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ENGINEERING DESIGN

SIXTH EDITION

George E. Dieter
University of Maryland

Linda C. Schmidt
University of Maryland

Mc Graw Hill

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ENGINEERING DESIGN: SIXTH EDITION

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Professor Dieter is a fellow of ASM International, TMS, AAAS, and ASEE. He has received the education award from ASM, TMS, and SME, as well as the Lamme Medal, the highest award of ASEE. He has been chair of the Engineering Deans Council, and president of ASEE. He is a member of the National Academy of Engineering. He also is the author of *Mechanical Metallurgy,* published by McGraw-Hill, now in its third edition.

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Dr. Schmidt is active in engineering design theory research and teaching engineering design to third- and fourth-year undergraduates and graduate students in mechanical engineering. She has coauthored a text on engineering decision-making, two editions of a text on product development, and a team-training curriculum for faculty using engineering student project teams. Dr. Schmidt was the guest editor of the *Journal of Engineering Valuation & Cost Analysis* and has served as an Associate Editor of the ASME *Journal of Mechanical Design.* Dr. Schmidt is a Fellow of ASME, and a member of SME and ASEE.

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ABBREVIATIONS AND ACRONYMS

AHP	Analytic Hierarchy Process
AM	Additive Manufacturing
ANSI	American National Standards Institute
ASTM	American Society for Testing and Material
BOM	Bill of Materials
CAE	Computer-Aided Engineering
CFD	Computational Fluid Dynamics
CIM	Computer-Integrated Manufacturing
COTS	Commercial Off-the-Shelf
CPM	Critical Path Method
CR	Customer Requirement
CTQ	Critical to Quality
DBD	Decision-Based Design
DFA	Design for Assembly
DFE	Design for the Environment
DFM	Design for Manufacture
DFMA	Design for Manufacture and Assembly
DV	Design Variable
EC	Engineering Characteristic
ERP	Enterprise Resource Planning
FEA	Finite Element Analysis
FMEA	Failure Modes and Effects Analysis
FTA	Fault Tree Analysis
GD&T	Geometric Dimensioning and Tolerancing
HOQ	House of Quality
ISO	International Organization for Standardization
JIT	Just-in-Time
LCC	Life-Cycle Costing
MARR	Minimum Attractive Rate of Return
MRP	Materials Requirements Planning
MTBF	Mean Time Between Failure
NDE	Nondestructive Evaluation
NIST	National Institute of Standards and Technology
OEM	Original Equipment Manufacturer
PDP	Product Design Process
PDS	Product Design Specification
PLM	Product Life-Cycle Management
QC	Quality Control
QFD	Quality Function Deployment
ROI	Return on Investment
RP	Rapid Prototyping
SPC	Statistical Process Control
SQC	Statistical Quality Control
TQM	Total Quality Management
TRIZ	Theory of Inventive Problem Solving
USPTO	United States Patent and Trademark Office
WBS	Work Breakdown Structure

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PREFACE TO SIXTH EDITION

THE SIXTH EDITION of *Engineering Design* continues its tradition of being more oriented to material selection, design for manufacturing, and design for quality than other broad-based design texts. The text is intended to be used in either a junior or senior engineering design course with an integrated, hands-on design project. At the University of Maryland, we present the design process material, Chapters 1 through 9, to junior students in a course introducing the design process. The whole text is used in the senior capstone design course that includes a complete design project, starting from selecting a market to creating a working prototype. Our intention is that students will consider this book to be a valuable part of their professional library. Toward this end we have continued and expanded the practice of giving key literature references and referrals to useful websites.

There has been a noteworthy reordering of chapters in the sixth edition so to as align them more closely to the overall design process utilized by this text. While the size of the printed book has been reduced, the scope of the text remains the same, with a few new and valuable sections.

New Topics

- Information Literacy
- Introduction to WordTree
- Biomimicry Design Generation Methods

A significant change in this edition has been to move theoretical and historical content online. This material is tangential to core information and may divert student attention from the application of the design process. One example of moved material includes sections on decision theory, decision trees, and utility theory from Chapter 7. Another change is in the presentation of total quality management (TQM): The printed text demonstrates TQM tools in an example, and a second example is given in the online material. Another example of material moved online involves the process-specific define manufacturing and assembly guidelines.

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Online Chapters

- Chapter 15: Design for Sustainability and the Environment
- Chapter 16: Design with Materials
- Chapter 17: Economic Decision Making
- Chapter 18: Legal and Ethical Issues in Engineering Design

Assigning online chapter material to students provides the opportunity for students to build on their concept design decisions and demonstrate independent learning. This material is easily accessible at www.mhhe.com/dieter6e.

Other instructor resources that can be found online include:

- Solutions Manual
- Lecture PowerPoints
- Image Library
- Guidelines for Design Reports and Sheets

ACKNOWLEDGMENTS

We want to acknowledge the willingness of students from our senior design course for permission to use material from their report in some of our examples. The JSR Design Team members are Josiah Davis, Jamil Decker, James Maresco, Seth McBee, Stephen Phillips, and Ryan Quinn. Special thanks to Peter Sandborn, Chandra Thamire, and Guangming Zhang, our colleagues in the Mechanical Engineering Department, University of Maryland, for their willingness to share their knowledge with us.

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College Park, MD
2020

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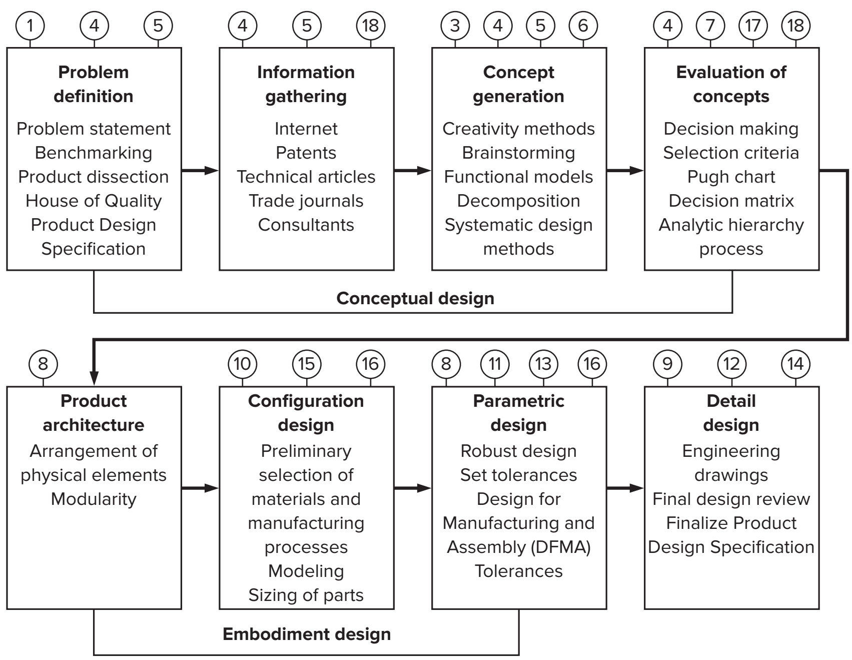
ROAD MAP TO *ENGINEERING DESIGN*



CHAPTER 1 Engineering Design
CHAPTER 2 Product-Development Process
CHAPTER 3 Team Behavior and Tools
CHAPTER 4 Gathering Information
CHAPTER 5 Problem Definition and Need Identification
CHAPTER 6 Concept Generation
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1

ENGINEERING DESIGN

1.1 INTRODUCTION

What is design? If you search the literature for an answer to that question, you will find about as many definitions as there are designs. Perhaps the reason is that the process of design is such a common human experience. *Webster's Dictionary* says that to design is "to fashion after a plan," but that leaves out the essential fact that to design is to create something that has never been. Certainly an engineering designer practices design by that definition, but so does an artist, a sculptor, a composer, a playwright, or any another creative member of our society.

Thus, although engineers are not the only people who design things, it is true that the professional practice of engineering is largely concerned with design; it is often said that design is the essence of engineering. *To design is to pull together something new or to arrange existing things in a new way to satisfy a recognized need of society.* An elegant word for "pulling together" is *synthesis*. We shall adopt the following formal definition of design: "Design establishes and defines solutions to and pertinent structures for problems not solved before, or new solutions to problems which have previously been solved in a different way."[1] The ability to design is both a science and an art. The science can be learned through techniques and methods to be covered in this text, but the art is best learned by doing design. It is for this reason that your design experience must involve some realistic project experience.

The emphasis that we have given to the creation of new things in our introduction to design should not unduly alarm you. To become proficient in design is a perfectly attainable goal for an engineering student, but its attainment requires the guided experience that we intend this text to provide. Design should not be confused with discovery. Discovery is getting the first sight of, or the first knowledge of something, as when Sir Isaac Newton discovered the concept of gravity. We can discover what has already existed but has not been known before, but a design is the product of

1. Blumrich, Josef F. "Design." *Science* 168, no. 3939 (1970): 1551–1554.

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planning and work. We will present a structured design process to assist you in doing design in Section 1.5.

We should note that a design may or may not involve *invention*. To obtain a legal patent on an invention requires that the design be a step beyond the limits of the existing knowledge (beyond the state of the art). Some designs are truly inventive, but most are not.

Design can be defined as either a noun or a verb. As a noun, it can be defined as specific parts or features of an item according to a plan, as in "My new design is ready for review." The definition as a verb is to formulate a plan for something, as in "I have to design three new models of the product for three different overseas markets." Note that the verb form of *design* is also written as "designing." Often the phrase "design process" is used to emphasize the use of the verb form of *design*. It is important to understand these differences and to use the word appropriately.

Good design requires both analysis and synthesis. Typically we approach complex problems like design by *decomposing* the problem into manageable parts. Because we need to understand how the part will perform in service, we must be able to calculate as much about the part's expected behavior as possible before it exists in physical form by using the appropriate disciplines of science and engineering science and the necessary computational tools. This is called *analysis*. It usually involves the simplification of the real world through models. *Synthesis* involves the identification of the design elements that will comprise the product, its decomposition into parts, and the combination of the part solutions into a total workable system.

One thing that should be clear by now is how engineering design extends well beyond the boundaries of science. The expanded boundaries and responsibilities of engineering create almost unlimited opportunities. A professional career in engineering will provide the opportunity to create dozens of designs and have the satisfaction of seeing them become working realities. "A scientist will be lucky if he makes one creative addition to human knowledge in his whole life, and many never do. A scientist can discover a new star but he cannot make one. He would have to ask an engineer to do it for him."[1]

1.2 ENGINEERING DESIGN PROCESS

The engineering design process can be used to achieve several different outcomes. One is the design of products, whether they be consumer goods such as refrigerators, power tools, or DVD players, or highly complex products such as a missile system or a jet transport plane. Another is a complex engineered system such as an electrical power generating station or a petrochemical plant, while yet another is the design of a building or a bridge. However, the emphasis in this text is on product design

1. Glegg, Gordon Lindsay. *The Design of Design*. Cambridge University Press, 1969, 1.

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because it is an area in which many engineers will apply their design skills. Moreover, examples taken from this area of design are easier to grasp without extensive specialized knowledge. This chapter presents the engineering design process from three perspectives. In Section 1.3 the design method is contrasted with the scientific method, and design is presented as a five-step problem-solving methodology. Section 1.4 takes the role of design beyond that of meeting technical performance requirements and introduces the idea that design must meet the needs of society at large. Section 1.5 lays out a cradle-to-the-grave road map of the design process, showing that the responsibility of the engineering designer extends from the creation of a design until its embodiment is disposed of in an environmentally safe way. Chapter 2 extends the engineering design process to the broader issue of product development by introducing more business-oriented issues such as product positioning and marketing.

1.2.1 Importance of the Engineering Design Process

In the 1980s when companies in the United States first began to seriously feel the impact of quality products from overseas, it was natural for them to place an emphasis on reducing their manufacturing costs through automation and moving plants to lower-labor-cost regions. However, it was not until the publication of a major study of the National Research Council (NRC)[1] that companies came to realize that the real key to world-competitive products lies in high-quality product design. This has stimulated a rash of experimentation and sharing of results about better ways to do product design. What was once a fairly cut-and-dried engineering process has become one of the cutting edges of engineering progress. This text aims at providing you with insight into the current best practices for doing engineering design.

The importance of design is nicely summed up in Figure 1.1. This shows that only a small fraction of the cost to produce a product (≈5 percent) is involved with the design process, while the other 95 percent of cost is consumed by the materials, capital, and labor to manufacture the product. However, the design process consists of the accumulation of many decisions that result in design commitments that affect about 70 to 80 percent of the manufactured cost of the product. In other words, the decisions made beyond the design phase can influence only about 25 percent of the total cost. If the design proves to be faulty just before the product goes to market, it will cost a great deal of money to correct the problem. To summarize: *Decisions made in the design process cost very little in terms of the overall product cost but have a major effect on the cost of the product*.

The second major impact of design is on product quality. The old concept of product quality was that it was achieved by inspecting the product as it came off the production line. Today we realize that true quality is designed into the product. Achieving quality through product design will be a theme that pervades this book. For now we point out that one aspect of quality is to incorporate within the product

1. "Improving Engineering Design," National Academy Press, Washington, D.C., 1991.

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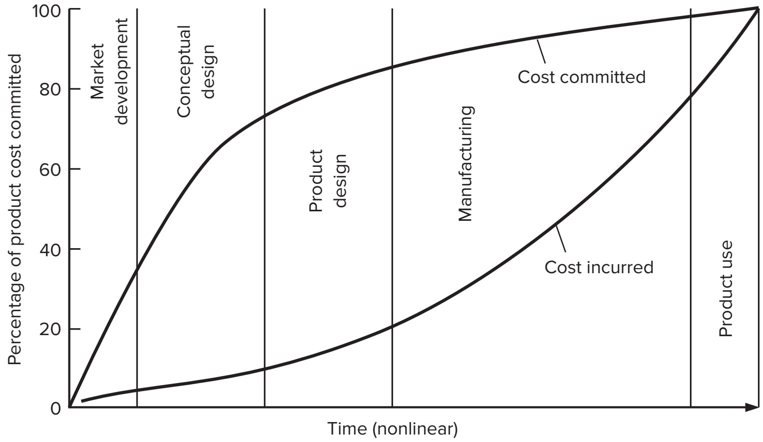

FIGURE 1.1
Product cost commitment during phases of the design process. (*After Ullman.*)

the performance and features that are truly desired by the customer who purchases the product. In addition, the design must be carried out so that the product can be made without defect at a competitive cost. To summarize: *You cannot compensate in manufacturing for defects introduced in the design phase*.

The third area where engineering design determines product competitiveness is product cycle time. Cycle time refers to the development time required to bring a new product to market. In many consumer areas the product with the latest "bells and whistles" captures the customers' fancy. The use of new organizational methods, the widespread use of computer-aided engineering, and rapid prototyping methods are contributing to reducing product cycle time. Not only does reduced cycle time increase the marketability of a product, but it reduces the cost of product development. Furthermore, the longer a product is available for sale the more sales and profits there will be. To summarize: *The design process should be conducted so as to develop quality, cost-competitive products in the shortest time possible*.

1.2.2 Types of Designs

Engineering design can be undertaken for many different reasons, and it may take different forms.

- *Original design*, also called *innovative design*. This form of design is at the top of the hierarchy. It employs an original, innovative concept to achieve a need. Sometimes, but rarely, the need itself may be original. A truly original design involves invention. Successful original designs occur rarely, but when they do occur they usually disrupt existing markets because they have in them the seeds of new technology of far-reaching consequences. The design of the microprocessor was one such original design.

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- *Adaptive design*. This form of design occurs when the design team adapts a known solution to satisfy a different need to produce a *novel application*. For example, adapting the ink-jet printing concept to spray binder to hold particles in place in a rapid prototyping machine.
- *Redesign*. Much more frequently, engineering design is employed to improve an existing design. The task may be to redesign a component in a product that is failing in service, or to redesign a component so as to reduce its cost of manufacture. Often redesign is accomplished without any change in the working principle or concept of the original design. For example, the shape may be changed to reduce a stress concentration, or a new material substituted to reduce weight or cost. When redesign is achieved by changing some of the design parameters, it is often called *variant design.*
- *Selection design.* Most designs employ standard components such as bearings, small motors, or pumps that are supplied by vendors specializing in their manufacture and sale. Therefore, in this case the design task consists of selecting the components with the needed performance, quality, and cost from the catalogs of potential vendors.

1.3 WAYS TO THINK ABOUT THE ENGINEERING DESIGN PROCESS

We often talk about "designing a system." By a system we mean the entire combination of hardware, information, and people necessary to accomplish some specified task. A system may be an electric power distribution network for a region of the nation, a complex piece of machinery such as an aircraft jet engine, or a combination of production steps to produce automobile parts. A large system usually is divided into *subsystems*, which in turn are made up of *components* or *parts*. The subsystems selected for the system's design are usually already existing products. For example, planes used for commercial flights can include lightweight liquid-crystal display (LCD) screens mounted on the back of each head rest. The design of the plane is a system design. The LCD screen is an already designed product that is selected as a subsystem for the plane.

1.3.1 A Simplified Iteration Model

There is no single universally accepted sequence of steps that leads to a workable design. Different writers or designers have outlined the design process in as few as 5 steps or as many as 25. Morris Asimow[1] was one of the first to write introspectively about design. He viewed the design process as a transformation of specific information on needs and general information on technology to produce a design outcome that must be evaluated (Figure 1.2). If the evaluation uncovers deficiencies

1. M. Asimow, *Introduction to Design,* Prentice-Hall, Englewood Cliffs, NJ, 1962.

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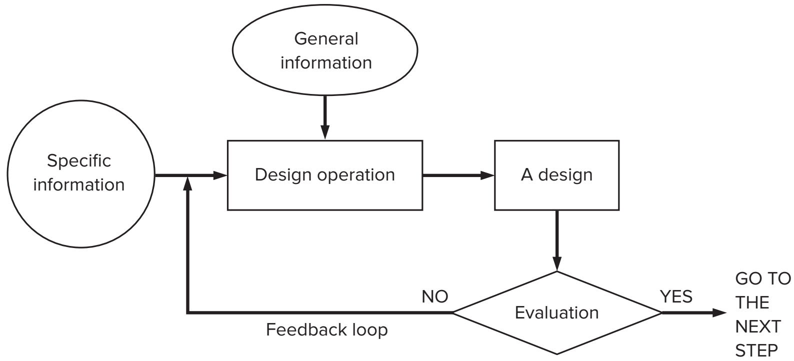

FIGURE 1.2
Basic module in the design process. (*After Asimow*.)

the design operation must be repeated. The information from the first design and all that was learned through the evaluation is fed back into the design process as input. This type of repetition is called *iteration*. Acquisition of information is a vital and often a very difficult step in the design process. The importance of sources of information is considered more fully in Chapter 4.

Once armed with the necessary information, the design team (or design engineer if the task is rather limited) carries out the design operation by using the appropriate technical knowledge through computational or experimental methods. At this stage it may be necessary to use an ideation process to generate a set of alternative design concepts. Then a decision-making method is used to select one of the alternative concepts to pursue. Next the design team may construct a mathematical model and conduct a simulation of the design performance on a computer, or construct a prototype model and test it for performance. After the design is set, the result must be evaluated for fitness.

1.3.2 Design Method Versus Scientific Method

In your scientific and engineering education you may have heard reference to the scientific method, a logical progression of events that leads to the solution of scientific problems. Percy Hill[1] has diagramed the comparison between the scientific method and the design method (Figure 1.3). The scientific method starts with a body of existing knowledge based on observed natural phenomena. Scientists have curiosity that causes them to question these laws of science; and as a result of their questioning, they eventually formulate a hypothesis. The hypothesis is subjected to logical analysis that either confirms or denies it. Often the analysis

1. P. H. Hill, *The Science of Engineering Design,* Holt, Rinehart and Winston, New York, 1970.

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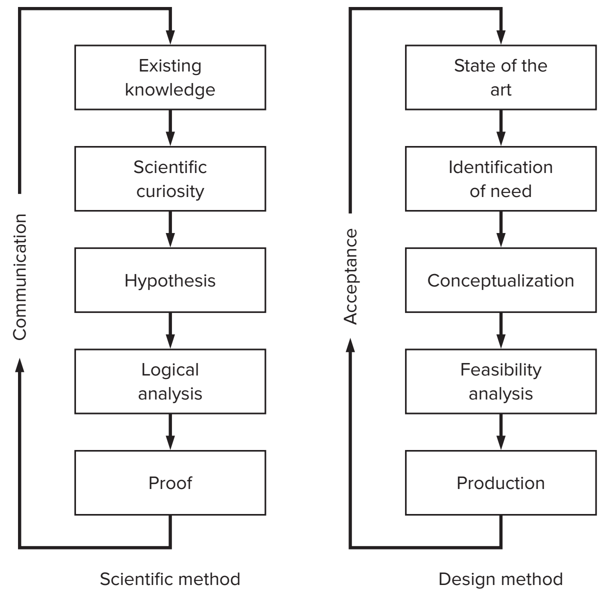

FIGURE 1.3
Comparison between the scientific method and the design method. (*After Percy Hill*.)

reveals flaws or inconsistencies, so the hypothesis must be changed in an iterative process.

Finally, when the new idea is confirmed to the satisfaction of its originator, it must be accepted as proof by fellow scientists. Once accepted, it is communicated to the community of scientists and it enlarges the body of existing knowledge. The knowledge loop is completed.

The design method is very similar to the scientific method if we allow for differences in viewpoint and philosophy. The design method starts with knowledge of the state of the art. That includes scientific knowledge, but it also includes devices, components, materials, manufacturing methods, and market and economic conditions. Rather than scientific curiosity, it is really the needs of society (usually expressed through economic factors) that provide the impetus. When a need is identified, it must be conceptualized as some kind of model. The purpose of the model is to help us predict the behavior of a design once it is converted to physical form. The outcomes of the model, whether it is a mathematical or a physical model, must be subjected to a feasibility analysis, almost always with iteration, until an acceptable product is produced or the project is abandoned. When the design enters the production phase, it begins to compete in the world of technology. The design loop is closed when the product is accepted as part of the current technology and thereby advances the state of the art of the particular area of technology.

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A more philosophical differentiation between science and design has been advanced by the Nobel Prize–winning economist Herbert Simon.[1] He points out that science is concerned with creating knowledge about naturally occurring phenomena and objects, while design is concerned with creating knowledge about phenomena and *objects of the artificial*. Artificial objects are those made by humans rather than nature. Thus, science is based on studies of the observed, while design is based on artificial concepts characterized in terms of functions, goals, and adaptation.

In the preceding brief outline of the design method, the identification of a need requires further elaboration. Needs are identified at many points in a business or organization. Most organizations have research or development departments whose job is to create ideas that are relevant to the goals of the organization. A very important avenue for learning about needs is the customers for the product or services that the company sells. Managing this input is usually the job of the marketing organization of the company. Other needs are generated by government agencies, trade associations, or the attitudes or decisions of the general public. Needs usually arise from dissatisfaction with the existing situation. The need drivers may be to reduce cost, increase reliability or performance, or just change because the public has become bored with the product.

1.3.3 A Problem-Solving Methodology

Designing can be approached as a problem to be solved. Many engineering science subjects use a traditional problem-solving process. These subjects include introductory statics, dynamics, and fluid mechanics. The problems in these subjects are clearly defined and usually have a single, correct answer. Engineering science problem solving is used when analyzing component performance and evaluating component options. These components usually comprise a larger subsystem than has previously been designed.

In contrast to engineering science problem solving, engineering design tasks are ill defined and have multiple solution alternatives. A design process has different steps than a traditional problem-solving process. A general description of the design process consists of the following steps.

- Definition of the problem
- Gathering of information
- Generation of alternative solutions
- Evaluation of alternatives and decision making
- Communication of the results

Design is iterative. *Iterative* means that a design team often must return to an earlier step in the process and repeat the steps, to move forward. This is often the result of new information based on the design team's work.

1. H. A. Simon, *The Sciences of the Artificial,* 3rd ed., The MIT Press, Cambridge, MA, 1996.

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Definition of the Problem

The most critical step in the solution of a problem is the *problem definition* or formulation. The true task is not always what it seems at first glance. The importance of problem definition is often overlooked because this step seemingly requires such a small part of the total design time. Figure 1.4 illustrates how the final design can differ greatly depending upon how the problem is defined.

The formulation of the problem should start by writing down a problem statement. The problem statement should express, as specifically as possible, the details of the design task. It should include definition of any special technical terms, performance objectives, the design of similar products, and any constraints placed on solution of the problem. The problem-definition step in a design project is covered in detail in Chapter 5.

Problem definition often is called *needs analysis*, *identification of customer requirements*, or *problem identification*. It is difficult to accurately determine the details of the design task at the beginning of the process for all but the most routine design task. New needs are established as the design process proceeds because new information is obtained throughout the process. There is a paradox inherent in the design process between the accumulation of problem (domain) knowledge and freedom to improve the design. When one is creating an original design, very little is known about its solution. As the design team proceeds with its work, it

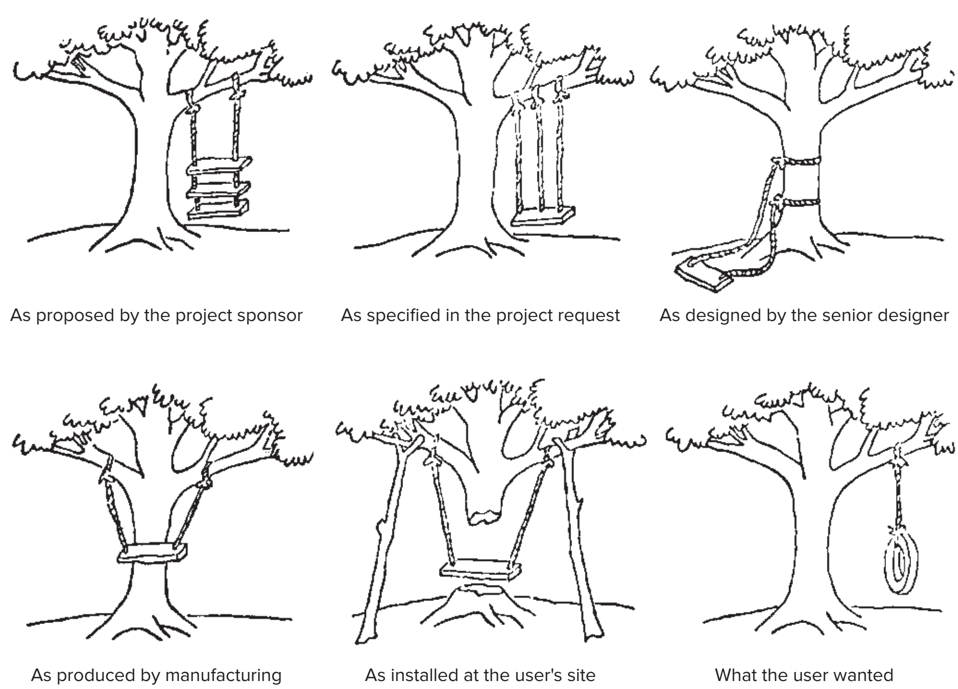

FIGURE 1.4
Note how the design depends on the viewpoint of the individual who defines the problem.

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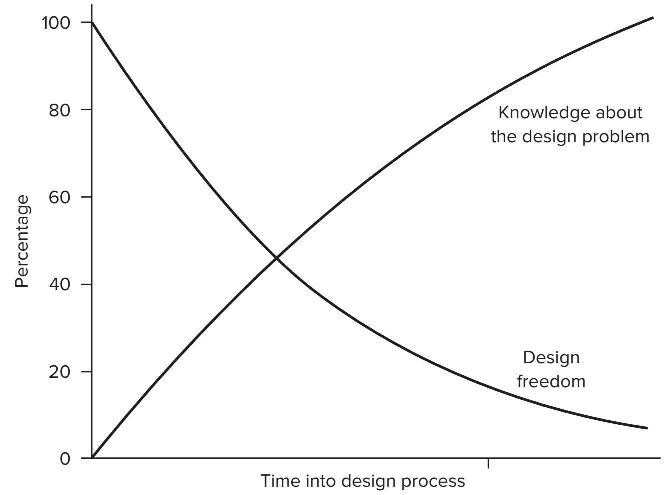

FIGURE 1.5
The design paradox between design knowledge and design freedom.

acquires more knowledge about the technologies involved and the possible solutions (Figure 1.5). The team has moved up the learning curve.

Gathering Information

The most critical step in the design process is identifying the information you need and acquiring it. This is challenging because the design task typically requires information from more than one discipline. The knowledge of new and best practices in engineering is continually changing. This is one reason why an engineer must develop a habit of lifelong learning.

Technical reports published as a result of government-sponsored research and development (R&D), company reports, trade journals, patents, catalogs, and handbooks and literature published by vendors and suppliers of material and equipment are important sources of information. The Internet is a very useful resource. Often the missing piece of information can be supplied by an Internet search, or by a telephone call or an e-mail to a key supplier. Discussions with in-house experts (often in the corporate R&D center) and outside consultants may prove helpful.

The following are some of the questions concerned with obtaining information:

- What do I need to find out?
- Where can I find it and how can I get it?
- How credible and accurate is the information?
- How should the information be interpreted for my specific need?
- When do I have enough information?
- What decisions result from the information?

Some suggestions for finding relevant information can be found in Chapter 4.

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Generation of Alternative Solutions

The ability to generate high-quality design alternatives is vital to successful design. Generating alternative solutions or design concepts involves the use of creativity-stimulation methods, the application of physical principles, quantitative reasoning, the ability to find and use information, and experience. An essential difference between traditional problem solving and design is that the design process generates multiple solutions. Therefore, the design process must include a step to evaluate the alternative design solutions and select the best alternative. This important subject is covered in Chapter 6.

Evaluation of Alternatives and Decision Making

The evaluation of alternatives involves systematic methods for selecting the best among several concepts, often in the face of incomplete information. Engineering analysis procedures provide the basis for making decisions about performance. Design for manufacturing analyses (Chapter 11) and cost estimation (Chapter 12) provide other important information. Various other types of engineering analysis also provide information. Simulation of performance with computer models is commonly used. Simulated service testing of an experimental model and testing of full-sized prototypes often provide critical data. Without this quantitative information it is not possible to make valid evaluations. Several methods for evaluating design concepts, or any other problem solutions, are given in Chapter 7.

Communication of the Results

It must always be kept in mind that the purpose of the design is to satisfy the needs of an internal review, a customer, or a client. The finalized design must be properly recorded and communicated, or it may lose much of its impact or significance. The communication is usually by oral presentation to the sponsor or review committee and by a written design report. Detailed engineering drawings, computer programs, three-dimensional (3-D) computer models, and working models are frequently among the "deliverables" to the customer.

It hardly needs to be emphasized that communication is not a one-time occurrence to be carried out at the end of the project. In a well-run design project there is continual oral and written dialog between the project manager and the customer.

Thus, as Figure 1.5 shows, the freedom of the team to go back and start over with their newly gained knowledge (experience) decreases greatly as their knowledge about the design problem grows. At the beginning the designer has the freedom to make changes without great cost penalty, but may not know what to do to make the design better. The paradox comes from the fact that when the design team finally masters the problem, their design is essentially frozen because of the great penalties involved with a change. The solution is for the design team to learn as much about the problem as early in the design process as it possibly can. This also places high priority on the team members learning to work independently toward a common goal (Chapter 3), being skilled in gathering information (Chapter 4), and being good at communicating relevant knowledge to their teammates. Design team members must become stewards of the knowledge they acquire. Figure 1.5 also shows why it is important to document in detail what has been done, so that the experience can be used by subsequent teams in future projects.

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1.4 DESCRIPTION OF DESIGN PROCESS

Morris Asimow[1] was among the first to give a detailed description of the complete design process in what he called the morphology of design. Figure 1.6 shows the various activities that make up the first three phases of design: conceptual design, embodiment design, and detail design. The purpose of this graphic is to remind you of the logical sequence of activities that leads from problem definition to the detail design.

1.4.1 Phase I. Conceptual Design

Conceptual design is the process by which the design is initiated, carried to the point of creating a number of possible solutions, and narrowed down to a single best concept. It is sometimes called the feasibility study. Conceptual design is the phase that requires the greatest creativity, involves the most uncertainty, and requires coordination among many functions in the business organization. The following are the discrete activities that we consider under conceptual design.

- *Identification of customer needs*: The goal of this activity is to completely understand the customers' needs and to communicate them to the design team.
- *Problem definition*: The goal of this activity is to create a statement that describes what has to be accomplished to satisfy the needs of the customer. This involves analysis of competitive products, the establishment of target specifications, and the listing of constraints and trade-offs. Quality function deployment (QFD) is a valuable tool for linking customer needs with design requirements. A detailed listing of the product requirements is called a product design specification (PDS). Problem definition, in its full scope, is treated in Chapter 5.
- *Gathering information*: Engineering design presents special requirements over engineering research in the need to acquire a broad spectrum of information. This subject is covered in Chapter 4.
- *Conceptualization*: Concept generation involves creating a broad set of concepts that potentially satisfy the problem statement. Team-based creativity methods, combined with efficient information gathering, are the key activities. This subject is covered in Chapter 6.
- *Concept selection*: Evaluation of the design concepts, modifying and evolving into a single preferred concept, are the activities in this step. The process usually requires several iterations. This is covered in Chapter 7.
- *Refinement of the PDS*: The product design specification is revisited after the concept has been selected. The design team must commit to achieving certain critical values of design parameters, usually called critical-to-quality (CTQ) parameters, and to living with trade-offs between cost and performance.
- *Design review*: Before committing funds to move to the next design phase, a design review will be held. The design review will ensure that the design is physically

1. I. M. Asimow, *Introduction to Design,* Prentice-Hall, Englewood Cliffs, NJ, 1962.

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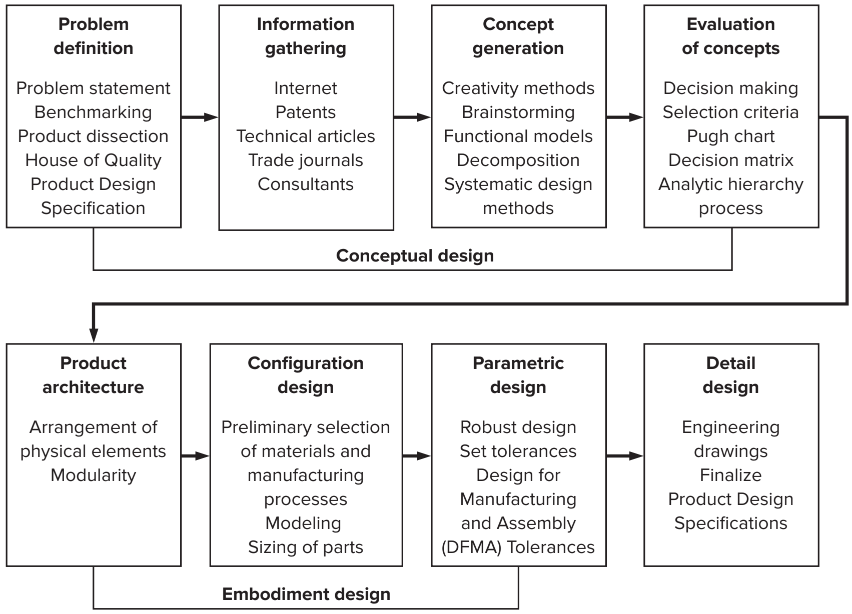

FIGURE 1.6
The design activities that make up the first three phases of the engineering design process.

realizable and that it is economically worthwhile. It will also look at a detailed product-development schedule. This is needed to devise a strategy to minimize product cycle time and to identify the resources in people, equipment, and money needed to complete the project.

1.4.2 Phase II. Embodiment Design

Structured development of the design concept occurs in this engineering design phase. It is the place where flesh is placed on the skeleton of the design concept. An embodiment of all the main functions that must be performed by the product must be undertaken. It is in this design phase that decisions are made on strength, material selection, size, shape, and spatial compatibility. Beyond this design phase, major changes become very expensive. This design phase is sometimes called preliminary design. Embodiment design is concerned with three major tasks—product architecture, configuration design, and parametric design.

- *Determining product architecture*: Product architecture is concerned with dividing the overall design system into subsystems or modules. In this step we decide how the physical components of the design are to be arranged and combined to carry out the functional duties of the design.
- *Configuration design of parts and components*: Parts are made up of features such as holes, ribs, splines, and curves. Configuring a part means to determine what

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features will be present and how those features are to be arranged in space relative to each other. While modeling and simulation may be performed in this stage to check out function and spatial constraints, only approximate sizes are determined to ensure that the part satisfies the PDS. Also, more specificity about materials and manufacturing is given here. The generation of a physical model of the part with rapid prototyping processes may be appropriate.

- *Parametric design of parts*: Parametric design starts with information on the configuration of the part and aims to establish its exact dimensions and tolerances. Final decisions on the material and manufacturing processes are also established if this has not been done previously. An important aspect of parametric design is to examine the part, assembly, and system for design robustness. *Robustness* refers to how consistently a component performs under variable conditions in its service environment. The methods developed by Dr. Genichi Taguchi for achieving robustness and establishing the optimum tolerance are discussed in Chapter 14. Parametric design also deals with determining the aspects of the design that could lead to failure (see Chapter 13). Another important consideration in parametric design is to design in such a way that manufacturability is enhanced (see Chapter 11).

1.4.3 Phase III. Detail Design

In this phase the design is brought to the stage of a complete engineering description of a tested and producible product. Missing information is added on the arrangement, form, dimensions, tolerances, surface properties, materials, and manufacturing processes of each part. This results in a specification for each *special-purpose part* and for each *standard part* to be purchased from suppliers. In the detail design phase the following activities are completed and documents are prepared:

- Detailed engineering drawings suitable for manufacturing. Routinely these are computer-generated drawings, and they often include 3-D CAD models.
- Verification testing of prototypes is successfully completed and verification data is submitted. All CTQ parameters are confirmed to be under control. Usually the building and testing of several preproduction versions of the product will be accomplished.
- Assembly drawings and assembly instructions also will be completed. The bill of materials for all assemblies will be completed.
- A detailed product specification, updated with all the changes made since the conceptual design phase, will be prepared.
- Decisions on whether to make each part internally or to buy from an external supplier will be made.
- With the preceding information, a detailed cost estimate for the product will be carried out.
- Finally, detail design concludes with a design review before the decision is made to pass the design information on to manufacturing.

Phases I, II, and III take the design from the realm of possibility to the real world of practicality. However, the design process is not finished with the delivery

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of a set of engineering drawings and specifications to the manufacturing organization. Many other technical and business decisions must be made to bring the design to the point where it can be delivered to the customer. Chief among these, as discussed in Section 9.5, are detailed plans for manufacturing the product, for planning its launch into the marketplace, and for disposing of it in an environmentally safe way after it has completed its useful life.

1.5 CONSIDERATIONS OF A GOOD DESIGN

Design is a multifaceted process. To gain a broader understanding of engineering design, we group various considerations of good design into three categories:

1. Achievement of performance requirements
2. Life-cycle issues
3. Social and regulatory issues

1.5.1 Achievement of Performance Requirements

It is obvious that to be feasible the design must demonstrate the required performance. Performance measures both the function and the behavior of the design, that is, how well the device does what it is designed to do. Performance requirements can be divided into primary performance requirements and complementary performance requirements. A major characteristic of a design is its *function*. The function of a design is how it is expected to behave. For example, the design may be required to grasp an object of a certain mass and move it 50 feet in 1 minute. Functional requirements are usually expressed in capacity measures such as forces, strength, deflection, or energy or power output or consumption. Complementary performance requirements are concerns such as the useful life of the design, its robustness to factors occurring in the service environment (see Chapter 14), its reliability (see Chapter 13), and ease, economy, and safety of maintenance. Issues such as built-in safety features and the noise level in operation must be considered. Finally, the design must conform to all legal requirements and design codes.

A product[1] is usually made up of a collection of parts, sometimes called piece-parts. A *part* is a single piece requiring no assembly. When two or more parts are joined it is called an *assembly.* Often large assemblies are composed of a collection of smaller assemblies called *subassemblies*. A similar term for part is *component*. The two terms are used interchangeably in this book, but in the design literature the word *component* sometimes is used to describe a subassembly with a small number of parts. Consider an ordinary ball bearing. It consists of an outer ring, inner ring, 10 or more balls depending on size, and a retainer to keep the balls from rubbing

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1. Another term for product is *device,* something devised or constructed for a particular purpose, such as a machine. Another term for a product is *artifact*, a man-made object.

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together. A ball bearing is often called a component, even though it consists of a number of parts.

Closely related to the function of a component in a design is its form. *Form* is what the component looks like and encompasses its shape, size, and surface finish. These, in turn, depend upon the material it is made from and the manufacturing processes that are used to make it.

A variety of analysis techniques must be employed in arriving at the features of a component in the design. By *feature* we mean specific physical attributes, such as the fine details of geometry, dimensions, and tolerances on the dimensions.[1] Typical geometrical features would be fillets, holes, walls, and ribs. The computer has had a major impact in this area by providing powerful analytical tools based on finite-element analysis. Calculations of stress, temperature, and other field-dependent variables can be made rather handily for complex geometry and loading conditions. When these analytical methods are coupled with interactive computer graphics, we have the exciting capability known as computer-aided engineering (CAE); see Section 1.6. Note that with this enhanced capability for analysis comes greater responsibility for providing better understanding of product performance at early stages of the design process.

Environmental requirements for performance deal with two separate aspects. The first concerns the service conditions under which the product must operate. The extremes of temperature, humidity, corrosive conditions, dirt, vibration, and noise must be predicted and allowed for in the design. The second aspect of environmental requirements pertains to how the product will behave with regard to maintaining a safe and clean environment, that is, green design. Often governmental regulations force these considerations in design, but over time they become standard design practice. Among these issues is the disposal of the product when it reaches the end of its useful life. Design for the Environment (DFE) is discussed in detail in Chapter 15 (online at www.mhhe.com/dieter6e).

Aesthetic requirements refer to "the sense of the beautiful." They are concerned with how the product is perceived by a customer because of its shape, color, surface texture, and such factors as balance, unity, and interest. This aspect of design usually is the responsibility of the industrial designer, as opposed to the engineering designer. The industrial designer is in part an applied artist. Decisions about the appearance of the product should be an integral part of the initial design concept. An important design consideration is adequate attention to *human factors engineering,* which uses the sciences of biomechanics, ergonomics, and engineering psychology to ensure that the design can be operated efficiently by humans. It applies physiological and anthropometric data to such design features as visual and auditory display of instrument panel and control systems. It is also concerned with human muscle power and response times. The industrial designer often is responsible for considering the human factors. For further information, see Section 8.9.

Manufacturing technology must be closely integrated with product design. There may be restrictions on the manufacturing processes that can be used, because of either selection of material or availability of equipment within the company.

1. In product development the term *feature* has an entirely different meaning as "an aspect or characteristic of the product." For example, a product feature for a power drill could be a laser beam attachment for alignment of the drill when drilling a hole.

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The final major design requirement is cost. Every design has requirements of an economic nature. These include such issues as product development cost, initial product cost, life-cycle product cost, tooling cost, and return on investment. In many cases cost is the most important design requirement. If preliminary estimates of product cost look unfavorable, the design project may never be initiated. Cost enters into every aspect of the design process.

1.5.2 Total Life Cycle

The total life cycle of a part starts with the conception of a need and ends with the retirement and disposal of the product.

Material selection is a key element in shaping the total life cycle (see Chapter 10). In selecting materials for a given application, the first step is evaluation of the service conditions. Next, the properties of materials that relate most directly to the service requirements must be determined. Except in almost trivial conditions, there is never a simple relation between service performance and material properties. The design may start with the consideration of static yield strength, but properties that are more difficult to evaluate, such as fatigue, creep, toughness, ductility, and corrosion resistance, may have to be considered. We need to know whether the material is stable under the environmental conditions. Does the microstructure change with temperature and therefore change the properties? Does the material corrode slowly or wear at an unacceptable rate?

Material selection cannot be separated from *manufacturability* (see Chapter 11). There is an inherent connection between design and material selection and the manufacturing processes. The objective in this area is a trade-off between the opposing factors of minimum cost and maximum durability. *Durability* is increased by designing so as to minimize material deterioration by corrosion, wear, or fracture. It is a general property of the product measured by months or years of successful service, and is closely related to reliability, a technical term that is measured by the probability of achieving a specified service life. Current societal issues of energy conservation, material conservation, and protection of the environment result in new pressures in the selection of materials and manufacturing processes. Energy costs, once nearly ignored in design, are now among the most prominent design considerations. Design for materials recycling also is becoming an important design consideration.

The life cycle of production and consumption that is characteristic of all products is illustrated by the materials cycle shown in Figure 1.7. This starts with the mining of a mineral or the drilling for oil or the harvesting of an agricultural fiber such as cotton. These raw materials must be processed to extract or refine a bulk material (e.g., an aluminum ingot) that is further processed into a finished engineering material (e.g., an aluminum sheet). At this stage an engineer designs a product that is manufactured from the material, and the part is put into service. Eventually the part wears out or becomes obsolete because a better product comes on the market. At this stage, one option is to junk the part and dispose of it in some way that eventually returns the material to the earth. However, society is becoming increasingly concerned with the depletion of natural resources and the haphazard disposal of solid

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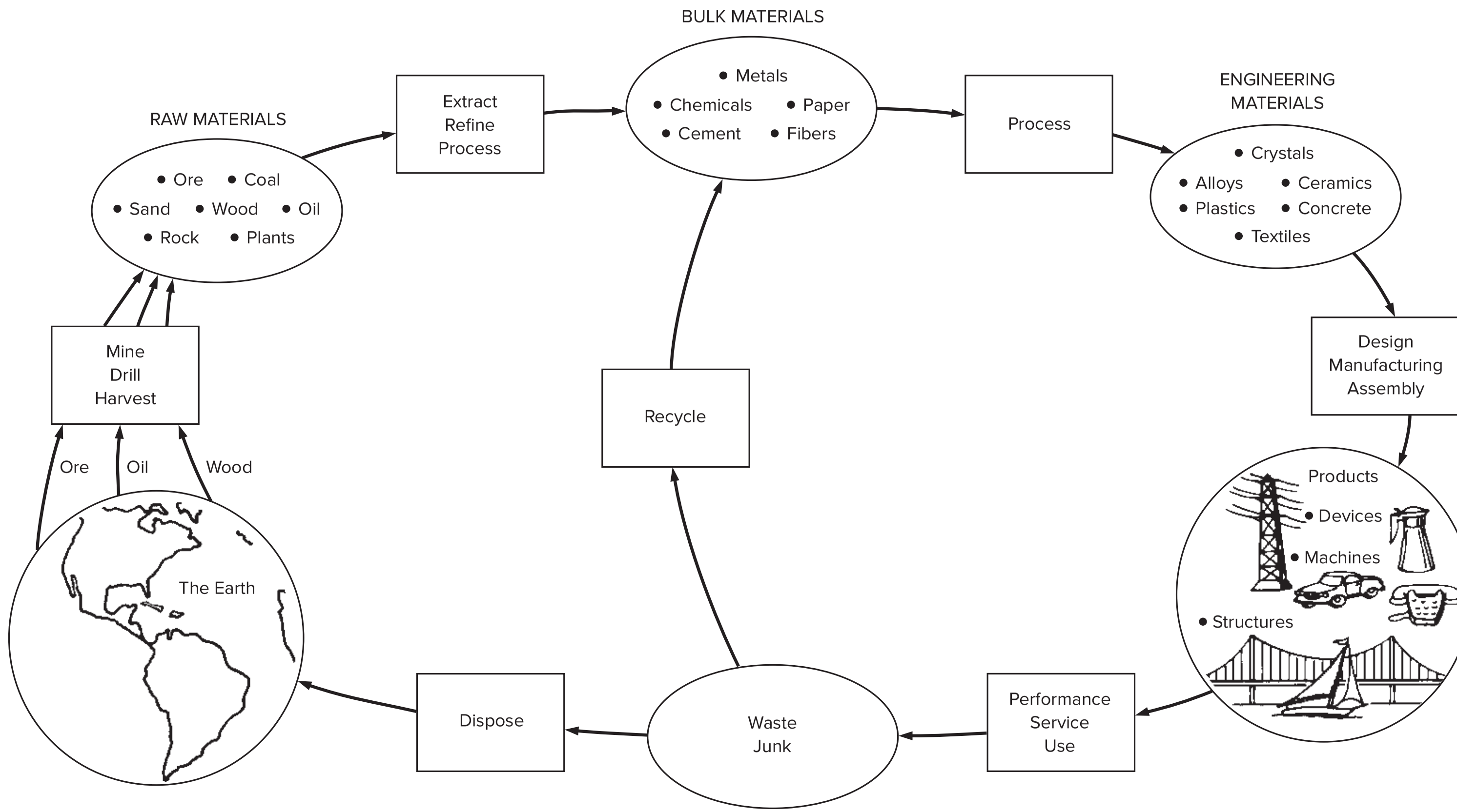

FIGURE 1.7
The total materials cycle. (*Materials and Man's Needs: Materials Science and Engineering*. Washington, DC: National Academy of Sciences, 1974.)

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materials. Thus, we look for economical ways to recycle waste materials (e.g., aluminum beverage cans).

1.5.3 Regulatory and Social Issues

Specifications and standards have an important influence on design practice. The standards produced by such societies as ASTM and International and American Society of Mechanical Engineers (ASME) represent voluntary agreement among many elements (users and producers) of industry. As such, they often represent minimum or least-common-denominator standards. When good design requires more than that, it may be necessary to develop your own company or agency standards.

The codes of ethics of all professional engineering societies require the engineer to protect public health and safety. Increasingly, legislation has been passed to require federal agencies to regulate many aspects of safety and health. The requirements of the Occupational Safety and Health Administration (OSHA), the Consumer Product Safety Commission (CPSC), the Environmental Protection Agency (EPA), and the Department of Homeland Security (DHS) place direct constraints on the designer in the interests of protecting health, safety, and security. Several aspects of the CPSC regulations have far-reaching influence on product design. Although the intended purpose of a product normally is quite clear, the unintended uses of that product are not always obvious. Under the CPSC regulations, the designer has the obligation to foresee as many unintended uses as possible, then develop the design in such a way as to prevent hazardous use of the product in an unintended but foreseeable manner. When unintended use cannot be prevented by functional design, clear, complete, unambiguous warnings must be permanently attached to the product. In addition, the designer must be cognizant of all advertising material, owner's manuals, and operating instructions that relate to the product to ensure that the contents of the material are consistent with safe operating procedures and do not promise performance characteristics that are beyond the capability of the design.

An important design consideration is adequate attention to human factors engineering, which uses the sciences of biomechanics, ergonomics, and engineering psychology to ensure that the design can be operated efficiently and safely. It applies physiological and anthropometric data to such design features as visual and auditory display of instruments and control systems. It is also concerned with human muscle power and response times. For further information, see Section 8.8.

1.6 COMPUTER-AIDED ENGINEERING

Plentiful computing has produced a major change in the way engineering design is practiced. The greatest impact of computer-aided engineering has been in engineering drawing. Three-dimensional solid modeling provides a complete geometric and mathematical description of the part geometry. Solid models can be sectioned to reveal interior details, or they can be readily converted into conventional

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two-dimensional (2-D) engineering drawings. Such a model is very rich in intrinsic information so that it can be used not only for physical design but also for analysis, design optimization, simulation, rapid prototyping, and manufacturing. For example, geometric 3-D modeling ties in nicely with the extensive use of finite-element modeling (FEM) and makes possible interactive simulations in such problems as stress analysis, fluid flow, the kinematics of mechanical linkages, and numerically controlled tool-path generation for machining operations.

The computer extends the designer's capabilities in several ways. First, by organizing and handling time-consuming and repetitive operations, it frees the designer to concentrate on more complex design tasks. Second, it allows the designer to analyze complex problems faster and more completely. Both of these factors make it possible to carry out more iterations of design. Finally, through a computer-based information system the designer can share more information sooner with people in the company, including manufacturing engineers, process planners, tool and die designers, and purchasing agents. Moreover, by using the Internet and satellite telecommunication, these persons can be on different continents 10 time zones away.

Team members perform their jobs in an overlapping and concurrent manner so as to minimize the time for product development. A computer database in the form of a solid model that can be accessed by all members of the design team, as in the Boeing 777 example, is a vital tool for this communication.

Computer-aided engineering became a reality when the power of the personal computer (PC) workstation, and later the laptop PC, became great enough at an

Boeing 777

The boldest example of the use of CAD is with the Boeing 777 long-range transport. Started in fall 1990 and completed in April 1994, this was the world's first completely paperless transport design. Employing the CATIA 3-D CAD system, it linked all of Boeing's design and manufacturing groups in Washington, as well as suppliers of systems and components worldwide. At its peak, the CAD system served some 7000 workstations spread over 17 time zones.

As many as 238 design teams worked on the project at a single time. Had they been using conventional paper design, they might have experienced many interferences among hardware systems, requiring costly design changes and revised drawings. This is a major cost factor in designing a complex system. The advantage of being able to see what everyone else was doing, through an integrated solid model and digital data system, saved in excess of 50 percent of the change orders and rework expected for a design of this magnitude.

The Boeing 777 has more than 130,000 unique engineered parts, and when rivets and other fasteners are counted, there are more than 3 million individual parts. The ability of the CAD system to identify interferences eliminated the need to build a physical model (mockup) of the airplane. Nevertheless, those experienced with transport design and construction reported that the parts of the 777 fit better the first time than those of any earlier commercial airliner.

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acceptable cost to free the design engineer from the limitations of the mainframe computer. Bringing the computing power of the mainframe computer to the desktop of the design engineer has created great opportunities for more creative, reliable, and cost-effective designs.

1.7 DESIGNING TO CODES AND STANDARDS

While we have often talked about design being a creative process, the fact is that much of design is not very different from what has been done in the past. There are obvious benefits in cost and time saved if the best practices are captured and made available for all to use. Designing with codes and standards has two chief aspects: (1) It makes the best practice available to everyone, thereby ensuring efficiency and safety, and (2) it promotes interchangeability and compatibility.

A *code* is a collection of laws and rules that assists a government agency in meeting its obligation to protect the general welfare by preventing damage to property or injury or loss of life to persons. A *standard* is a generally agreed-upon set of procedures, criteria, dimensions, materials, or parts. Engineering standards may describe the dimensions, tolerances, and sizes of small parts such as screws and bearings, the minimum properties of materials, or an agreed-upon procedure to measure a property such as fracture toughness.

The terms *standards* and *specifications* are sometimes used interchangeably. The distinction is that standards refer to generalized situations; specifications refer to specific designs. Codes tell the engineer what to do and when and under what circumstances to do it. Codes usually are legal requirements, as in the building code or the fire code. Standards tell the engineer how to do it and are usually regarded as recommendations that do not have the force of law. Codes often incorporate national standards into them by reference, and in this way standards become legally enforceable.

In addition to protecting the public, standards play an important role in reducing the cost of design and of products. The use of standard components and materials leads to cost reduction in many ways. The use of design standards saves the designer, when involved in original design work, from spending time on finding solutions to a multitude of recurring, identical problems. Moreover, designs based on standards provide a firm basis for negotiation and better understanding between the buyer and seller of a product. Failure to incorporate up-to-date standards in a design may lead to difficulties with product liability (see Chapter 18 online at www.mhhe.com/dieter6e).

The engineering design process is concerned with balancing four goals: proper function, optimum performance, adequate reliability, and low cost. The greatest cost saving comes from reusing existing parts in design. The main savings come from eliminating the need for new tooling in production and from a significant reduction in the parts that must be stocked to provide service over the lifetime of the product. In much of new product design only 20 percent of the parts are new, about 40 percent are existing parts used with minor modification, and the other 40 percent are existing parts reused without modification.

1.8
DESIGN REVIEW

The design review is a vital aspect of the design process. It provides an opportunity for specialists from different disciplines to interact with generalists to ask critical questions and exchange vital information. A *design review* is a retrospective study of the design up to that point in time. It provides a systematic method for identifying problems with the design, determining future courses of action, and initiating action to correct any problem areas.

Depending on the size and complexity of the product, design reviews should be held from three to six times in the life of the project. The minimum review schedule consists of conceptual, interim, and final reviews. The conceptual review occurs once the conceptual design (Chapter 7) has been established. This review has the greatest impact on the design, since many of the design details are still fluid and changes can be made at this stage with least cost. The interim review occurs when the embodiment design is finalized and the product architecture, subsystems, performance characteristics, and critical design parameters are established. It looks critically at the interfaces between the subsystems. The final review takes place at completion of the detail design and establishes whether the design is ready for transfer to manufacturing.

Each review looks at two main aspects. The first is concerned with the technical elements of the design; the second is concerned with the business aspects of the product (see Chapter 2). The essence of the technical review of the design is to compare the findings against the detailed product design specification that is formulated at the problem definition phase of the project. The PDS is a detailed document that describes what the design must be in terms of performance requirements, the environment in which it must operate, the product life, quality, reliability, cost, and a host of other design requirements. The PDS is the basic reference document for both the product design and the design review. The business aspect of the review is concerned with tracking the costs incurred in the project, projecting how the design will affect the expected marketing and sales of the product, and maintaining the time schedule. An important outcome of the review is to determine what changes in resources, people, and money are required to produce the appropriate business outcome. It must be realized that a possible outcome of any review is to withdraw the resources and terminate the project.

A formal design review process requires a commitment to good documentation of what has been done and a willingness to communicate this to all parties involved in the project. The minutes of the review meeting should clearly state what decisions were made and should include a list of "action items" for future work. Because the PDS is the basic control document, care must be taken to keep it always updated.

1.8.1 Redesign

A common situation is redesign. There are two categories of redesigns: *fixes* and *updates*. A fix is a design modification that is required due to less-than-acceptable

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performance once the product has been introduced into the marketplace. On the other hand, updates are usually planned as part of the product's life cycle before the product is introduced to the market. An update may add new features and improve performance to the product or improve its appearance to keep it competitive.

The most common situation in redesign is the modification of an existing product to meet new requirements. For example, the banning of the use of fluorinated hydrocarbon refrigerants because of the "ozone-hole problem" required the extensive redesign of refrigeration systems. Often redesign results from failure of the product in service. A much simpler situation is the case where one or two dimensions of a component must be changed to match some change made by the customer for that part. Yet another situation is the continuous evolution of a design to improve performance. An extreme example of this is shown in Figure 1.8. The steel railroad wheel had been in its present design for nearly 150 years. In spite of improvements in metallurgy and the understanding of stresses, the wheels still failed at the rate of about 200 per year, often causing disastrous derailments. The chief cause of failure was thermal buildup caused by failure of a railcar's braking system. Long-term research by the Association of American Railroads has resulted in the improved, current design. The chief design change is that the flat plate, the web between the bore and the rim, has been replaced by an S-shaped plate. The curved shape allows the plate to act like a spring, flexing when overheated, avoiding the buildup of stresses that are transmitted through the rigid flat plates. The wheel's tread has also been redesigned to extend the rolling life of the wheel. Car wheels last for about 200,000 miles. Traditionally, when a new wheel was placed in service it lost from

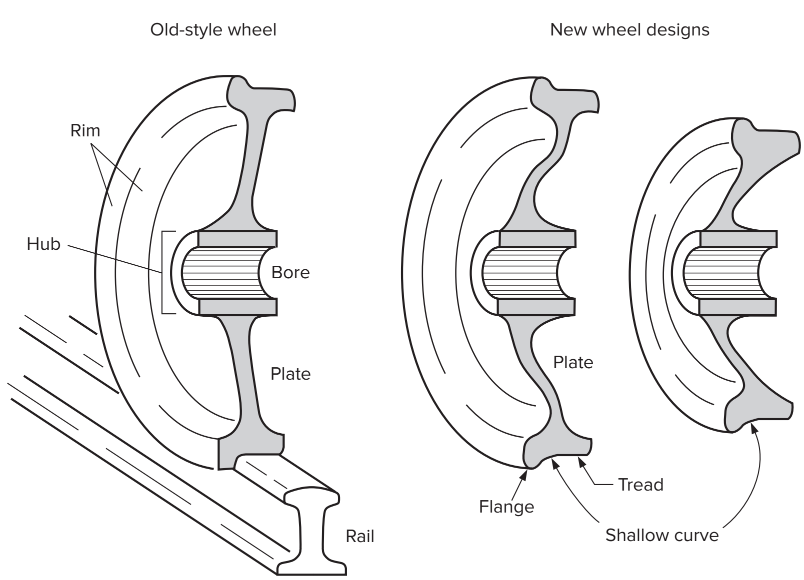

FIGURE 1.8
An example of a design update. Old design of railcar wheel versus improved design.

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30 to 40 percent of its tread and flange while it wore away to a new shape during the first 25,000 miles of service. After that the accelerated wear stopped and normal wear ensued. In the new design the curve between the flange and the tread has been made less concave, more like the profile of a “worn” wheel. The new wheels last for many thousands of miles longer, and the rolling resistance is lower, saving on fuel cost.

1.9
SOCIETAL CONSIDERATIONS IN ENGINEERING DESIGN

The first fundamental canon of the Accreditation Board for Engineering and Technology, Inc. (ABET) Code of Ethics states that “engineers shall hold paramount the safety, health, and welfare of the public in the performance of their profession.” A similar statement has been in engineering codes of ethics since the early 1920s, yet there is no question that what society perceives to be proper treatment by the profession has changed greatly in the intervening time. Today’s 24-hour news cycle, social media, and Internet make the general public, in a matter of hours, aware of events taking place anywhere in the world. That, coupled with a generally much higher standard of education and standard of living, has led to the development of a society that has high expectations, reacts to achieve change, and organizes to protest perceived wrongs. At the same time, technology has had major effects on the everyday life of the average citizen. All of us are intertwined in complex technological systems: an electric power grid, a national network of air traffic controllers, and wireless Internet connection services.

Thus, in response to real or imagined ills, society has developed mechanisms for countering some of the ills and/or slowing down the rate of technical change. The major social forces that have had an important impact on engineering design are occupational safety and health, consumer rights, environmental protection, and the freedom of information and public disclosure movement. The result of these social forces has been a great increase in federal regulations (in the interest of protecting the public) over many aspects of commerce and business and/or a drastic change in the economic payoff for new technologically oriented ventures.

The following are some general ways in which increased societal awareness of technology, and subsequent regulation, have influenced the practice of engineering design:

- Greater influence of lawyers on engineering decisions, often leading to product liability actions
- More time spent in planning and predicting the future effects of engineering projects
- Increased emphasis on “defensive research and development,” which is intended to protect the corporation against possible litigation
- Increased effort expended on satisfying sustainability for products and companies

Clearly, these societal pressures have placed much greater constraints on how engineers can carry out their designs. Moreover, the increasing litigiousness of U.S.

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society requires a greater awareness of legal and ethical issues on the part of each engineer (see Chapter 18 online at www.mhhe.com/dieter6e).

It seems clear that the future is likely to involve more technology, not less, so that engineers will face demands for innovation and design of technical systems of unprecedented complexity. While many of these challenges will arise from the requirement to translate new scientific knowledge into hardware, others will stem from the need to solve problems in "socialware." By socialware we mean the patterns of organization and management instructions needed for the hardware to function effectively.[1]

Another area where the interaction between technical and human networks is becoming stronger is in consideration of risk, reliability, and safety (see Chapter 13). No longer can safety factors simply be looked up in codes or standards. Engineers must recognize that design requirements depend on public policy as much as industry performance requirements. This is an area of design where government influence has increased.

There are five key roles of government in interacting with technology:

- As a stimulus to free enterprise through manipulation of the tax system
- By influencing interest rates and the supply of venture capital through changes in fiscal policy to control the growth of the economy
- As a major customer for high technology, chiefly in military systems
- As a funding source (patron) for research and development
- As a regulator of technology

Engineering is concerned with problems whose solution is needed and/or desired by society. The purpose of this section is to reinforce that point, and hopefully to show the engineering student how important a broad knowledge of economics and social science is to modern engineering practice.

1.10 SUMMARY

Engineering design is a challenging activity because it deals with largely unstructured problems that are important to the needs of society. An engineering design process creates something that did not exist before, requires choices between many variables and parameters, and often requires balancing multiple and sometimes conflicting requirements. Product design has been identified as the real key to world-competitive business. The steps in the design process are:

Phase I. Conceptual design

- Recognition of a need
- Definition of the problem
- Gathering of information
- Developing a design concept
- Choosing between competing concepts (evaluation)

1. E. Wenk, Jr., *Engineering Education,* November 1988, pp. 99–102.

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Phase II: Embodiment design
- Determining product architecture—arrangement of the physical functions
- Configuration design—preliminary selection of materials, modeling and sizing of parts
- Parametric design—creating a robust design, selecting final dimensions and tolerances

Phase III: Detail design—finalizing all details of design, creating final drawings and specifications

While many consider that the engineering design process ends with detail design, there are many issues that must be resolved before a product can be shipped to the customer. These additional phases of design are often folded into what is called the product-development process (see Chapter 2).

Among the most important of these factors are required functions with associated performance characteristics, the environment in which it must operate, target product cost, service life, provisions for maintenance and logistics, aesthetics, expected market and quantity to be produced, man-machine interface requirements (ergonomics), quality and reliability, safety and environmental concerns, and provision for testing.

NEW TERMS AND CONCEPTS

Analysis	Form	Robust design
Code	Function	Specification
Component	Green design	Standard
Computer-aided engineering	Human factors engineering	Subsystem
Configuration design	Iterative	Synthesis
Critical to quality	Needs analysis	System
Design feature	Product design specification	Total life cycle
Detail design	Problem definition	Useful life
Embodiment design	Product architecture	

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PROBLEMS AND EXERCISES

1.1. A major manufacturer of snowmobiles needs to find new products to keep the workforce employed year round. Starting with what you know or can find out about snowmobiles, make reasonable assumptions about the capabilities of the company. Then develop a needs analysis that leads to some suggestions for new products that the company could make and sell. Give the strengths and weaknesses of your suggestions.

1.2. Take a problem from one of your engineering science classes, and add and subtract those things that would frame it more as an engineering design problem.

1.3. There is a need in underdeveloped countries for building materials. One approach is to make building blocks (4 by 6 by 12 in.) from highly compacted soil. Your assignment is to design a block-making machine with the capacity for producing 600 blocks per day at a capital cost of less than $300. Develop a needs analysis, a definitive problem statement, and a plan for the information that will be needed to complete the design.

1.4. The steel wheel for a freight car has three basic functions: (1) to act as a brake drum, (2) to support the weight of the car and its cargo, and (3) to guide the freight car on the rails. Freight car wheels are produced by either casting or rotary forging. They are subjected to complex conditions of dynamic thermal and mechanical stresses. Safety is of great importance because derailment can cause loss of life and property. Develop a broad systems approach to the design of an improved cast-steel car wheel.

1.5. The need for material conservation and reduced cost has increased the desirability of corrosion-resistant coatings on steel. Develop several design concepts for producing 12-in.-wide low-carbon-steel sheet that is coated on one side with a thin layer, e.g., 0.001 in., of nickel.

1.6. The support of thin steel strip on a cushion of air introduces exciting prospects for the processing and handling of coated steel strip. Develop a feasibility analysis for the concept.

1.7. Consider the design of aluminum bicycle frames. A prototype model failed in fatigue after 1600 km of riding, whereas most steel frames can be ridden for over 60,000 km. Describe a design program that will solve this problem.

1.8. You are a design engineer working for a natural gas transmission company. You are assigned to a design team that is charged with preparing the proposal to the state Public Utility Commission to build a plant to receive liquefied natural gas from ocean-going tankers and unload it into your company's gas transmission system. What technical issues and societal issues will your team have to deal with?

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1.9. You are a senior design engineer at the design center of a major U.S. manufacturer of power tools. Over the past 5 years your company has outsourced component manufacturing and assembly to plants in Mexico and China. Although your company still has a few plants operating in the United States, most production is overseas. Think about how your job as the leader of a product development team has changed since your company made this change, and suggest how it will evolve in the future.

1.10 The oil spill from BP well Deepwater Horizon is one of the world's greatest environmental disasters. Nearly 5 million barrels of crude oil spewed into the Gulf of Mexico for 3 months. As a team, do research on the following issues: (a) the technology of drilling for oil in water deeper than 1000 feet; (b) the causes of the well blowout; (c) the short-term damage to the U.S. economy; (d) the long-term effects on the United States; and (e) the impact on the owner of the well, BP Global.

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2

PRODUCT-DEVELOPMENT PROCESS

2.1 INTRODUCTION

Chapter 1 was a broad overview of engineering design. Engineering design can exist in many modes, and engineering design projects are quite different from problems solved in engineering analysis courses. Chapter 1 presents a brief description of the phases of an engineering design project.

One of the most common modes of engineering design is *product design*, the creation of a physical artifact that is used by people to satisfy an unmet need, usually with some commercial objective. This means that the potential market for the product must be carefully analyzed before funds for developing the product can be approved. Thus, there are additional business and engineering decisions to be made before final approval of the product design can occur.

This chapter lays out a product development process that is more encompassing than the engineering design process described in Chapter 1. This chapter presents organizational structures for the design and product development functions and discusses markets and the vital function of marketing in detail. Because the most successful products are often innovative products, we conclude the chapter with some ideas about technological innovation.

2.2 PRODUCT-DEVELOPMENT PROCESS

A generally accepted model of the phases of the product development process is shown in Figure 2.1. The six phases shown in this diagram generally agree with those proposed by Asimow for the design process (see Section 1.4) with the addition of Phase 0, Business Planning.

Note that each phase in the figure narrows to a point. This symbolizes the *gate* or review that the project must successfully pass through before moving on to the next stage or phase of the process. This stage-gate product development process is

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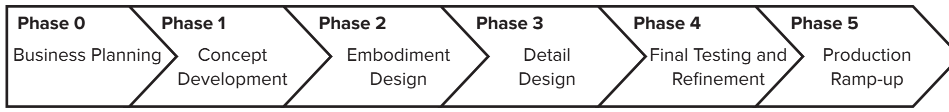

FIGURE 2.1
The product-development process in stage-gate format.

used by many companies to encourage rapid product development and to cull out the least promising projects before large sums of money are committed. The amount of money to develop a project increases markedly from phase 0 to phase 5. However, the money spent in product development is small compared to what it would cost in sunk capital and lost brand reputation if a defective product has to be recalled from the market. Thus, an important reason for using the *stage-gate process* is to quickly "get it right."

Phase 0 is the planning that should be done before the approval of the product development project. Product planning is usually done in two steps. The first step is a quick investigation and scoping of the project to determine the possible markets and whether the product is in alignment with the corporate strategic plan. It also involves a preliminary engineering assessment to determine technical and manufacturing feasibility. If things look promising after this quick examination, the planning operation goes into a detailed investigation to build the *business case* for the project. This could take several months to complete and involves personnel from marketing, design, manufacturing, finance, and possibly legal departments. In making the business case, marketing completes a detailed marketing analysis that involves market segmentation to identify the target market, the product positioning, and the product benefits. Design digs more deeply to evaluate the technical capability, possibly including some proof-of-concept analysis or testing to validate some very preliminary design concepts, while manufacturing identifies possible production constraints/costs and thinks about a supply chain strategy. A critical part of the business case is the financial analysis, which uses sales and cost projections from marketing to predict the profitability of the project. Typically this involves a discounted cash flow analysis (see Chapter 17 [online at www.mhhe.com/dieter6e]) with a sensitivity analysis to project the effects of possible risks. The gate at the end of phase 0 is crucial, and the decision of whether to proceed is made in a formal and deliberate manner, for costs will become considerable once the project advances to phase 1. The review board ensures that the corporate policies have been followed and that all of the necessary criteria have been met or exceeded. High among these is exceeding a corporate goal for return on investment (ROI). If the decision is to proceed, then a multifunctional team with a designated leader is established. The product design project is formally on its way.

Phase 1, Concept Development, considers the different ways the product and each subsystem can be designed. The development team takes what is known about the potential customers from phase 0, adds its own knowledge base, and fashions this into a carefully crafted product design specification (PDS). This process of determining the needs and wants of the customer is more detailed than the initial market survey done in phase 0. It is aided by using tools such as surveys and focus

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groups, benchmarking, and quality function deployment (QFD). The generation of a number of product concepts follows. The designers' creative instincts must be stimulated, design tools are used to assist in the development of promising concepts. Now, having arrived at a small set of feasible concepts, the one best suited for development into a product must be determined using selection methods. Conceptual design is the heart of the product development process, for without an excellent concept you cannot have a highly successful product. These aspects of conceptual design are covered in Chapters 5, 6, and 7.

Phase 2*,* Embodiment Design, is where the functions of the product are examined, leading to the division of the product into various subsystems. In addition, alternative ways of arranging the subsystems into a *product architecture* are studied. The interfaces between subsystems are identified and studied. Successful operation of the entire system relies on careful understanding of the interface between each subsystem. Phase 2 is where the form and features of the product begin to take shape, and for this reason it is called *embodiment design*.[1] Selections are made for materials and manufacturing processes, and the configuration and dimensions of parts are established. Those parts whose function is *critical to quality* are identified and given special analysis to ensure *design robustness*.[2] Careful consideration is given to the product-human interface (ergonomics), and changes to form are made if needed. Likewise, final touches will be made to the styling introduced by the industrial designers. In addition to a complete computer-based geometrical model of the product, critical parts may be built with rapid prototyping methods and physically tested. At this stage of development, marketing will most likely have enough information to set a price target for the product. Manufacturing will begin to place contracts for long-delivery tooling and to define the assembly process. By this time the legal department will have identified and worked out any patent licensing issues.

Phase 3*,* Detail Design, is the phase where the design is brought to the state of a complete engineering description of a tested and producible product. Missing information is added on the arrangement, form, dimensions, tolerances, surface properties, materials, and manufacturing of each part in the product. These result in a specification for each special-purpose part to be manufactured and the decision whether it will be made in the factory of the corporation or outsourced to a supplier. At the same time the design engineers are wrapping up all of these details, the manufacturing engineers are finalizing a process plan for each part and designing the tooling to make these parts. They also work with design engineers to finalize any issue of product robustness and define the quality assurance processes that will be used to achieve a quality product. The output of the detail design phase is the *control documentation* for the product. This takes the form of CAD files for the product assembly and for each part and its tooling. It also involves detailed plans for production and quality assurance, as well as many legal documents in the form of contracts and those protecting intellectual property. At the end of phase 3, a major review is held

1. Embodiment means to give a perceptible shape to a concept.
2. Robustness in a design context does not mean strong or tough. It means a design whose performance is insensitive to the variations introduced in manufacturing, or by the environment in which the product operates.

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to determine whether it is appropriate to let contracts for building the production tooling, although contracts for long lead-time items such as polymer injection molding dies are most likely let before this date.

Phase 4, Final Testing and Refinement, is concerned with making and testing many preproduction versions of the product. The first (alpha) prototypes are usually made with *production-intent parts*. These are working models of the product made from parts with the same dimensions and using the same materials as the production version of the product but not necessarily made with the actual processes and tooling that will be used with the production version. This is done for speed in getting parts and to minimize the cost of product development. The purpose of the alpha test is to determine whether the product will actually work as designed and whether it will satisfy the most important customer needs. The beta tests are conducted on products assembled from parts made by the actual production processes and tooling. They are extensively tested in-house and by selected customers in their own use environments. The purpose of these tests is to satisfy any doubts about the performance and reliability of the product, and to make the necessary engineering changes before the product is released to the general market. Only in the case of a completely "botched design" would a product fail at this stage-gate, but it might be delayed for a serious fix that could delay the product launch. During phase 4 the marketing people work on developing promotional materials for the product launch, and the manufacturing people fine-tune the fabrication and assembly processes and train the workforce that will make the product. Finally, the sales force puts the finishing touches on the sales plan.

At the end of phase 4 a major review is carried out to determine whether the work has been done in a quality way and whether the developed product is consistent with the original intent. Because large monetary sums must be committed beyond this point, a careful update is made of the financial estimates and the market prospects before funds are committed for production.

Phase 5, Production Ramp-up, the manufacturing operation begins to make and assemble the product using the intended production system. Most likely they will go through a *learning curve* as they work out any production yield and quality problems. Early products produced during ramp-up often are supplied to preferred customers and studied carefully to find any defects. Production usually increases gradually until full production is reached and the product is *launched* and made available for general distribution. For major products there will certainly be a public announcement and often special advertising and customer inducements. Some 6 to 12 months after product launch there will be a final major review. The latest financial information on sales, costs, profits, development cost, and time to launch will be reviewed, but the main focus of the review is to determine what were the strengths and weaknesses of the product development process. The emphasis is on *lessons learned* so that the next product development team can do even better.

The stage-gate development process is successful because it introduces schedule and approval to what is often an ad hoc process.[1] The process is relatively simple,

1. R. G. Cooper, *Winning at New Products*, 3d ed., Perseus Books, Cambridge, MA, 2001.

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and the requirements at each gate are readily understood by managers and engineers. It is not intended to be a rigid system. Most companies modify it to suit their own circumstances. Neither is it intended to be a strictly serial process, although Figure 2.1 gives that impression. Because the product development process (PDP) teams are multifunctional, the activities as much as possible are carried out concurrently. Thus, marketing will be going on at the same time as the designers are working on their tasks, while manufacturing does their thing. However, as the team progresses through the stages, the level of design work decreases and manufacturing activities increase.

2.2.1 Factors for Success

In commercial markets the cost to purchase a product is of paramount importance. It is important to understand what the product cost implies and how it relates to the product price. More details about costing can be found in Chapter 12. Cost and price are distinctly different concepts. The product cost includes the cost of materials, components, manufacturing, and assembly. The accountants also include other less obvious costs such as the prorated costs of capital equipment (the plant and its machinery), tooling cost, development cost, inventory costs, and likely warranty costs, in determining the total cost of producing a unit of product. The price is the amount of money that a customer is willing to pay to buy the product. The difference between the price and the cost is the profit per unit of product sold.

$$\text{Profit} = \text{Product Price} - \text{Product Cost} \tag{2.1}$$

This equation is the most important equation in engineering and in the operation of any business. If a corporation cannot make a profit, it soon is forced into bankruptcy, its employees lose their positions, and the owner or stockholders lose their investment. Everyone employed by a corporation seeks to maximize this profit while maintaining the strength and vitality of the product lines. The same statement can be made for a business that provides services instead of products. The price paid by the customer for a specified service must be more than the cost to provide that service if the business is to make a profit and prosper.

There are four key factors that determine the success of a product in the marketplace:

1. The quality, performance, and price of the product
2. The cost of the product over its life cycle
3. The cost of product development
4. The time needed to bring the product to the market

Let's discuss the product first. Is it attractive and easy to use? Is it reliable? Does it meet the needs of the customer? Is it better than the products now available in the marketplace? If the answer to all of these questions is an unqualified Yes, the customer may want to buy the product, but only if the price is right.

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Equation (2.1) offers only two ways to increase profit on an existing product line with a mature market base. We can increase the product's price, justified by adding new features or improving quality, or we can reduce the product's cost, through improvements in the production process. In the highly competitive world market for consumer products the latter is more likely than the former.

Developing a product involves many people with talents in different disciplines. It takes time, and it costs a lot of money. Thus, if we can reduce the product development cost, the profit will be increased. First, consider development time. Development time, also known as the time to market, is the time interval from the start of the product development process (the kickoff) to the time that the product is available for purchase (the product release date). The product release date is a very important target for a development team because many significant benefits follow from being first to market. There are at least three competitive advantages for a company that has development teams that can develop products quickly. First, the product's life is extended. For each month cut from the development schedule, a month is added to the life of the product in the marketplace, generating an additional month of revenues from sales, and profit. We show the revenue benefits of being first to market in Figure 2.2. The shaded region between the two curves showing time of market entry is the enhanced revenue due to the extra sales.

A second benefit of early product release is increased market share. The first product to market has 100 percent of the market share in the absence of a competing product. For existing products with periodic development of new models it is generally recognized that the earlier a product is introduced to compete with older models, without sacrificing quality, reliability, or performance and price, the better chance it has for acquiring and retaining a large share of the market. The effect of gaining a larger market share on sales revenue is illustrated in Figure 2.2. The crosshatched region between the two curves at the top of the graph shows the enhanced sales revenue due to increased market share.

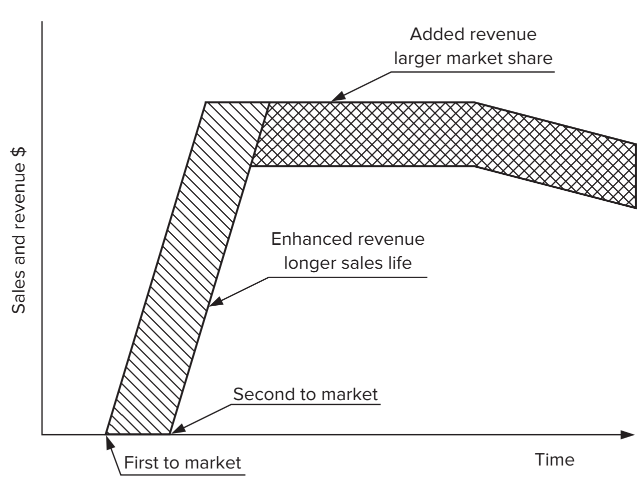

FIGURE 2.2
Increased sales revenue due to extended product life and larger market share.

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A third advantage of a short development cycle is higher *profit margins*. Profit margin is the net profit divided by the sales. If a new product is introduced before competing products are available, the corporation can command a higher price for the product, which enhances the profit. With time, competitive products will enter the market and force prices down. However, in many instances, relatively large profit margins can be maintained because the company that is first to market has more time than the competitor to learn methods for reducing manufacturing costs. They also learn better processing techniques and have the opportunity to modify assembly lines and manufacturing cells to reduce the time needed to manufacture and assemble the product. The advantage of being first to market, when a manufacturing *learning curve* exists, is shown graphically in Figure 2.3. The manufacturing learning curve reflects the reduced cost of processing, production, and assembly with time. These cost reductions are due to many innovations introduced by the workers after mass production begins. With experience, it is possible to drive down production costs.

Development costs represent a very important investment for the company involved. Development costs include the salaries of the members of the development team, money paid to subcontractors, costs of preproduction tooling, and costs of supplies and materials. These development costs can be significant, and most companies must limit the number of development projects in which they invest. The size of the investment can be appreciated by noting that the development cost of a new automobile is an estimated $1 billion, with an additional investment of $500 to $700 million for the new tooling required for high-volume production. For a product such as a power tool, the development cost can reach several million dollars, depending on the features to be introduced with the new product.

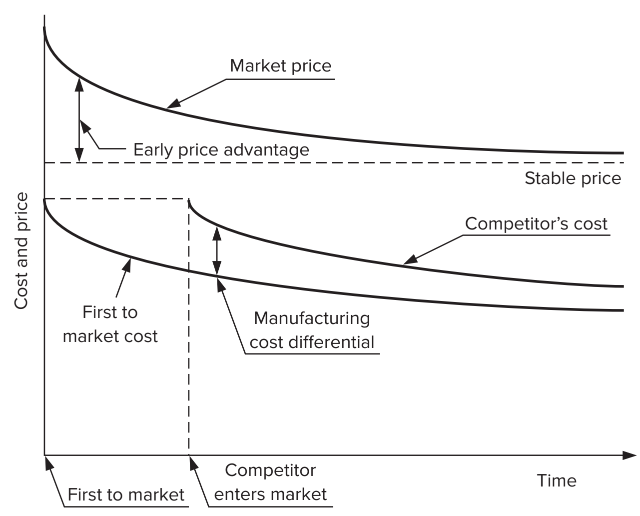

FIGURE 2.3
The team that brings the product first to market enjoys an initial price advantage and subsequent cost advantages from manufacturing efficiencies.

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2.2.2 Static Versus Dynamic Products

Some product designs are static, in that the changes in their design take place over long periods through incremental changes occurring at the subsystem and component levels. Examples of static products are automobiles and most consumer appliances such as refrigerators and dishwashers. Dynamic products such as wireless mobile phones, digital video recorders and players, and software change the basic design concept as often as the underlying technology changes.

Static products exist in a market where the customer is not eager to change, technology is stable, and fashion or styling play little role. These markets are characterized by a stable number of producers with high price competition and little product research. There is a mature, stable technology, with competing products similar to each other. The users are generally familiar with the technology and do not demand significant improvement. Industry standards may even restrict change, and parts of the product are assembled from components made by others. Because of the importance of cost, emphasis is more on manufacturing research than on product design research.

With dynamic products, customers are willing to, and may even demand, change. The market is characterized by many small producers doing active market research and seeking to reduce product cycle time. Companies actively seek new products employing rapidly advancing technology. There is high product differentiation and low industry standardization. More emphasis is placed on product research than on manufacturing research.

A number of factors serve to protect a product from competition. A product that requires high capital investment to manufacture or requires complex manufacturing processes tends to be resistant to competition. At the other end of the product chain, the need for an extensive distribution system may be a barrier to entry.[1] A strong patent position may keep out competition, as may strong brand identification and loyalty on the part of the customer.

2.2.3 Variations on the Generic Product Development Process

The PDP described at the beginning of Section 2.2 was based on the assumption that the product is being developed in response to an identified market need, a *market pull* situation. This is a common situation in product development, but there are other situations that need to be recognized.[2]

The opposite of market pull is *technology push*. This is the situation where the company starts with a new proprietary technology and looks for a market in which to apply this technology. Often successful technology push products involve basic materials or basic process technologies, because these can be deployed in thousands of applications and the probability of finding successful applications is therefore

1. The Internet has made it easier to set up direct marketing systems for products.
2. K. T. Ulrich and S. D. Eppinger, *Product Design and Development,* 6d ed., pp. 18–24, McGraw-Hill, New York, 2015.

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