM uses an integrated information technology (IT) environment that allows manufacturers to create, manage, store, and share product data throughout the concept, design, build, and life stages of the product's lifecycle. It is a business process that plans for the lifecycle of a product from "proposal to disposal" (Figure 1.18).

Although many new technologies emerged in the 1990s, two have had a profound effect on engineering



design. The first is Web technology combined with the Internet, which helped make it possible for product data management (PDM) users to access data from remote locations through the Web. The second is the realization that geometry and other product information (i.e., product definition) can be reused by virtually all business processes downstream of the design process through derivatives of the original CAD file. This reuse ability provides an immense benefit through the elimination of redundant or inefficient activities (such as the rekeying of data), enabling concurrent work, as well as avoiding transcription and translation errors.

So fundamental has been the impact of these two developments that they have led to a profound change to the way PDM, CAD/CAM, and other computer-aided technologies are developed and used. The increasing use of the same product definition outside the design phase of the lifecycle led not only to tighter coupling of related technologies, such as CAD, CAM, and CAE, but also to the convergence of these technologies with PDM. The Internet put an end to any site location and geographical constraints. Together, these two developments made it possible, for the first time, to solve the emerging needs of businesses operating in the highly competitive, heavily outsourced global environment.

Business can now:

- Cut costs and time to market through more effective use and reuse of resources
- Be nimble and quick to react to market changes through the ability to focus on core business and increased collaboration with suppliers and partners
- Increase innovation through better visibility of product data to all personnel within both the enterprise and the extended enterprise

With a standard Web browser as the user interface and encryption technology to provide secure access across the Internet, it is possible for multidisciplined teams to work concurrently on the same product data from anywhere around the world. Another significant development is the emergence of the Web browser as the "standard" user interface. This has provided consistency in the presentation of and interaction with product data, making it easier for team members to communicate. The result is that project teams can include members from a wide range of disciplines as well, including suppliers, partners, customers, and other interested parties. These virtual project teams can be set up and disbanded as the organization business evolves.

As PLM methods and tools have evolved, it has become a strategic business approach for the effective management

and use of corporate intellectual capital. Corporate intellectual capital (CIC) is the sum of retained knowledge that an organization accumulates in the course of delivering its products. In contemporary terms, this accumulation of knowledge, coupled with an easily accessible digital product definition, allows companies to leverage this information to make better business decisions. However, much effort is required to package that product and process data into a form in which it can be shared. In addition to the usual product and process data that is captured, many companies also capture operational product data while the product is in use. This performance data can then be compared to the nominal design and production data to make decisions about how the product is behaving over time or how it can be improved in the next iteration.

Corporate intellectual capital (CIC), as it relates to product design and manufacturing, often includes the following:

- Product definition—all the information relating to what the product (or service) is: its specifications and geometry; materials definitions and how it is designed, manufactured, delivered, and supported.
- Product history—any information relating to what the organization has done in the past that is of relevance for the delivery of the organization's product, such as audit trails required for legal or regulatory purposes or archives relating to past products.
- Process definition—all information used to plan and execute the production and supply chain aspects of product realization, such as machining processes, supplier capability, and work instructions.
- Process history—an archive of the actual processes, tools, and techniques used to make the product, including how that information deviates from the product definition and product history.
- Best practice—this summarizes the experience gathered by the organization in the course of delivery of its products.

CIC consists of two types of data:

- Content objects—product definition and all related information.
- Metadata—data that describe the content, such as creation and last modified dates, author/owner, version/status, how it can be used and by whom, and so forth.

PLM allows everyone—from manufacturing to marketing and from purchasing to field support—to work faster and smarter. This allows the entire network of companies—working together to conceptualize, design, build, and support products—to operate as a single entity. PLM allows companies to share common business processes and a common knowledge of the product throughout all of the stages of its lifecycle, from concept to retirement.

Collaboration breeds innovation and product lifecycle management breaks down the technology silos that have limited interaction between the people who design products and the people who build, sell, and use them. Using the collaborative power of the computing architectures, digital product data, and simulation, PLM increases a company's ability to produce innovative product designs, while reducing cycle times, streamlining manufacturing, and cutting production costs.

PLM simultaneously supports and enables three distinct yet deeply interconnected processes:

- Supply chain collaboration—to help access the product expertise and experience within a company and beyond.
- Product development—to help develop better products in a better design environment.
- Enterprise process integration—to help integrate product information with all company business processes.

1.3.10 e-Business

e-Business is the process of buying and selling products over the Internet. However, this revolutionary method of buying and selling can have a profound effect on the design and manufacture of products. e-Business can become the means to exploit the combined power of the Internet and information technology to fundamentally change the design and manufacturing processes. This means using CAD, virtual product representation, PDM, and EDM to conceive, design, build, market, and sell the most innovative, highest-quality, most attractive products to customers.

1.3.11 Design Teams

The membership of a design team will vary according to the complexity and type of design. In small companies, design teams may be only a few individuals, such as a design engineer, a drafter, and a manufacturing engineer. A typical team in a concurrent engineering design process will include individuals from design, manufacturing, quality, materials, vendors, and managers. Team members rotate in and out, and involvement levels rise and fall as the design moves from concept to manufacture. Daily meetings are common during critical times in the design process, although weekly or even monthly meetings of the design team are more common. Face-to-face meetings of design and production teams have been greatly reduced due to the ability to widely share digital product data. Global design teams are possible through the use of the Web and other Internet-based tools. It now is possible to share design information, including CAD models, across the Web.

The coordination of the design team is critical to the success of the design and in meeting deadlines. Communications becomes a very important element for successful design. The use of computers in the design process can facilitate good communication between members of the design team. 3-D model data can be shared by the design team that will allow many of the design processes, such as analysis and manufacturing, to collaboratively work on and have input into the final design.

If the design is complex, subassemblies are created by the design team within the constraints of the 3-D CAD master model. The shared 3-D CAD database is the way the team can make sure that the design of each subassembly will work through a *model-centered* refinement process. By dividing the design into subassemblies, more members of the design team can work on the design's virtual model, which can reduce modeling time and product development time that is critical in today's global economy and fierce competitive environment.

1.3.12 Members of Design Teams

The number and types of individuals that comprise a design team largely are determined by the size of the design project. Even when they are assigned to a team, all members may not be involved at all times. In a collaborative engineering environment the team members work together to meet the common goal. Potential members of a design team working in a PLM environment might include:

- Product design engineer—responsible for the overall product design.
- 2. Product manager—the person who has the ultimate responsibility for a design and its team.
- Mechanical engineer—responsible for mechanical and electromechanical product development.
- Electrical engineer—responsible for electronic components of the design.

- Manufacturing engineer—responsible for the manufacturing processes used to create the product.
- Software engineer—responsible for any computer software code needed for a product.
- Detailer/drafter—assists the engineers with the 3-D modeling and documentation of the product.
- 8. Materials engineer—responsible for the selection of the material best suited for a product.
- Quality control engineer—responsible for meeting the quality guidelines for the product and its manufacture.
- Industrial designer—responsible for the product's appearance, form, and human factors analysis.
- Vendor representatives—responsible for any outsourcing required by the company making the design.

1.3.13 Types of Design Projects

Not all designs are totally new designs of products. In fact, most designs have at least some common features with a previous design. Design projects are grouped as:

- 1. Modification of an existing design
- 2. Improvement of an existing design
- 3. Development of a new product

1.4 Ideation

Ideation is a structured approach to thinking for the purpose of solving a problem. Ideation is that phase of the design process in which the basic design is conceived (conceptual phase). Feasibility studies often are performed to define the problem, identify important factors that limit the scope of the design, evaluate anticipated difficulties, and consider the consequences of the design. The ideation process consists of three important steps: problem identification, preliminary ideas, and preliminary design. Each of these areas can be further subdivided, as shown in Figure 1.19.

1.4.1 Problem Identification

Problem identification is an ideation process in which the parameters of the design project are set before an attempt is made to find a solution to the design. Problem identification includes the following elements:

Problem statement, which summarizes the problem to be solved.

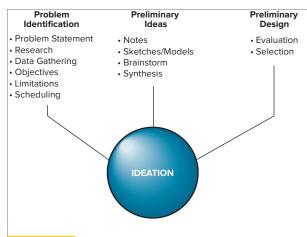


Figure 1.19 Ideation process

The ideation process includes problem identification, preliminary idea development, and preliminary design. Ideation is the start of the design process.

Research, which gathers relevant information useful to the design team.

Data gathering, sometimes called feasibility study, which determines market needs, benchmarking with the competition, and rough physical measurements, such as weight and size.

Objectives, which list the things to be accomplished by the team.

Limitations, which list the factors in the design specifications.

Scheduling, which organizes activities into a sequence.

Engineering design problems must be defined clearly before the design process can begin. The problem definition includes input from as many of the following constituents as possible: customers, marketing, management, engineering, manufacturing, supply chain, and customer support. Data to determine consumer needs is gathered through surveys, such as personal or telephone interviews, mail questionnaires, and focus groups. Customer input can also be gathered through data collection from existing products through service calls and warranty information. Marketing determined the average income, demographics, typical jobs, and other information on cellular phone users, as well as the opinions of the customers regarding the proposed design.

The competition is surveyed to "benchmark" a product line. A benchmark in this context is a product similar to the one being considered for design. Previous iterations of objects from the existing product line may also be reviewed to determine if previously discarded ideas could now be used with certain customers.

Journal and trade magazines are reviewed for reports on developments in related technologies. A patent search may be done, and consultants specializing in areas where the design team is weak may be hired. This process of researching similar products and technologies and applying the results to the new design is called *synthesis*.

After all the data is gathered, the information is shared with the product development team before preliminary ideas are developed (Figure 1.20). **Presentation graphics** are used to display the data in the form of data visualizations, charts, and graphs and are thus an important element in the information-sharing process.

After the problem statement is created and the research and data gathering are completed, objectives are developed by the team. Objectives specifically state what is to be accomplished during the design process and may include factors related to manufacturing, materials, marketing, and other areas. Included in this process are limitations or constraints on the project, such as time, material, size, weight, environmental factors, and cost.

Scheduling of the design activities is one of the last stages in problem identification. To plan and schedule simple projects, a Gantt chart may be used. In a Gantt chart, horizontal bars are used to represent resources or activities, and time is represented by the length of the bars. A method of scheduling large projects is the project



Figure 1.20 Sharing the data gathered

Many times, preliminary data is shared with the team in the form of charts and graphs. The team then uses the data to finalize the goals of the project.

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evaluation and review technique (PERT), with which activities are scheduled in such a way as to optimize progress toward completion. The critical path method (CPM), used with PERT, defines those activities that must be completed in sequential order while other activities are taking place.

Figure 1.21 is an example of a simple CPM chart. The circles represent events that are the start or completion of a mental or physical task. The lines between the circles represent the actual performance of a task and indicate an increment of time. The numbers along the lines show the amount of time allotted to complete each task. The critical path is the thicker line, which may also be in a different color.

1.4.2 Preliminary Ideas Statement

After the problem identification is complete, the team begins to develop preliminary ideas for solving the problem. This stage of the process sometimes is referred to as brainstorming. **Brainstorming** is the process of suggesting as many solutions to a problem as possible. A brainstorming session normally has a leader or moderator and a recorder. Before a session starts, results of the ideation phase, such as marketing surveys and product research, are shared with the group. This synthesizing process is used as a catalyst to generate as many ideas as possible by giving the group a starting point for the design solution. Ideas are suggested freely, without criticism or discussion of feasibility. The length of the session varies but ends when the free flow of ideas begins to slow down.

Brainstorming results in a list of ideas, along with some preliminary sketches or computer models (Figure 1.22). The computer models would not be dimensionally accurate, but would approximate the preliminary

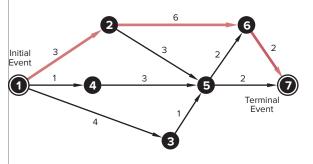


Figure 1.21 CPM chart created for a simple project

The thick line represents the critical path, for those activities that must be completed in sequential order while progressing through the project.



Figure 1.22 Brainstorming

Brainstorming by the team will result in a list of possible solutions, as well as rough sketches or computer models. During brainstorming, members of the design team will generate as many ideas as possible, without criticism or discussion of feasibility.

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idea. All ideas are sketched or modeled, listed, and shared with the whole team. Eventually, two to six ideas are selected for further analysis. The number of ideas chosen depends on the complexity of the design and the amount of time and resources available.

1.4.3 Preliminary Design

After brainstorming, the ideas are evaluated, using the problem statements, project goals, and limitations as criteria for selecting the go-forward options. Industrial designers historically created preliminary models out of foam or other material, but more often today they refine the computer models created in the preliminary ideas phase to develop digital representations that can be further analyzed and tested in virtual computing environments in lieu of building so many physical prototypes.

The choice for the final design may be easy if only one design meets the criteria. However, there is often more than one viable design solution. When this happens, an evaluation table may be used to "score" each design idea relative to the goals of the project.

deation Graphics and Visualization In the ideation phase, rough sketches and conceptual computer models called ideation drawings or models are produced. **Ideation** drawings communicate new ideas through the use of

rough sketches and dimensional information. These drawings are a synthesis of the information gathered in the preliminary stages of the design process and may combine what was visualized in the mind with what has been put on paper or in the computer. Copying drawings or modifying computer models encourages new ideas to evolve from existing concepts. In a model-centered design process, preliminary 3-D models are often created to capture the ideation process. These **ideation models** capture general geometric characteristics of the object, but they are created in a way that they can be easily modeled and detailed within the CAD software.

Presentation Graphics Presentation graphics are used to present data in more easily understood forms, such as charts or graphs, animated sequences, data visualizations, or even images of ideation models. Preliminary engineering and cost analyses also may be graphed. Presentation graphics are a very important part of the design review meeting. Ideation requires skills in sketching, visualization, geometric modeling, and presentation graphics.

While this ideation process works well for a new product never made before, most products are revisions or new versions that have some improvement or relationship to an existing product. They use existing geometry definitions, specifications, and performance data to develop new geometry definitions, production processes, and post-production support of the product.

1.4.4 Ideation Resources

Inventive or creative ideas can come from a number of sources. Personal experience is a great source of ideas, as is the existing knowledge of an organization. Outside sources for ideas can come from consumer surveys, competition reviews, patent searches, library searches, and searches on the Web. Vendors and professional organizations can be helpful when gathering information for new designs. *Thomas Register* is an excellent resource for gathering information about companies and their products. *Thomas Register* and many other vendors maintain websites, and some vendors have CD-ROMs available with their products from which images can be inserted into CAD drawings and models.

1.4.5 The Designer's Notebook

Designers should get into the habit of taking meticulous notes to ensure that ideas and decisions are kept for future reference. A designer will create many notes and documents which normally become part of the design file. Historically, this was done in a well-documented design notebook containing design sketches (Figure 1.23) with notes, calculations, signatures, and dates. One important reason for keeping good notes is to make it easier to document original designs, which is very important when applying for a patent. This information also is important to defend against possible lawsuits arising from the use of the product. The notebook is also a way of creating a history of design for a company (Figure 1.24). This historical record enabled new designers to quickly determine how design has progressed in a company. This historical record also became important when modifying existing designs or creating a related product. When this occurs, design decisions and previous design solutions may become a

starting point for the modified design. This can save much time and money in the development of the new product.

The notebook is very similar to a diary that records the development of the design solution. It does not have to be neat, but it should be legible and contain all the notes, sketches, and calculations on sequentially numbered pages. A simple bound notebook may be all that is needed for a designer's notebook for a single project.

Today's technology allows collaborative engineering through design across the World Wide Web (WWW), as described in more detail later in this chapter. Keeping a designer's notebook can be accomplished through a computer-based electronic notebook by serving, delivering, and storing the data created by the design team. New PLM tools for visualization and 3-D data sharing allow

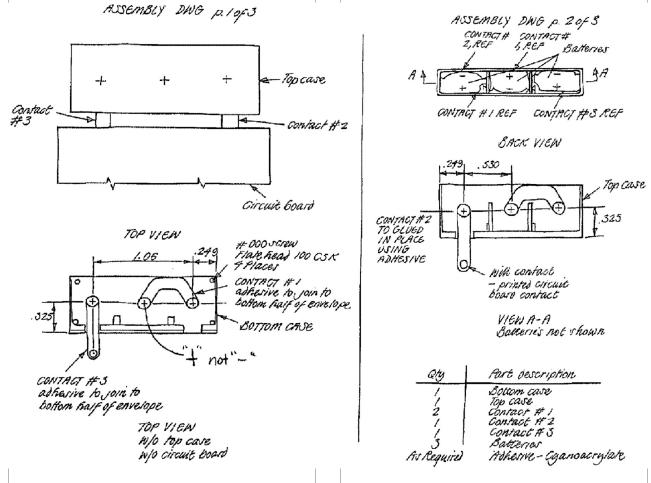


Figure 1.23 Pages from a designer's notebook

These sketches and notes are from an engineer's notebook showing the assembly drawing of a battery case. Ullman, David G. *The Mechanical Design Process*, 3rd edition. Copyright © 2003 by McGraw-Hill Education. Reprinted by permission.

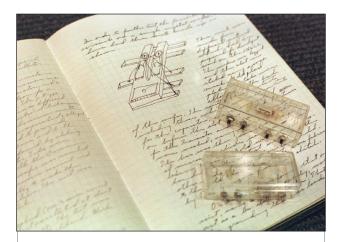


Figure 1.24 Designer's notebook as a historical record

Jack Kilby was the primary design engineer for the first integrated circuit while working at Texas Instruments in 1958. Pictured above is his design notebook and page from the notebook with his notes describing the basic concept behind the integrated circuit.

©PAUL BUCK/AFP/Getty Images

designers and others to share information from a secure, shared, and common digital product definition. This digital product definition contains much of the same information that a paper-based notebook would have contained, and much more, including product behavior simulations, materials analyses, and manufacturing or assembly definitions. This allows digital product information to be securely accessed by a wide variety of people in different departments and even different locations.

1.5 Refinement

Refinement is a repetitive (iterative or cyclical) process used to test the preliminary design, make changes if necessary, and determine if the design meets the goals of the project (Figure 1.25). Refinement is the second major stage in the collaborative engineering design process and consists of three main areas: modeling, design analysis, and design visualization. These areas are subdivided further into activities that ultimately result in the selection of a single design solution. Historically this process would have included a series of mark-ups and revisions to a product's engineering drawings; however, in a digital model-centered design process, the activities in the refinement stage use the evolving 3-D CAD model as input.

The refinement stage normally begins with designers or CAD modelers using the rough sketches and computer

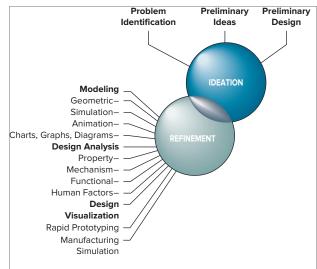


Figure 1.25 Refinement process

The refinement process includes modeling, design analysis, and visualization. These elements are used to determine if the design meets the goals set earlier in the design process. Refinement is an iterative process, which means that changes made to the design may cause elements in the refinement stage to be repeated.

models to create dimensionally accurate models or drawings (Figure 1.26). At this point, the engineers will likely have selected the materials for the component parts, considering such factors as heat, light, noise, vibration, humidity, strength, weight, size, loads, cost, and many others. The engineers work closely with the designer or CAD modeler so that the materials selected will work well with the proposed geometric form.

The preliminary design is often tested many times virtually, using finite element analysis software tools, kinematic and dynamics software tools, motion simulations, and spatial analysis before physical prototypes are built. The design is analyzed relative to the project objectives and problem statement, and manufacturing begins to determine the processes needed to produce the product. The preliminary design is also market tested to a small group. At this stage changes may be recommended in the initial design. The final step in the refinement stage is selection of the final design for the product.

The refinement stage is heavily dependent on graphics to document, visualize, analyze, and communicate the design idea. These models and drawings are often called design drawings (or models). Refinement models and drawings are technical models and drawings used to analyze and communicate preliminary design ideas (see Figure 1.26).

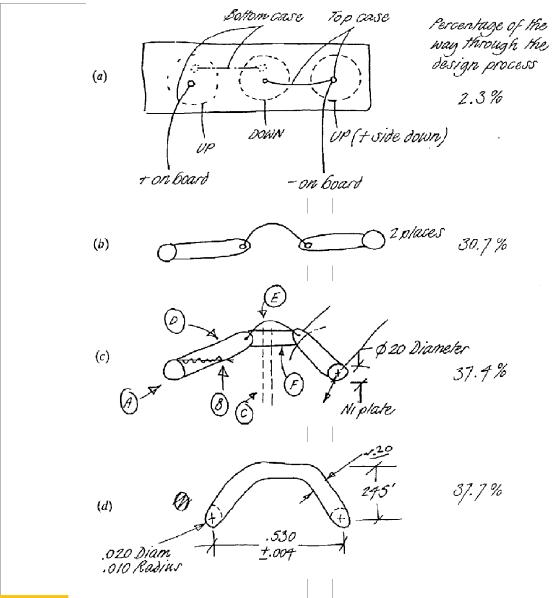


Figure 1.26 Refinement of a battery contact design

Engineering drawings and models that are more dimensionally accurate are produced in the refinement stage. Ullman, David G. *The Mechanical Design Process*, 5th edition. Copyright © 2016 by McGraw-Hill Education. Reprinted by permission.

1.5.1 Modeling

Modeling is the process of representing abstract ideas, words, and forms, through the orderly use of simplified text and images. Engineers use models for thinking, visualizing, communicating, predicting, controlling, and training. Models are classified as either descriptive or predictive.

A **descriptive model** presents abstract ideas, products, or processes in a recognizable form. An example of a

descriptive model is an engineering drawing or 3-D CAD model of a building or automobile (Figure 1.27). The drawing or model serves as a means of communication but cannot be used to predict behavior or performance. A **predictive model** is one that can be used to understand and predict the behavior/performance of ideas, products, or processes. An example of a predictive model is a finite element model of a bridge support, which is used



Figure 1.27 Descriptive model

The descriptive model of a hospital shows its size, shape, and relative position.

Source: National Cancer Institute (NCI)

to predict the mechanical behavior of the bridge under applied loads. (See Section 9.1.2 for a discussion of finite element models.)

During the refinement process, two types of models are useful: mathematical models and scale models.

A mathematical model uses mathematical equations to represent system components. This technique is useful for understanding and predicting the performance of large, complex systems. Normally, a large system is broken into its simpler components before being modeled. Figure 1.28 is an example of a mathematical model used to predict the power loss of thrust bearings when velocity is increased. By reading the graph, you can predict how much loss there will be without having to test the bearings physically at every operating speed. This results in a tremendous savings in time and cost during the refinement stage of the design process.

A **scale model** is a physical model created with relative physical proportions to represent system components. This is one of the most useful and easily understandable of all the modeling processes. The model can be full size or a replica made to scale. Before the advent of 3-D CAD modeling, physical models were made by skilled craftspersons from clay, wood, foam, or other materials (Figure 1.29). Physical models are extremely useful for

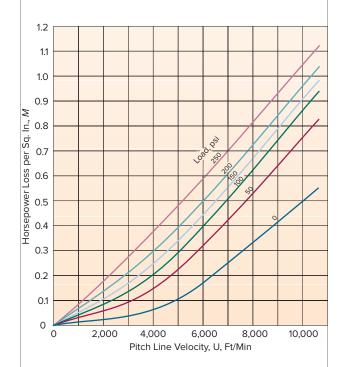


Figure 1.28 Predictive model

A mathematical model is used to predict the power loss of a thrust bearing at various speeds.

Source: Data from Machinery's Handbook, 25th ed.



Figure 1.29 Real model

Real models created from clay are used for spatial, aesthetic, and property analyses.

©Hero Images/Getty Images RF

conducting spatial, aesthetic, human factors, and property analyses. For example, the cellular phone could be modeled in foam or wood and given to the human factors engineers and the consumers group on the design team to get their feedback on the interaction between the model and the human test subjects. In addition, the circuitry of the cellular phone could be created as a working model using breadboarding, which is a technique used by electrical engineers and technicians to test new circuits.

For most products today, 3-D CAD modeling, simulations, visualizations, and rapid prototyping, have reduced the need for creating physical models using traditional techniques. Rapid prototyping is a broad term used to describe several related processes that create real models directly from a 3-D CAD database (Figure 1.30). This can dramatically reduce the time between design and initial production.

In some cases, it is not practical, cost effective, or safe to make a physical prototype. In other cases, the prototype would not respond the way the actual product would. For these situations, as well as others, virtual reality (VR) systems offer a viable analysis approach (Figure 1.31). VR systems use the principles of perception to develop completely immersive environments in which the user can interact with the object through some or all of the senses. In such an environment, the user has the feeling of actually interacting with the virtual model.

VR technology uses models that correspond closely to the real object, often being derived from the CAD models of an object created during the design stage. Also, the



Figure 1.30 Prototype model made with 3-D printing Real model of a shoe created with a rapid prototyping system.

©Maciej Frolow/Getty Images



Figure 1.31 Virtual reality technology

This technology allows a more complete use of the senses to explore and evaluate design concepts.

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system must be able to monitor all actions taken by the user. This includes changing the point of view when the user's head position changes or depicting a virtual hand when the user is reaching out and grasping the virtual object. In addition, the user needs to receive feedback that closely mimics the environment's responses to the user's actions. The visual and auditory fields must be controlled completely by the system, and this often is done with headsets. Technology has been developed that provides kinesthetic and haptic (touch) feedback to the user when interacting with the object in the virtual world. The virtual model would feel like it has weight when it is being

moved around by the user. While virtual environments are incredibly useful to evaluate products, a particular challenge remains: Any discrepancies or faults with the product discovered in the virtual reality environment must still be addressed (and fixed) by returning to the CAD environment to adjust the models or drawings of the object.

1.5.2 Computer Simulation and Animation

Computer simulation is the precise modeling and depiction of complex situations that involve a time or behavioral element. The 3-D computer model is often used instead of a physical model to analyze a product for material behavior properties, fluid dynamics characteristics, and many other analyses. Material properties can be assigned to a computer model in the simulation software so that it behaves and looks like the real product. For example, instead of a scale model of a new aircraft being made and tested in a wind tunnel, a computer model can be used to simulate the aircraft in the wind-tunnel test (Figure 1.32).

Computer animation is the imprecise modeling of complex situations that involve a time or behavioral element. The major difference between simulation and animation is the degree of precision. An animation only approximately replicates a real situation; a simulation accurately replicates a real situation. For example, to

determine the aerodynamic characteristics of an airplane using computer simulation, the aircraft and the fluid properties of air must be represented precisely, or inaccurate information will be obtained. On the other hand, if all that is needed is a visual representation of the aircraft in flight, then the computer model need not be precise, and an animation of the vehicle is sufficient.

1.5.3 Design Analysis

Design analysis is the evaluation of a proposed design, based on the criteria established in the ideation phase. It is the second major area within the refinement process, and the whole design team is involved. Typical analyses performed on designs include the following:

Property analysis, which evaluates a design based on its physical properties, such as strength, size, volume, center of gravity, weight, and center of rotation, as well as on its thermal, fluid, and mechanical properties.

Mechanism analysis, which determines the motions and loads associated with mechanical systems made of rigid bodies connected by joints.

Functional analysis, which determines if the design does what it is intended to do; in other words, if the design performs the tasks and meets the requirements specified in the ideation phase.

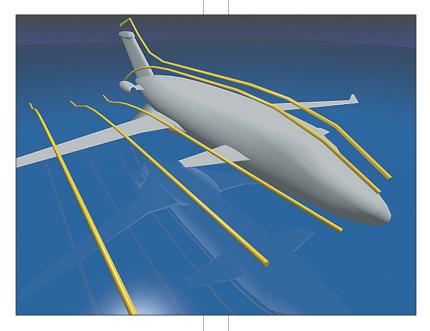


Figure 1.32 Computer model simulating an aircraft in a wind tunnel

The computer model supplements or replaces physical models in engineering analysis.

©Gary Bertoline

Human factors analysis, which evaluates a design to determine if the product serves the physical, emotional, quality, mental, and safety needs of the consumer.

Aesthetic analysis, which evaluates a design based on its aesthetic qualities.

Market analysis, which determines if the design meets the needs of the consumer, based on the results of surveys or focus groups.

Financial analysis, which determines if the price of the proposed design will be in the projected price range set during the ideation phase.

Property Analysis Normally, property analysis is associated with the engineering role in a company and includes finite element modeling. Property analysis determines if the product is safe and can stand up to the rigors of everyday use. Product models are tested under ordinary and extraordinary conditions, and the information gained can determine if changes must be made to the design. For example, a component might fail under extreme operating conditions. The design team then would recommend changes in the component itself (or in related parts of the product) to correct the deficiency, and the model then

would be reanalyzed. This iterative process is a major part of the design analysis phase.

Finite element modeling (FEM) is an analytical tool used in solid mechanics to determine the static and dynamic responses of components under various conditions, such as different temperatures (Figure 1.33). The fluid mechanics of designs also can be determined using FEM. The interaction of a part with a fluid flow, such as water or air, is simulated through the use of color bands. For example, Figure 1.34 shows motion analysis of an assembly. The range of motion is shown using a different color.

The FEM process uses the 3-D computer model as input. Through a process called discretization or meshing (Figure 1.35), the continuous 3-D solid model is changed into a model comprised of multiple polygonal shapes, such as rectangles and triangles, which are called "elements." Each corner of each element is called a "node." After discretization, the boundary conditions are defined. These conditions describe how an object is located in space. For example, an object bolted down to a surface is called fully constrained; in contrast, an object allowed to spin on a shaft is partially constrained. Once the boundary condition is defined, properties, such as material, temperature, and forces, are assigned to the model.

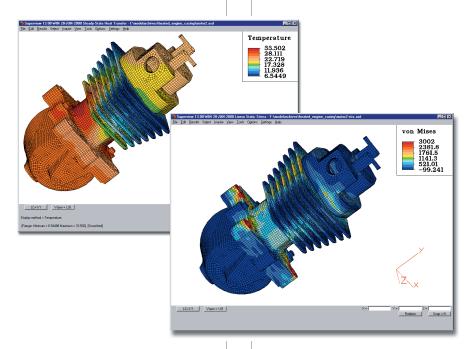


Figure 1.33 Thermal analysis

The use of color assists the user in visually determining the areas of high temperature. Blue is the coolest and red is the hottest area on this part.

Source: Algor, Inc. via Autodesk.



Figure 1.34 Motion analysis

A motion analysis of an assembly is determined using FEM. Source: Algor, Inc. via Autodesk.

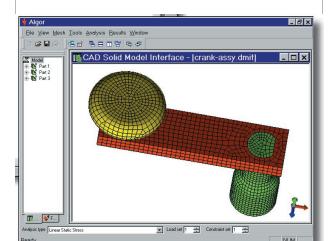


Figure 1.35 Discretization

Before a finite element analysis can be performed, the solid CAD model must be broken into smaller, discrete parts, using a process called discretization. Lines are added to the model after discretization to represent the boundaries of each discrete part of the model.

Source: Algor, Inc. via Autodesk.

The model is then evaluated under varying conditions. For example, stress forces are applied fully to a constrained model and the results are shown on screen in multiple colors (Figure 1.36). The colors represent



Figure 1.36 Boundary conditions applied

After the finite element model is created, the boundary conditions, such as temperature or load, are defined. The model is then analyzed by the computer. The results are shown using color, or by deforming the model if a load is applied.

Source: Algor, Inc. via Autodesk.

various levels of stress. The model might also deform to illustrate the effect of the forces being applied. The model even could be animated to show the deformation taking place and to show the incremental increases in the levels of stress. This process allows the designer to determine if the model will perform safely under normal and extreme operating conditions.

The results of the property analysis are used to recommend changes in the design. This analysis is a critical step in the refinement process.

Mechanism Analysis The process concerned with the calculation of motions and loads in mechanical systems comprised of rigid bodies connected by joints is called mechanism analysis. A clamping device is an example of such a system. Mechanism analysis includes assembly, kinematic, and dynamic analyses.

Assembly analysis is used to define the individual rigid bodies of the mechanism and to assemble them correctly, considering both geometry and velocities (Figure 1.37). When the computer model is used to make the assembly and assign the velocities, the computer uses the engineers' input to determine complex geometric and trigonometric relationships.

Kinematic analysis determines the motion of assemblies without regard to the loads. For example, kinematic analysis is used to find the position of any point on the mechanism at any time during movement of the assembly, to determine clearances and range of motion. Computer

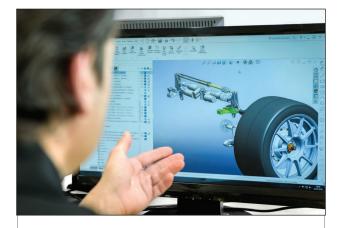


Figure 1.37 Assembly analysis

Assembly analysis to determine proper clearances between mating parts.

©Monty Rakusen/Getty Images RF

modeling can be used to trace motion paths in 3-D models (Figure 1.38).

Dynamic analysis determines the loads that drive or create the motion of a mechanism. This type of analysis can be in the form of a computer simulation, as described in the preceding section (Figure 1.39).

Functional Analysis The judgment process in which factors such as cost, appearance, profitability, marketability, and safety are used to determine the worth of a design is called **functional analysis**. Some factors are based on empirical evidence, such as product testing to see if it performs or functions as it was intended. For example, the design of a new computer printer could be tested to determine consistent print quality, frequency of failure, or cost relative to the intended market. In this example, the new printer would not be functional if it failed too often, cost too much, or produced poor print quality. The whole project might have to be modified by returning to the ideation phase.

Human Factors Analysis The process used to determine how a design interacts with the dimensions, range of motion, senses, and mental capabilities of the population that will use the product is called **human factors analysis**. For example, the human dimensions of the hand and the distance from the ear to the mouth are important attributes which must be taken into account in the design of a cellular phone and its dialing keypad. Human dimensions can be found in *The Measure of Man*, by Henry Dreyfuss.

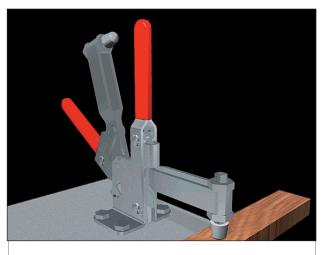


Figure 1.38 Kinematic analysis

The kinematic analysis of a mechanism is used to evaluate the range of motion during operation.

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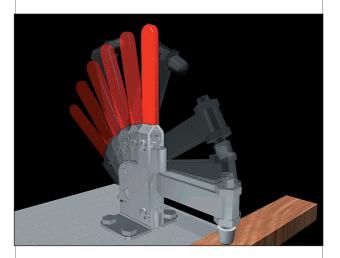


Figure 1.39 Dynamic analysis

This dynamic analysis of a clamp evaluates the forces involved with the movement of the mechanism.

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There is also computer software that can be used to define a human model, using such criteria as age, gender, build, race, and other factors. The human model thus created then is merged with the computer model of the product, and static and dynamic simulations are conducted.

The design of a product also must match human capabilities, as well as human dimensions. For example, can the controls of the cellular phone keypad be seen in a dimly lit room? Are they confusing to the novice user?

Quite often, the results of this human factors analysis are used to guide the development of graphics and text in the technical and user's manuals.

Aesthetic Analysis The process that evaluates a design based on aesthetic qualities is called aesthetic analysis. The look and feel of the product are analyzed by industrial designers, marketing personnel, environmental and human factors engineers, and the customer. This is the design process stage that is difficult to measure and quantify. However, it is important because this is where products are given the human touch that is so necessary in the design of most products and structures. Aesthetics are more important in some industries than in others. Also, in the design of automobile bodies, extensive aesthetic analyses are done to create a body style that is both pleasing and desirable. Aesthetic qualities are hard to quantify, yet they often make the difference in the product's success or failure in the marketplace.

Market and Financial Analyses A market analysis is performed before a product is sold or even produced. This market analysis determines the needs and wants of the customer so that the product produced is the product wanted by the consumer. A market analysis determines the demographic characteristics, such as age, gender, education, salary, geographic location, and so forth, of a typical consumer.

Financial analysis determines the capital available for a project, as well as the projected expenses to design, manufacture, assemble, market, and service a product. Financial analysis also determines the return on investment (ROI) that can be anticipated for a new product. The ROI is the ratio of annual profit to investment expected from a product.

1.6 Design Review Meetings

A design review is a formal meeting where the design team presents their progress to management. More experienced members of the design team prepare a presentation that might include calculations, charts and graphs, sketches, technical drawings, and 3-D models. It now is possible to have design review meetings across great distances using the Web and other Internet-based conferencing technologies. The purpose of the design review meeting is to determine if the design of the product is meeting its requirements and objectives and should continue or end. Later in the design phase, design review meetings occasionally are held to report progress and feedback from those outside the actual design team.

1.7 Implementation

Implementation is the third and final phase in collaborative engineering design and is the process used to change the final design from an idea into a product, process, or structure. At this point, the design is finalized and any changes become very expensive. The **implementation process** includes nearly every phase of the business, such as planning, production, financing, marketing, service, and documentation (Figure 1.40). The goal of this phase is to make the design solution a reality for the enterprise and the consumer. Just as the 3-D model was used to drive the refinement process, the model database also drives the implementation phase. Similarly, information from the implementation phase goes into the database for use in future product development.

1.7.1 Planning

The **planning process** determines the most effective method of moving a product through the production cycle. Manufacturing engineers and technologists are the leaders in the planning process, as they schedule the machines and jobs necessary to create the product. Planning requires process sheets, data and material flow diagrams, project modeling and work organization charts, bills of material, work instructions, assembly instructions, and other documents (Figure 1.41). Modern planning techniques use geometry and metadata derivatives of the 3-D CAD model created during the design stage as inputs to computeraided process planning (CAPP), material requirements

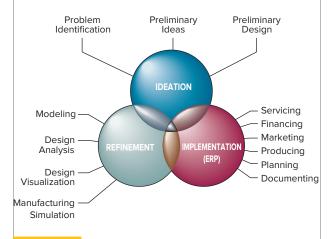


Figure 1.40 Implementation process

The implementation process includes nearly every phase of the business. In this phase of the design process, the final design moves from idea to final product.

Material Specs. Purchased Stock Size Pcs. Per Pur. Size Weight		Part Name		Date Issued Date Sup'd.		TA 1274	
Oper. No.	Operation Description		Dept.	Machine	Set Up Hr.	Rate Pc/Hr.	Tools
20	+.015 Drill 1 hole .32005		Drill	Mach 513 Deka 4	1.5	254	Drill Fixture L-76. Jig #10393
30	+.015 Deburr .312005 Dia. Hole		Drill	Mach 510 Drill	.1	424	Multi-Tooth burring Tool
40	Chamfer .900/.875, Bore .828/.875 dia. (2 Passes), Bore .7600/.7625 (1 Pass)		Lathe	Mach D109 Lathe	1.0	44	Ramet-1, TPG 221, Chamfer Tool
50	Tap Holes as designated - 1/4 Min. Full Thread		Tap	Mach 514 Drill Tap	2.0	180	Fixture #CR-353, Tap, 4 Flute Sp.
60	Bore Hole 1.133 to 1.138 D	ia.	Lathe	H & H E107	3.0	158	L44 Turrent Fixture. Hartford
							Superspacer, pl. #45, Holder #L46,
	***************************************						FDTW-100, Inser #21, Chk. Fixture
70	Deburr .005 to .010, Both Sides, Hand Feed To Hard Stop		Lathe	E162 Lathe	.5	176	Collect #CR179, 1327 RPM
80	Broach Keyway To Remove Thread Burrs		Drill	Mach. 507 Drill	.4	91	B87 Fixture, L59 Broach, Tap875120 G-H6
90	Hone Thread I.D. 822/.828		Grind	Grinder		120	
95	Hone .7600/.7625		Grind	Grinder		120	

Figure 1.41 Process plan

This process plan shows the machining operations, the tools used, setup time, and rate per hour. This level of planning is necessary to estimate cost and to ensure the smooth movement of parts during production.

planning (MRP), requirements management, and just-intime (JIT) scheduling software tools.

CAPP uses the computer model of the design to determine which machines and processes should be used. MRP calculates the raw materials needed to produce the product and uses solid models to assist in these calculations. For example, the solid model of a part can be analyzed to determine the volumes of various parts, and the results then can be used to calculate the amounts of different materials needed to make the parts.

Just-in-time (JIT) is an operational philosophy that tries to reduce cycle time while eliminating waste. Anything related to the manufacture of a product that does not add value to the product is considered waste. For example, inventory sitting idle in a warehouse for a long period of time does not add value to a product. A JIT system prevents waste by taking deliveries on orders only as they are needed.

1.7.2 Production

Production is the process used to transform raw materials into finished products and structures, using labor, equipment, capital, and facilities. The production process might require engineering drawings, change orders, technical specifications, bills of material, and many other documents depending on the nature of the company and

the product being produced. Drawings or 3-D models are used to lay out the factory floor, and computer models can be used to run machine tools that make the parts and simulate the assembly process and the movement of materials in the factory (Figure 1.42).

1.7.3 Marketing

The marketing process anticipates customer needs and directs the flow of goods from the producer to the consumer (Figure 1.43). Marketing plays a very important role in the ideation, refinement, and implementation stages and is much more than just selling or advertising: Marketing makes sure that the right products are produced and find their way to the consumer. To successfully sell a new product, marketing requires product illustrations and presentation graphics. Computer models and technical drawings can be used as the basis for creating the illustrations needed (Figure 1.44).

1.7.4 Finance

The **finance process** analyzes the feasibility of producing a product, relative to capital requirements and return on investment (ROI). In any enterprise, finance is the management of cash flow such that the means always are