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Mechanical Engineering

Shigley's Mechanical Engineering Design, Eighth Edition

Budynas–Nisbett

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Contents

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Preface

Objectives

This text is intended for students beginning the study of mechanical engineering design. The focus is on blending fundamental development of concepts with practical specification of components. Students of this text should find that it inherently directs them into familiarity with both the basis for decisions and the standards of industrial components. For this reason, as students transition to practicing engineers, they will find that this text is indispensable as a reference text. The objectives of the text are to:

- Cover the basics of machine design, including the design process, engineering mechanics and materials, failure prevention under static and variable loading, and characteristics of the principal types of mechanical elements.
- Offer a practical approach to the subject through a wide range of real-world applications and examples.
- Encourage readers to link design and analysis.
- Encourage readers to link fundamental concepts with practical component specification.

New to This Edition

This eighth edition contains the following significant enhancements:

- *New chapter on the Finite Element Method.* In response to many requests from reviewers, this edition presents an introductory chapter on the finite element method. The goal of this chapter is to provide an overview of the terminology, method, capabilities, and applications of this tool in the design environment.
- *New transmission case study.* The traditional separation of topics into chapters sometimes leaves students at a loss when it comes time to integrate dependent topics in a larger design process. A comprehensive case study is incorporated through standalone example problems in multiple chapters, then culminated with a new chapter that discusses and demonstrates the integration of the parts into a complete design process. Example problems relevant to the case study are presented on engineering paper background to quickly identify them as part of the case study.
- *Revised and expanded coverage of shaft design.* Complementing the new transmission case study is a significantly revised and expanded chapter focusing on issues relevant to shaft design. The motivating goal is to provide a meaningful presentation that allows a new designer to progress through the entire shaft design process – from general shaft layout to specifying dimensions. The chapter has been moved to immediately follow the fatigue chapter, providing an opportunity to seamlessly transition from the fatigue coverage to its application in the design of shafts.
- *Availability of information to complete the details of a design.* Additional focus is placed on ensuring the designer can carry the process through to completion.

By assigning larger design problems in class, the authors have identified where the students lack details. For example, information is now provided for such details as specifying keys to transmit torque, stress concentration factors for keyways and retaining ring grooves, and allowable deflections for gears and bearings. The use of internet catalogs and engineering component search engines is emphasized to obtain current component specifications.

- *Streamlining of presentation.* Coverage of material continues to be streamlined to focus on presenting straightforward concept development and a clear design procedure for student designers.

Content Changes and Reorganization

A new Part 4: *Analysis Tools* has been added at the end of the book to include the new chapter on finite elements and the chapter on statistical considerations. Based on a survey of instructors, the consensus was to move these chapters to the end of the book where they are available to those instructors wishing to use them. Moving the statistical chapter from its former location causes the renumbering of the former chapters 2 through 7. Since the shaft chapter has been moved to immediately follow the fatigue chapter, the component chapters (Chapters 8 through 17) maintain their same numbering. The new organization, along with brief comments on content changes, is given below:

Part 1: Basics

Part 1 provides a logical and unified introduction to the background material needed for machine design. The chapters in Part 1 have received a thorough cleanup to streamline and sharpen the focus, and eliminate clutter.

- *Chapter 1, Introduction.* Some outdated and unnecessary material has been removed. A new section on problem specification introduces the transmission case study.
- *Chapter 2, Materials.* New material is included on selecting materials in a design process. The Ashby charts are included and referenced as a design tool.
- *Chapter 3, Load and Stress Analysis.* Several sections have been rewritten to improve clarity. Bending in two planes is specifically addressed, along with an example problem.
- *Chapter 4, Deflection and Stiffness.* Several sections have been rewritten to improve clarity. A new example problem for deflection of a stepped shaft is included. A new section is included on elastic stability of structural members in compression.

Part 2: Failure Prevention

This section covers failure by static and dynamic loading. These chapters have received extensive cleanup and clarification, targeting student designers.

- *Chapter 5, Failures Resulting from Static Loading.* In addition to extensive cleanup for improved clarity, a summary of important design equations is provided at the end of the chapter.
- *Chapter 6, Fatigue Failure Resulting from Variable Loading.* Confusing material on obtaining and using the S-N diagram is clarified. The multiple methods for obtaining notch sensitivity are condensed. The section on combination loading is rewritten for greater clarity. A chapter summary is provided to overview the analysis roadmap and important design equations used in the process of fatigue analysis.

Part 3: Design of Mechanical Elements

Part 3 covers the design of specific machine components. All chapters have received general cleanup. The shaft chapter has been moved to the beginning of the section. The arrangement of chapters, along with any significant changes, is described below:

- *Chapter 7, Shafts and Shaft Components.* This chapter is significantly expanded and rewritten to be comprehensive in designing shafts. Instructors that previously did not specifically cover the shaft chapter are encouraged to use this chapter immediately following the coverage of fatigue failure. The design of a shaft provides a natural progression from the failure prevention section into application toward components. This chapter is an essential part of the new transmission case study. The coverage of setscrews, keys, pins, and retaining rings, previously placed in the chapter on bolted joints, has been moved into this chapter. The coverage of limits and fits, previously placed in the chapter on statistics, has been moved into this chapter.
- *Chapter 8, Screws, Fasteners, and the Design of Nonpermanent Joints.* The section on setscrews, keys, and pins, has been moved from this chapter to Chapter 7. The coverage of bolted and riveted joints loaded in shear has been returned to this chapter.
- *Chapter 9, Welding, Bonding, and the Design of Permanent Joints.* The section on bolted and riveted joints loaded in shear has been moved to Chapter 8.
- *Chapter 10, Mechanical Springs.*
- *Chapter 11, Rolling-Contact Bearings.*
- *Chapter 12, Lubrication and Journal Bearings.*
- *Chapter 13, Gears – General.* New example problems are included to address design of compound gear trains to achieve specified gear ratios. The discussion of the relationship between torque, speed, and power is clarified.
- *Chapter 14, Spur and Helical Gears.* The current AGMA standard (ANSI/AGMA 2001-D04) has been reviewed to ensure up-to-date information in the gear chapters. All references in this chapter are updated to reflect the current standard.
- *Chapter 15, Bevel and Worm Gears.*
- *Chapter 16, Clutches, Brakes, Couplings, and Flywheels.*
- *Chapter 17, Flexible Mechanical Elements.*
- *Chapter 18, Power Transmission Case Study.* This new chapter provides a complete case study of a double reduction power transmission. The focus is on providing an example for student designers of the process of integrating topics from multiple chapters. Instructors are encouraged to include one of the variations of this case study as a design project in the course. Student feedback consistently shows that this type of project is one of the most valuable aspects of a first course in machine design. This chapter can be utilized in a tutorial fashion for students working through a similar design.

Part 4: Analysis Tools

Part 4 includes a new chapter on finite element methods, and a new location for the chapter on statistical considerations. Instructors can reference these chapters as needed.

- *Chapter 19, Finite Element Analysis.* This chapter is intended to provide an introduction to the finite element method, and particularly its application to the machine design process.

- *Chapter 20, Statistical Considerations.* This chapter is relocated and organized as a tool for users that wish to incorporate statistical concepts into the machine design process. This chapter should be reviewed if Secs. 5–13, 6–17, or Chap. 11 are to be covered.

Supplements

The 8th edition of *Shigley's Mechanical Engineering Design* features McGraw-Hill's ARIS (Assessment Review and Instruction System). ARIS makes homework meaningful—and manageable—for instructors and students. Instructors can assign and grade text-specific homework within the industry's most robust and versatile homework management system. Students can access multimedia learning tools and benefit from unlimited practice via algorithmic problems. Go to aris.mhhe.com to learn more and register!
The array of tools available to users of *Shigley's Mechanical Engineering Design* includes:

Student Supplements

- *Tutorials—Presentation of major concepts, with visuals.* Among the topics covered are pressure vessel design, press and shrink fits, contact stresses, and design for static failure.
- *MATLAB® for machine design.* Includes visual simulations and accompanying source code. The simulations are linked to examples and problems in the text and demonstrate the ways computational software can be used in mechanical design and analysis.
- *Fundamentals of engineering (FE) exam questions for machine design.* Interactive problems and solutions serve as effective, self-testing problems as well as excellent preparation for the FE exam.
- *Algorithmic Problems.* Allow step-by-step problem-solving using a recursive computational procedure (algorithm) to create an infinite number of problems.

Instructor Supplements (under password protection)

- *Solutions manual.* The instructor's manual contains solutions to most end-of-chapter nondesign problems.
- *PowerPoint® slides.* Slides of important figures and tables from the text are provided in PowerPoint format for use in lectures.

List of Symbols

This is a list of common symbols used in machine design and in this book. Specialized use in a subject-matter area often attracts fore and post subscripts and superscripts. To make the table brief enough to be useful the symbol kernels are listed. See Table 14–1, pp. 715–716 for spur and helical gearing symbols, and Table 15–1, pp. 769–770 for bevel-gear symbols.

A	Area, coefficient
$\mathbf{A}$	Area variate
a	Distance, regression constant
$\hat{a}$	Regression constant estimate
$\mathbf{a}$	Distance variate
B	Coefficient
Bhn	Brinell hardness
$\mathbf{B}$	Variate
b	Distance, Weibull shape parameter, range number, regression constant, width
$\hat{b}$	Regression constant estimate
$\mathbf{b}$	Distance variate
C	Basic load rating, bolted-joint constant, center distance, coefficient of variation, column end condition, correction factor, specific heat capacity, spring index
c	Distance, viscous damping, velocity coefficient
CDF	Cumulative distribution function
COV	Coefficient of variation
$\mathbf{c}$	Distance variate
D	Helix diameter
d	Diameter, distance
E	Modulus of elasticity, energy, error
e	Distance, eccentricity, efficiency, Naperian logarithmic base
F	Force, fundamental dimension force
f	Coefficient of friction, frequency, function
fom	Figure of merit
G	Torsional modulus of elasticity
g	Acceleration due to gravity, function
H	Heat, power
H_B	Brinell hardness
HRC	Rockwell C-scale hardness
h	Distance, film thickness
$\hbar_{CR}$	Combined overall coefficient of convection and radiation heat transfer
I	Integral, linear impulse, mass moment of inertia, second moment of area
i	Index
$\mathbf{i}$	Unit vector in x-direction

J	Mechanical equivalent of heat, polar second moment of area, geometry factor
$\mathbf{j}$	Unit vector in the y-direction
K	Service factor, stress-concentration factor, stress-augmentation factor, torque coefficient
k	Marin endurance limit modifying factor, spring rate
$\mathbf{k}$	k variate, unit vector in the z-direction
L	Length, life, fundamental dimension length
LN	Lognormal distribution
l	Length
M	Fundamental dimension mass, moment
$\mathbf{M}$	Moment vector, moment variate
m	Mass, slope, strain-strengthening exponent
N	Normal force, number, rotational speed
$\mathbf{N}$	Normal distribution
n	Load factor, rotational speed, safety factor
n_d	Design factor
P	Force, pressure, diametral pitch
PDF	Probability density function
p	Pitch, pressure, probability
Q	First moment of area, imaginary force, volume
q	Distributed load, notch sensitivity
R	Radius, reaction force, reliability, Rockwell hardness, stress ratio
$\mathbf{R}$	Vector reaction force
r	Correlation coefficient, radius
$\mathbf{r}$	Distance vector
S	Sommerfeld number, strength
$\mathbf{S}$	S variate
s	Distance, sample standard deviation, stress
T	Temperature, tolerance, torque, fundamental dimension time
$\mathbf{T}$	Torque vector, torque variate
t	Distance, Student's t-statistic, time, tolerance
U	Strain energy
$\mathbf{U}$	Uniform distribution
u	Strain energy per unit volume
V	Linear velocity, shear force
v	Linear velocity
W	Cold-work factor, load, weight
$\mathbf{W}$	Weibull distribution
w	Distance, gap, load intensity
$\mathbf{w}$	Vector distance
X	Coordinate, truncated number
x	Coordinate, true value of a number, Weibull parameter
$\mathbf{x}$	x variate
Y	Coordinate
y	Coordinate, deflection
$\mathbf{y}$	y variate
Z	Coordinate, section modulus, viscosity
z	Standard deviation of the unit normal distribution
$\mathbf{z}$	Variate of z

α	Coefficient, coefficient of linear thermal expansion, end-condition for springs, thread angle
β	Bearing angle, coefficient
Δ	Change, deflection
δ	Deviation, elongation
ϵ	Eccentricity ratio, engineering (normal) strain
$\boldsymbol{\epsilon}$	Normal distribution with a mean of 0 and a standard deviation of s
ε	True or logarithmic normal strain
Γ	Gamma function
γ	Pitch angle, shear strain, specific weight
λ	Slenderness ratio for springs
$\boldsymbol{\lambda}$	Unit lognormal with a mean of l and a standard deviation equal to COV
μ	Absolute viscosity, population mean
ν	Poisson ratio
ω	Angular velocity, circular frequency
ϕ	Angle, wave length
ψ	Slope integral
ρ	Radius of curvature
σ	Normal stress
σ'	Von Mises stress
$\boldsymbol{\sigma}$	Normal stress variate
$\hat{\sigma}$	Standard deviation
τ	Shear stress
$\boldsymbol{\tau}$	Shear stress variate
θ	Angle, Weibull characteristic parameter
¢	Cost per unit weight
$	Cost

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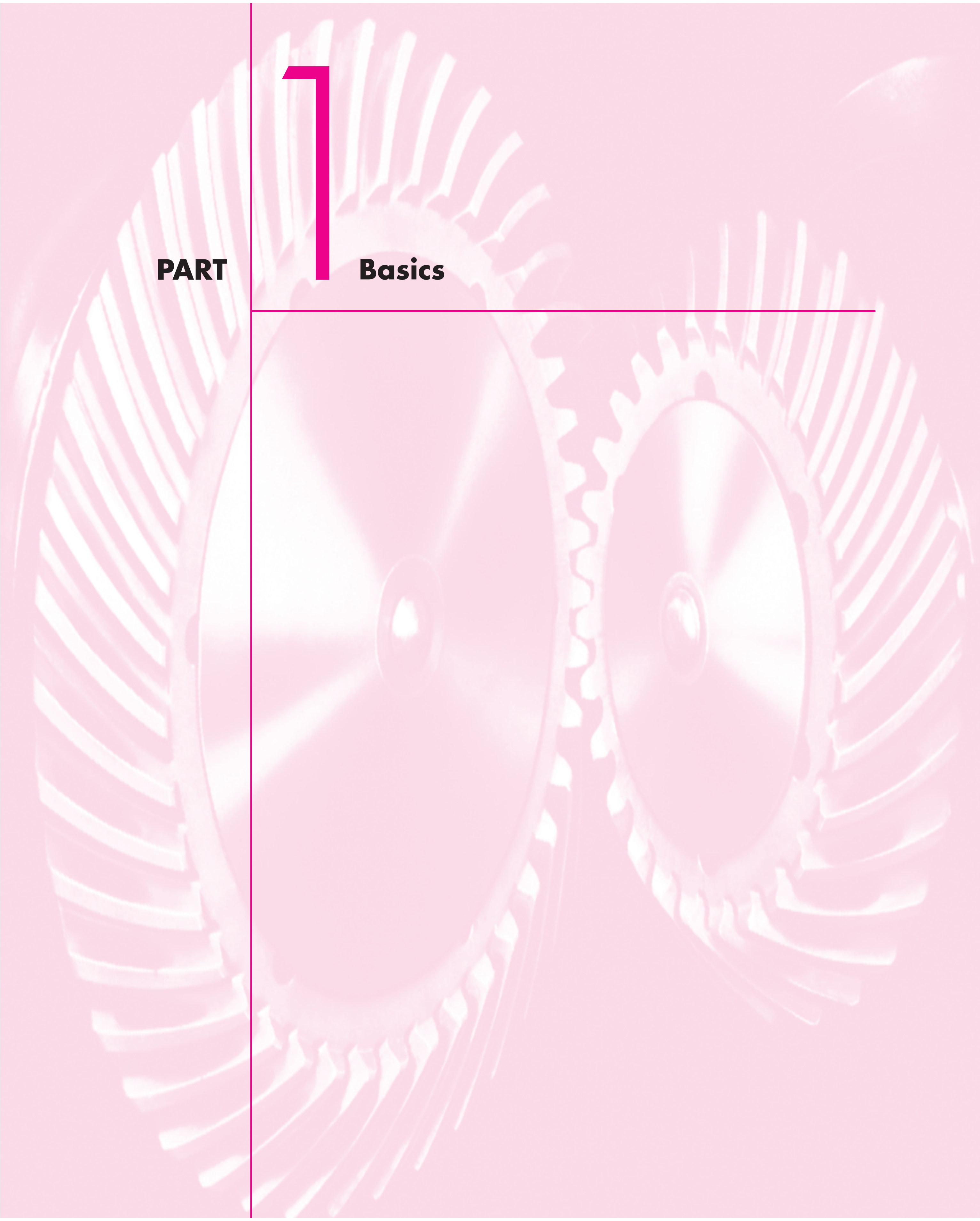
PART 1 Basics



1 Introduction to Mechanical Engineering Design

Chapter Outline

Mechanical design is a complex undertaking, requiring many skills. Extensive relationships need to be subdivided into a series of simple tasks. The complexity of the subject requires a sequence in which ideas are introduced and iterated.

We first address the nature of design in general, and then mechanical engineering design in particular. Design is an iterative process with many interactive phases. Many resources exist to support the designer, including many sources of information and an abundance of computational design tools. The design engineer needs not only to develop competence in their field but must also cultivate a strong sense of responsibility and professional work ethic.

There are roles to be played by codes and standards, ever-present economics, safety, and considerations of product liability. The survival of a mechanical component is often related through stress and strength. Matters of uncertainty are ever-present in engineering design and are typically addressed by the design factor and factor of safety, either in the form of a deterministic (absolute) or statistical sense. The latter, statistical approach, deals with a design's *reliability* and requires good statistical data.

In mechanical design, other considerations include dimensions and tolerances, units, and calculations.

The book consists of four parts. Part 1, *Basics,* begins by explaining some differences between design and analysis and introducing some fundamental notions and approaches to design. It continues with three chapters reviewing material properties, stress analysis, and stiffness and deflection analysis, which are the key principles necessary for the remainder of the book.

Part 2, *Failure Prevention,* consists of two chapters on the prevention of failure of mechanical parts. Why machine parts fail and how they can be designed to prevent failure are difficult questions, and so we take two chapters to answer them, one on preventing failure due to static loads, and the other on preventing fatigue failure due to time-varying, cyclic loads.

In Part 3, *Design of Mechanical Elements,* the material of Parts 1 and 2 is applied to the analysis, selection, and design of specific mechanical elements such as shafts, fasteners, weldments, springs, rolling contact bearings, film bearings, gears, belts, chains, and wire ropes.

Part 4, *Analysis Tools,* provides introductions to two important methods used in mechanical design, finite element analysis and statistical analysis. This is optional study material, but some sections and examples in Parts 1 to 3 demonstrate the use of these tools.

There are two appendixes at the end of the book. Appendix A contains many useful tables referenced throughout the book. Appendix B contains answers to selected end-of-chapter problems.

1–1 Design

To design is either to formulate a plan for the satisfaction of a specified need or to solve a problem. If the plan results in the creation of something having a physical reality, then the product must be functional, safe, reliable, competitive, usable, manufacturable, and marketable.

Design is an innovative and highly iterative process. It is also a decision-making process. Decisions sometimes have to be made with too little information, occasionally with just the right amount of information, or with an excess of partially contradictory information. Decisions are sometimes made tentatively, with the right reserved to adjust as more becomes known. The point is that the engineering designer has to be personally comfortable with a decision-making, problem-solving role.

Design is a communication-intensive activity in which both words and pictures are used, and written and oral forms are employed. Engineers have to communicate effectively and work with people of many disciplines. These are important skills, and an engineer's success depends on them.

A designer's personal resources of creativeness, communicative ability, and problem-solving skill are intertwined with knowledge of technology and first principles. Engineering tools (such as mathematics, statistics, computers, graphics, and languages) are combined to produce a plan that, when carried out, produces a product that is *functional, safe, reliable, competitive, usable, manufacturable, and marketable,* regardless of who builds it or who uses it.

1–2 Mechanical Engineering Design

Mechanical engineers are associated with the production and processing of energy and with providing the means of production, the tools of transportation, and the techniques of automation. The skill and knowledge base are extensive. Among the disciplinary bases are mechanics of solids and fluids, mass and momentum transport, manufacturing processes, and electrical and information theory. Mechanical engineering design involves all the disciplines of mechanical engineering.

Real problems resist compartmentalization. A simple journal bearing involves fluid flow, heat transfer, friction, energy transport, material selection, thermomechanical treatments, statistical descriptions, and so on. A building is environmentally controlled. The heating, ventilation, and air-conditioning considerations are sufficiently specialized that some speak of heating, ventilating, and air-conditioning design as if it is separate and distinct from mechanical engineering design. Similarly, internal-combustion engine design, turbomachinery design, and jet-engine design are sometimes considered discrete entities. Here, the leading string of words preceding the word design is merely a product descriptor. Similarly, there are phrases such as machine design, machine-element design, machine-component design, systems design, and fluid-power design. All of these phrases are somewhat more focused *examples* of mechanical engineering design. They all draw on the same bodies of knowledge, are similarly organized, and require similar skills.

1–3 Phases and Interactions of the Design Process

What is the design process? How does it begin? Does the engineer simply sit down at a desk with a blank sheet of paper and jot down some ideas? What happens next? What factors influence or control the decisions that have to be made? Finally, how does the design process end?

The complete design process, from start to finish, is often outlined as in Fig. 1–1. The process begins with an identification of a need and a decision to do something about it. After many iterations, the process ends with the presentation of the plans for satisfying the need. Depending on the nature of the design task, several design phases may be repeated throughout the life of the product, from inception to termination. In the next several subsections, we shall examine these steps in the design process in detail.

Identification of need generally starts the design process. Recognition of the need and phrasing the need often constitute a highly creative act, because the need may be only a vague discontent, a feeling of uneasiness, or a sensing that something is not right. The need is often not evident at all; recognition is usually triggered by a particular

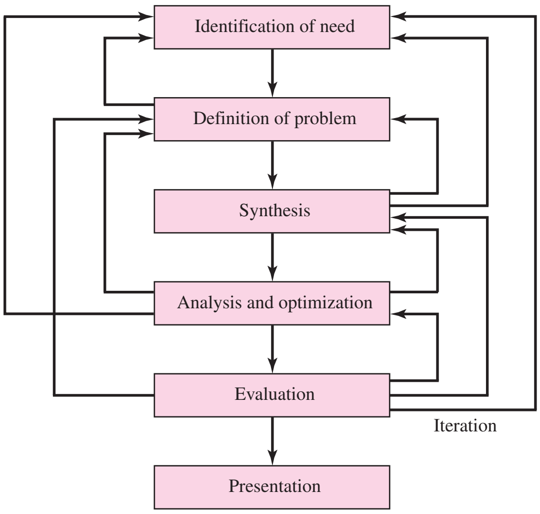


Figure 1–1

The phases in design, acknowledging the many feedbacks and iterations.

adverse circumstance or a set of random circumstances that arises almost simultaneously. For example, the need to do something about a food-packaging machine may be indicated by the noise level, by a variation in package weight, and by slight but perceptible variations in the quality of the packaging or wrap.

There is a distinct difference between the statement of the need and the definition of the problem. The *definition of problem* is more specific and must include all the specifications for the object that is to be designed. The specifications are the input and output quantities, the characteristics and dimensions of the space the object must occupy, and all the limitations on these quantities. We can regard the object to be designed as something in a black box. In this case we must specify the inputs and outputs of the box, together with their characteristics and limitations. The specifications define the cost, the number to be manufactured, the expected life, the range, the operating temperature, and the reliability. Specified characteristics can include the speeds, feeds, temperature limitations, maximum range, expected variations in the variables, dimensional and weight limitations, etc.

There are many implied specifications that result either from the designer's particular environment or from the nature of the problem itself. The manufacturing processes that are available, together with the facilities of a certain plant, constitute restrictions on a designer's freedom, and hence are a part of the implied specifications. It may be that a small plant, for instance, does not own cold-working machinery. Knowing this, the designer might select other metal-processing methods that can be performed in the plant. The labor skills available and the competitive situation also constitute implied constraints. Anything that limits the designer's freedom of choice is a constraint. Many materials and sizes are listed in supplier's catalogs, for instance, but these are not all easily available and shortages frequently occur. Furthermore, inventory economics requires that a manufacturer stock a minimum number of materials and sizes. An example of a specification is given in Sec. 1–16. This example is for a case study of a power transmission that is presented throughout this text.

The synthesis of a scheme connecting possible system elements is sometimes called the *invention of the concept* or *concept design*. This is the first and most important step in the synthesis task. Various schemes must be proposed, investigated, and quantified in terms of established metrics.[1] As the fleshing out of the scheme progresses, analyses must be performed to assess whether the system performance is satisfactory or better, and, if satisfactory, just how well it will perform. System schemes that do not survive analysis are revised, improved, or discarded. Those with potential are optimized to determine the best performance of which the scheme is capable. Competing schemes are compared so that the path leading to the most competitive product can be chosen. Figure 1–1 shows that *synthesis* and *analysis and optimization* are intimately and iteratively related.

We have noted, and we emphasize, that design is an iterative process in which we proceed through several steps, evaluate the results, and then return to an earlier phase of the procedure. Thus, we may synthesize several components of a system, analyze and optimize them, and return to synthesis to see what effect this has on the remaining parts of the system. For example, the design of a system to transmit power requires attention to the design and selection of individual components (e.g., gears, bearings, shaft). However, as is often the case in design, these components are not independent. In order to design the shaft for stress and deflection, it is necessary to know the applied forces. If the forces are transmitted through gears, it is necessary to know the gear specifications in order to determine the forces that will be transmitted to the shaft. But stock gears come with certain bore sizes, requiring knowledge of the necessary shaft diameter. Clearly, rough estimates will need to be made in order to proceed through the process, refining and iterating until a final design is obtained that is satisfactory for each individual component as well as for the overall design specifications. Throughout the text we will elaborate on this process for the case study of a power transmission design.

Both analysis and optimization require that we construct or devise abstract models of the system that will admit some form of mathematical analysis. We call these models mathematical models. In creating them it is our hope that we can find one that will simulate the real physical system very well. As indicated in Fig. 1–1, *evaluation* is a significant phase of the total design process. Evaluation is the final proof of a successful design and usually involves the testing of a prototype in the laboratory. Here we wish to discover if the design really satisfies the needs. Is it reliable? Will it compete successfully with similar products? Is it economical to manufacture and to use? Is it easily maintained and adjusted? Can a profit be made from its sale or use? How likely is it to result in product-liability lawsuits? And is insurance easily and cheaply obtained? Is it likely that recalls will be needed to replace defective parts or systems?

Communicating the design to others is the final, vital *presentation* step in the design process. Undoubtedly, many great designs, inventions, and creative works have been lost to posterity simply because the originators were unable or unwilling to explain their accomplishments to others. Presentation is a selling job. The engineer, when presenting a new solution to administrative, management, or supervisory persons, is attempting to sell or to prove to them that this solution is a better one. Unless this can be done successfully, the time and effort spent on obtaining the solution have been largely wasted. When designers sell a new idea, they also sell themselves. If they are repeatedly successful in selling ideas, designs, and new solutions to management, they begin to receive salary increases and promotions; in fact, this is how anyone succeeds in his or her profession.

[1]An excellent reference for this topic is presented by Stuart Pugh, *Total Design—Integrated Methods for Successful Product Engineering,* Addison-Wesley, 1991. A description of the *Pugh method* is also provided in Chap. 8, David G. Ullman, *The Mechanical Design Process,* 3rd ed., McGraw-Hill, 2003.

Design Considerations

Sometimes the strength required of an element in a system is an important factor in the determination of the geometry and the dimensions of the element. In such a situation we say that strength is an important design consideration. When we use the expression design consideration, we are referring to some characteristic that influences the design of the element or, perhaps, the entire system. Usually quite a number of such characteristics must be considered and prioritized in a given design situation. Many of the important ones are as follows (not necessarily in order of importance):

1. Functionality
2. Strength/stress
3. Distortion/deflection/stiffness
4. Wear
5. Corrosion
6. Safety
7. Reliability
8. Manufacturability
9. Utility
10. Cost
11. Friction
12. Weight
13. Life
14. Noise
15. Styling
16. Shape
17. Size
18. Control
19. Thermal properties
20. Surface
21. Lubrication
22. Marketability
23. Maintenance
24. Volume
25. Liability
26. Remanufacturing/resource recovery

Some of these characteristics have to do directly with the dimensions, the material, the processing, and the joining of the elements of the system. Several characteristics may be interrelated, which affects the configuration of the total system.

1–4 Design Tools and Resources

Today, the engineer has a great variety of tools and resources available to assist in the solution of design problems. Inexpensive microcomputers and robust computer software packages provide tools of immense capability for the design, analysis, and simulation of mechanical components. In addition to these tools, the engineer always needs technical information, either in the form of basic science/engineering behavior or the characteristics of specific off-the-shelf components. Here, the resources can range from science/engineering textbooks to manufacturers' brochures or catalogs. Here too, the computer can play a major role in gathering information.[2]

Computational Tools

Computer-aided design (CAD) software allows the development of three-dimensional (3-D) designs from which conventional two-dimensional orthographic views with automatic dimensioning can be produced. Manufacturing tool paths can be generated from the 3-D models, and in some cases, parts can be created directly from a 3-D database by using a rapid prototyping and manufacturing method (stereolithography)—*paperless manufacturing!* Another advantage of a 3-D database is that it allows rapid and accurate calculations of mass properties such as mass, location of the center of gravity, and mass moments of inertia. Other geometric properties such as areas and distances between points are likewise easily obtained. There are a great many CAD software packages available such

[2]An excellent and comprehensive discussion of the process of "gathering information" can be found in Chap. 4, George E. Dieter, *Engineering Design, A Materials and Processing Approach,* 3rd ed., McGraw-Hill, New York, 2000.

as Aries, AutoCAD, CadKey, I-Deas, Unigraphics, Solid Works, and ProEngineer, to name a few.

The term *computer-aided engineering* (CAE) generally applies to all computer-related engineering applications. With this definition, CAD can be considered as a subset of CAE. Some computer software packages perform specific engineering analysis and/or simulation tasks that assist the designer, but they are not considered a tool for the creation of the design that CAD is. Such software fits into two categories: engineering-based and non-engineering-specific. Some examples of engineering-based software for mechanical engineering applications—software that might also be integrated within a CAD system—include finite-element analysis (FEA) programs for analysis of stress and deflection (see Chap. 19), vibration, and heat transfer (e.g., Algor, ANSYS, and MSC/NASTRAN); computational fluid dynamics (CFD) programs for fluid-flow analysis and simulation (e.g., CFD++, FIDAP, and Fluent); and programs for simulation of dynamic force and motion in mechanisms (e.g., ADAMS, DADS, and Working Model).

Examples of non-engineering-specific computer-aided applications include software for word processing, spreadsheet software (e.g., Excel, Lotus, and Quattro-Pro), and mathematical solvers (e.g., Maple, MathCad, Matlab, Mathematica, and TKsolver).

Your instructor is the best source of information about programs that may be available to you and can recommend those that are useful for specific tasks. One caution, however: Computer software is no substitute for the human thought process. *You* are the driver here; the computer is the vehicle to assist you on your journey to a solution. Numbers generated by a computer can be far from the truth if you entered incorrect input, if you misinterpreted the application or the output of the program, if the program contained bugs, etc. It is your responsibility to assure the validity of the results, so be careful to check the application and results carefully, perform benchmark testing by submitting problems with known solutions, and monitor the software company and user-group newsletters.

Acquiring Technical Information

We currently live in what is referred to as the *information age,* where information is generated at an astounding pace. It is difficult, but extremely important, to keep abreast of past and current developments in one's field of study and occupation. The reference in Footnote 2 provides an excellent description of the informational resources available and is highly recommended reading for the serious design engineer. Some sources of information are:

- *Libraries (community, university, and private).* Engineering dictionaries and encyclopedias, textbooks, monographs, handbooks, indexing and abstract services, journals, translations, technical reports, patents, and business sources/brochures/catalogs.
- *Government sources.* Departments of Defense, Commerce, Energy, and Transportation; NASA; Government Printing Office; U.S. Patent and Trademark Office; National Technical Information Service; and National Institute for Standards and Technology.
- *Professional societies.* American Society of Mechanical Engineers, Society of Manufacturing Engineers, Society of Automotive Engineers, American Society for Testing and Materials, and American Welding Society.
- *Commercial vendors.* Catalogs, technical literature, test data, samples, and cost information.
- *Internet.* The computer network gateway to websites associated with most of the categories listed above.[3]

[3]Some helpful Web resources, to name a few, include www.globalspec.com, www.engnetglobal.com, www.efunda.com, www.thomasnet.com, and www.uspto.gov.

This list is not complete. The reader is urged to explore the various sources of information on a regular basis and keep records of the knowledge gained.

1–5 The Design Engineer's Professional Responsibilities

In general, the design engineer is required to satisfy the needs of customers (management, clients, consumers, etc.) and is expected to do so in a competent, responsible, ethical, and professional manner. Much of engineering course work and practical experience focuses on competence, but when does one begin to develop engineering responsibility and professionalism? To start on the road to success, you should start to develop these characteristics early in your educational program. You need to cultivate your professional work ethic and process skills before graduation, so that when you begin your formal engineering career, you will be prepared to meet the challenges.

It is not obvious to some students, but communication skills play a large role here, and it is the wise student who continuously works to improve these skills—*even if it is not a direct requirement of a course assignment!* Success in engineering (achievements, promotions, raises, etc.) may in large part be due to competence but if you cannot communicate your ideas clearly and concisely, your technical proficiency may be compromised.

You can start to develop your communication skills by keeping a neat and clear journal/logbook of your activities, entering dated entries frequently. (Many companies require their engineers to keep a journal for patent and liability concerns.) Separate journals should be used for each design project (or course subject). When starting a project or problem, in the definition stage, make journal entries quite frequently. Others, as well as yourself, may later question why you made certain decisions. Good chronological records will make it easier to explain your decisions at a later date.

Many engineering students see themselves after graduation as practicing engineers designing, developing, and analyzing products and processes and consider the need of good communication skills, either oral or writing, as secondary. This is far from the truth. Most practicing engineers spend a good deal of time communicating with others, writing proposals and technical reports, and giving presentations and interacting with engineering and nonengineering support personnel. You have the time now to sharpen your communication skills. When given an assignment to write or make any presentation, technical *or* nontechnical, accept it enthusiastically, and work on improving your communication skills. It will be time well spent to learn the skills now rather than on the job.

When you are working on a design problem, it is important that you develop a systematic approach. Careful attention to the following action steps will help you to organize your solution processing technique.

- *Understand the problem.* Problem definition is probably the most significant step in the engineering design process. Carefully read, understand, and refine the problem statement.
- *Identify the known.* From the refined problem statement, describe concisely what information is known and relevant.
- *Identify the unknown and formulate the solution strategy.* State what must be determined, in what order, so as to arrive at a solution to the problem. Sketch the component or system under investigation, identifying known and unknown parameters. Create a flowchart of the steps necessary to reach the final solution. The steps may require the use of free-body diagrams; material properties from tables; equations

from first principles, textbooks, or handbooks relating the known and unknown parameters; experimentally or numerically based charts; specific computational tools as discussed in Sec. 1–4; etc.

- *State all assumptions and decisions.* Real design problems generally do not have unique, ideal, closed-form solutions. Selections, such as choice of materials, and heat treatments, require decisions. Analyses require assumptions related to the modeling of the real components or system. All assumptions and decisions should be identified and recorded.
- *Analyze the problem.* Using your solution strategy in conjunction with your decisions and assumptions, execute the analysis of the problem. Reference the sources of all equations, tables, charts, software results, etc. Check the credibility of your results. Check the order of magnitude, dimensionality, trends, signs, etc.
- *Evaluate your solution.* Evaluate each step in the solution, noting how changes in strategy, decisions, assumptions, and execution might change the results, in positive or negative ways. If possible, incorporate the positive changes in your final solution.
- *Present your solution.* Here is where your communication skills are important. At this point, you are selling yourself and your technical abilities. If you cannot skillfully explain what you have done, some or all of your work may be misunderstood and unaccepted. Know your audience.

As stated earlier, all design processes are interactive and iterative. Thus, it may be necessary to repeat some or all of the above steps more than once if less than satisfactory results are obtained.

In order to be effective, all professionals must keep current in their fields of endeavor. The design engineer can satisfy this in a number of ways by: being an active member of a professional society such as the American Society of Mechanical Engineers (ASME), the Society of Automotive Engineers (SAE), and the Society of Manufacturing Engineers (SME); attending meetings, conferences, and seminars of societies, manufacturers, universities, etc.; taking specific graduate courses or programs at universities; regularly reading technical and professional journals; etc. An engineer's education does not end at graduation.

The design engineer's professional obligations include conducting activities in an ethical manner. Reproduced here is the *Engineers' Creed* from the National Society of Professional Engineers (NSPE)[4]:

> *As a Professional Engineer I dedicate my professional knowledge and skill to the advancement and betterment of human welfare.*
> *I pledge:*
> *To give the utmost of performance;*
> *To participate in none but honest enterprise;*
> *To live and work according to the laws of man and the highest standards of professional conduct;*
> *To place service before profit, the honor and standing of the profession before personal advantage, and the public welfare above all other considerations.*
> *In humility and with need for Divine Guidance, I make this pledge.*

[4]Adopted by the National Society of Professional Engineers, June 1954. "The Engineer's Creed." Reprinted by permission of the National Society of Professional Engineers. This has been expanded and revised by NSPE. For the current revision, January 2006, see the website www.nspe.org/ethics/ehl-code.asp, or the pdf file, www.nspe.org/ethics/code-2006-Jan.pdf.

1–6 Standards and Codes

A *standard* is a set of specifications for parts, materials, or processes intended to achieve uniformity, efficiency, and a specified quality. One of the important purposes of a standard is to place a limit on the number of items in the specifications so as to provide a reasonable inventory of tooling, sizes, shapes, and varieties.

A *code* is a set of specifications for the analysis, design, manufacture, and construction of something. The purpose of a code is to achieve a specified degree of safety, efficiency, and performance or quality. It is important to observe that safety codes *do not* imply *absolute safety*. In fact, absolute safety is impossible to obtain. Sometimes the unexpected event really does happen. Designing a building to withstand a 120 mi/h wind does not mean that the designers think a 140 mi/h wind is impossible; it simply means that they think it is highly improbable.

All of the organizations and societies listed below have established specifications for standards and safety or design codes. The name of the organization provides a clue to the nature of the standard or code. Some of the standards and codes, as well as addresses, can be obtained in most technical libraries. The organizations of interest to mechanical engineers are:

Aluminum Association (AA)
American Gear Manufacturers Association (AGMA)
American Institute of Steel Construction (AISC)
American Iron and Steel Institute (AISI)
American National Standards Institute (ANSI)[5]
ASM International[6]
American Society of Mechanical Engineers (ASME)
American Society of Testing and Materials (ASTM)
American Welding Society (AWS)
American Bearing Manufacturers Association (ABMA)[7]
British Standards Institution (BSI)
Industrial Fasteners Institute (IFI)
Institution of Mechanical Engineers (I. Mech. E.)
International Bureau of Weights and Measures (BIPM)
International Standards Organization (ISO)
National Institute for Standards and Technology (NIST)[8]
Society of Automotive Engineers (SAE)

1–7 Economics

The consideration of cost plays such an important role in the design decision process that we could easily spend as much time in studying the cost factor as in the study of the entire subject of design. Here we introduce only a few general concepts and simple rules.

[5]In 1966 the American Standards Association (ASA) changed its name to the United States of America Standards Institute (USAS). Then, in 1969, the name was again changed, to American National Standards Institute, as shown above and as it is today. This means that you may occasionally find ANSI standards designated as ASA or USAS.

[6]Formally American Society for Metals (ASM). Currently the acronym ASM is undefined.

[7]In 1993 the Anti-Friction Bearing Manufacturers Association (AFBMA) changed its name to the American Bearing Manufacturers Association (ABMA).

[8]Former National Bureau of Standards (NBS).

First, observe that nothing can be said in an absolute sense concerning costs. Materials and labor usually show an increasing cost from year to year. But the costs of processing the materials can be expected to exhibit a decreasing trend because of the use of automated machine tools and robots. The cost of manufacturing a single product will vary from city to city and from one plant to another because of overhead, labor, taxes, and freight differentials and the inevitable slight manufacturing variations.

Standard Sizes

The use of standard or stock sizes is a first principle of cost reduction. An engineer who specifies an AISI 1020 bar of hot-rolled steel 53 mm square has added cost to the product, provided that a bar 50 or 60 mm square, both of which are preferred sizes, would do equally well. The 53-mm size can be obtained by special order or by rolling or machining a 60-mm square, but these approaches add cost to the product. To ensure that standard or preferred sizes are specified, designers must have access to stock lists of the materials they employ.

A further word of caution regarding the selection of preferred sizes is necessary. Although a great many sizes are usually listed in catalogs, they are not all readily available. Some sizes are used so infrequently that they are not stocked. A rush order for such sizes may mean more on expense and delay. Thus you should also have access to a list such as those in Table A–17 for preferred inch and millimeter sizes.

There are many purchased parts, such as motors, pumps, bearings, and fasteners, that are specified by designers. In the case of these, too, you should make a special effort to specify parts that are readily available. Parts that are made and sold in large quantities usually cost somewhat less than the odd sizes. The cost of rolling bearings, for example, depends more on the quantity of production by the bearing manufacturer than on the size of the bearing.

Large Tolerances

Among the effects of design specifications on costs, tolerances are perhaps most significant. Tolerances, manufacturing processes, and surface finish are interrelated and influence the producibility of the end product in many ways. Close tolerances may necessitate additional steps in processing and inspection or even render a part completely impractical to produce economically. Tolerances cover dimensional variation and surface-roughness range and also the variation in mechanical properties resulting from heat treatment and other processing operations.

Since parts having large tolerances can often be produced by machines with higher production rates, costs will be significantly smaller. Also, fewer such parts will be rejected in the inspection process, and they are usually easier to assemble. A plot of cost versus tolerance/machining process is shown in Fig. 1–2, and illustrates the drastic increase in manufacturing cost as tolerance diminishes with finer machining processing.

Breakeven Points

Sometimes it happens that, when two or more design approaches are compared for cost, the choice between the two depends on a set of conditions such as the quantity of production, the speed of the assembly lines, or some other condition. There then occurs a point corresponding to equal cost, which is called the *breakeven point.*

Figure 1–2

Cost versus tolerance/machining process.
(From David G. Ullman, The Mechanical Design Process, *3rd ed., McGraw-Hill, New York, 2003.)*

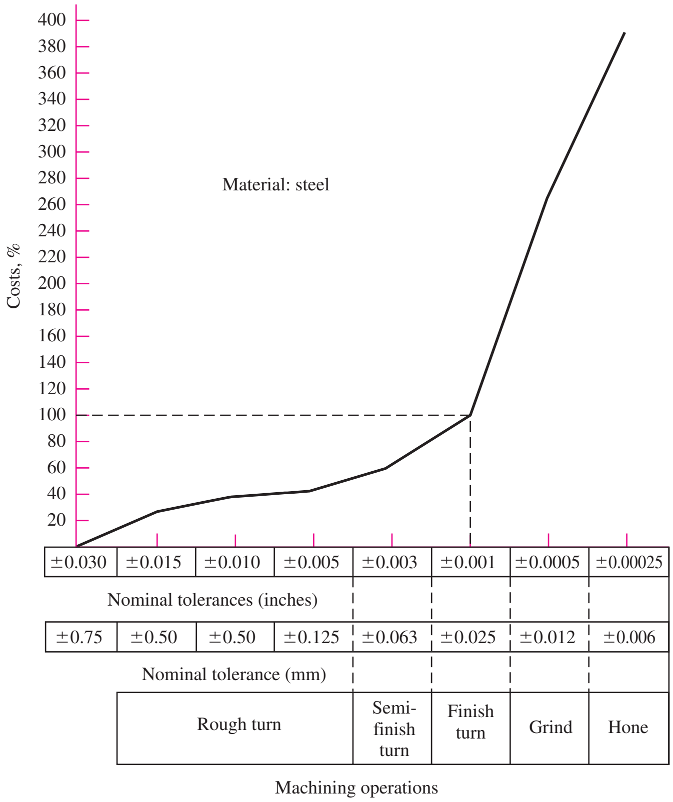
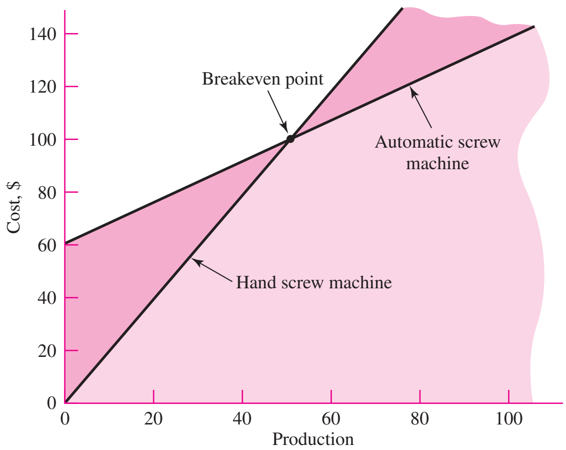


Figure 1–3

A breakeven point.



As an example, consider a situation in which a certain part can be manufactured at the rate of 25 parts per hour on an automatic screw machine or 10 parts per hour on a hand screw machine. Let us suppose, too, that the setup time for the automatic is 3 h and that the labor cost for either machine is \$20 per hour, including overhead. Figure 1–3 is a graph of cost versus production by the two methods. The breakeven point for this example corresponds to 50 parts. If the desired production is greater than 50 parts, the automatic machine should be used.

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