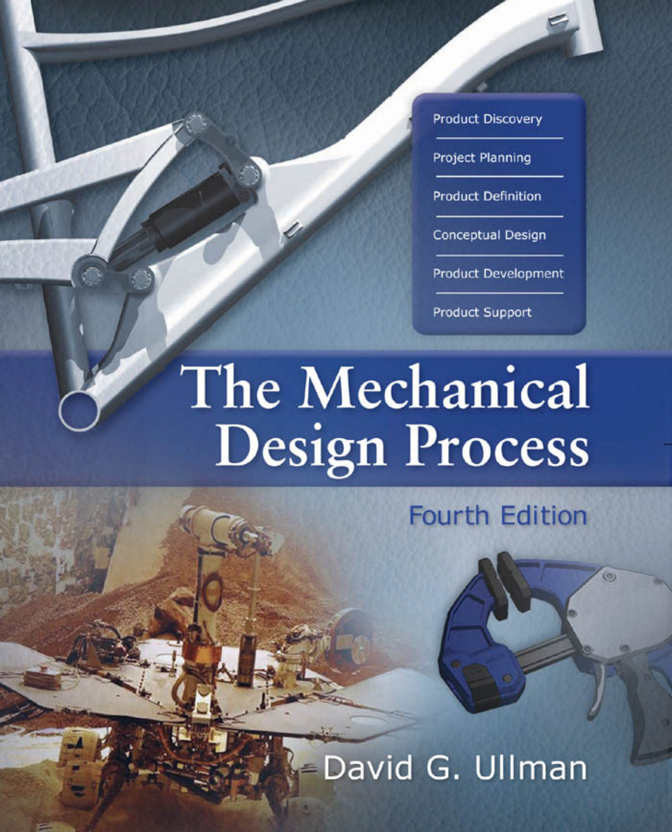

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Fourth Edition

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David G. Ullman is an active product designer who has taught, researched, and written about design for over thirty years. He is president of Robust Decisions, Inc., a supplier of software products and training for product development and decision support. He is Emeritus Professor of Mechanical Design at Oregon State University. He has professionally designed fluid/thermal, control, and transportation systems. He has published over twenty papers focused on understanding the mechanical product design process and the development of tools to support it. He is founder of the American Society Mechanical Engineers (ASME)—Design Theory and Methodology Committee and is a Fellow in the ASME. He holds a Ph.D. in Mechanical Engineering from the Ohio State University.

CONTENTS

PREFACE

I have been a designer all my life. I have designed bicycles, medical equipment, furniture, and sculpture, both static and dynamic. Designing objects has come easy for me. I have been fortunate in having whatever talents are necessary to be a successful designer. However, after a number of years of teaching mechanical design courses, I came to the realization that I didn't know how to teach what I knew so well. I could show students examples of good-quality design and poor-quality design. I could give them case histories of designers in action. I could suggest design ideas. But I could not tell them what to do to solve a design problem. Additionally, I realized from talking with other mechanical design teachers that I was not alone.

This situation reminded me of an experience I had once had on ice skates. As a novice skater I could stand up and go forward, lamely. A friend (a teacher by trade) could easily skate forward and backward as well. He had been skating since he was a young boy, and it was second nature to him. One day while we were skating together, I asked him to teach me how to skate backward. He said it was easy, told me to watch, and skated off backward. But when I tried to do what he did, I immediately fell down. As he helped me up, I asked him to tell me exactly what to do, not just show me. After a moment's thought, he concluded that he couldn't actually describe the feat to me. I still can't skate backward, and I suppose he still can't explain the skills involved in skating backward. The frustration that I felt falling down as my friend skated with ease must have been the same emotion felt by my design students when I failed to tell them exactly what to do to solve a design problem.

This realization led me to study the process of mechanical design, and it eventually led to this book. Part has been original research, part studying U.S. industry, part studying foreign design techniques, and part trying different teaching approaches on design classes. I came to four basic conclusions about mechanical design as a result of these studies:

1. The only way to learn about design is to do design.
2. In engineering design, the designer uses three types of knowledge: knowledge to generate ideas, knowledge to evaluate ideas and make decisions, and knowledge to structure the design process. Idea generation comes from experience and natural ability. Idea evaluation comes partially from experience and partially from formal training, and is the focus of most engineering education. Generative and evaluative knowledge are forms of domain-specific knowledge. Knowledge about the design process and decision making is largely independent of domain-specific knowledge.
3. A design process that results in a quality product can be learned, provided there is enough ability and experience to generate ideas and enough experience and training to evaluate them.

4. A design process should be learned in a dual setting: in an academic environment and, at the same time, in an environment that simulates industrial realities.

I have incorporated these concepts into this book, which is organized so that readers can learn about the design process at the same time they are developing a product. Chaps. 1–3 present background on mechanical design, define the terms that are basic to the study of the design process, and discuss the human element of product design. Chaps. 4–12, the body of the book, present a step-by-step development of a design method that leads the reader from the realization that there is a design problem to a solution ready for manufacture and assembly. This material is presented in a manner independent of the exact problem being solved. The techniques discussed are used in industry, and their names have become buzzwords in mechanical design: quality function deployment, decision-making methods, concurrent engineering, design for assembly, and Taguchi's method for robust design. These techniques have all been brought together in this book. Although they are presented sequentially as step-by-step methods, the overall process is highly iterative, and the steps are merely a guide to be used when needed.

As mentioned earlier, domain knowledge is somewhat distinct from process knowledge. Because of this independence, a successful product can result from the design process regardless of the knowledge of the designer or the type of design problem. Even students at the freshman level could take a course using this text and learn most of the process. However, to produce any reasonably realistic design, substantial domain knowledge is required, and it is assumed throughout the book that the reader has a background in basic engineering science, material science, manufacturing processes, and engineering economics. Thus, this book is intended for upper-level undergraduate students, graduate students, and professional engineers who have never had a formal course in the mechanical design process.

ADDITIONS TO THE FOURTH EDITION

Knowledge about the design process is increasing rapidly. A goal in writing the fourth edition was to incorporate this knowledge into the unified structure—one of the strong points of the first three editions. Throughout the new edition, topics have been updated and integrated with other best practices in the book. Some specific additions to the new edition include:

1. Improved material to ensure team success.
2. Over twenty blank templates are available for download from the book's website (www.mhhe.com/ullman4e) to support activities throughout the design process. The text includes many of them filled out for student reference.
3. Improved material on project planning.

4. Improved sections on Design for the Environment and Design for Sustainability.
5. Improved material on making design decisions.
6. A new section on using contradictions to generate ideas.
7. New examples from the industry, with new photos and diagrams to illustrate the examples throughout.

Beyond these, many small changes have been made to keep the book current and useful.

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CHAPTER 1

Why Study the Design Process?

KEY QUESTIONS

- What can be done to design quality mechanical products on time and within budget?
- What are the ten key features of design best practice that will lead to better products?
- What are the phases of a product's life cycle?
- How are design problems different from analysis problems?
- Why is it during design, the more you know, the less design freedom you have?
- What are the Hanover Principles?

1.1 INTRODUCTION

Beginning with the simple potter's wheel and evolving to complex consumer products and transportation systems, humans have been designing mechanical objects for nearly five thousand years. Each of these objects is the end result of a long and often difficult design process. This book is about that process. Regardless of whether we are designing gearboxes, heat exchangers, satellites, or doorknobs, there are certain techniques that can be used during the design process to help ensure successful results. Since this book is about the *process* of mechanical design, it focuses not on the design of any one type of object but on techniques that apply to the design of all types of mechanical objects.

If people have been designing for five thousand years and there are literally millions of mechanical objects that work and work well, why study the design process? The answer, simply put, is that there is a continuous need for new, cost-effective, high-quality products. Today's products have become so complex that most require a team of people from diverse areas of expertise to develop an idea into hardware. The more people involved in a project, the greater is the need for assistance in communication and structure to ensure nothing important is overlooked and customers will be satisfied. In addition, the global marketplace has fostered the need to develop new products at a very rapid and accelerating pace. To compete in this market, a company must be very efficient in the design of its products. It is the process that will be studied here that determines the efficiency of new product development. Finally, it has been estimated that 85% of the problems with new products not working as they should, taking too long to bring to market, or costing too much are the result of a poor design process.

The goal of this book is to give you the tools to develop an efficient design process regardless of the product being developed. In this chapter the important features of design problems and the processes for solving them will be introduced. These features apply to any type of design problem, whether for mechanical, electrical, software, or construction projects. Subsequent chapters will focus more on mechanical design, but even these can be applied to a broader range of problems.

Consider the important factors that determine the success or failure of a product (Fig. 1.1). These factors are organized into three ovals representing those factors important to product design, business, and production.

Product design factors focus on the product's function, which is a description of what the object does. The importance of function to the designer is a major topic of this book. Related to the function are the product's form, materials, and manufacturing processes. Form includes the product's architecture, its shape, its color, its texture, and other factors relating to its structure. Of equal importance to form are the materials and manufacturing processes used to produce the product. These four variables—function, form, materials, and manufacturing processes—

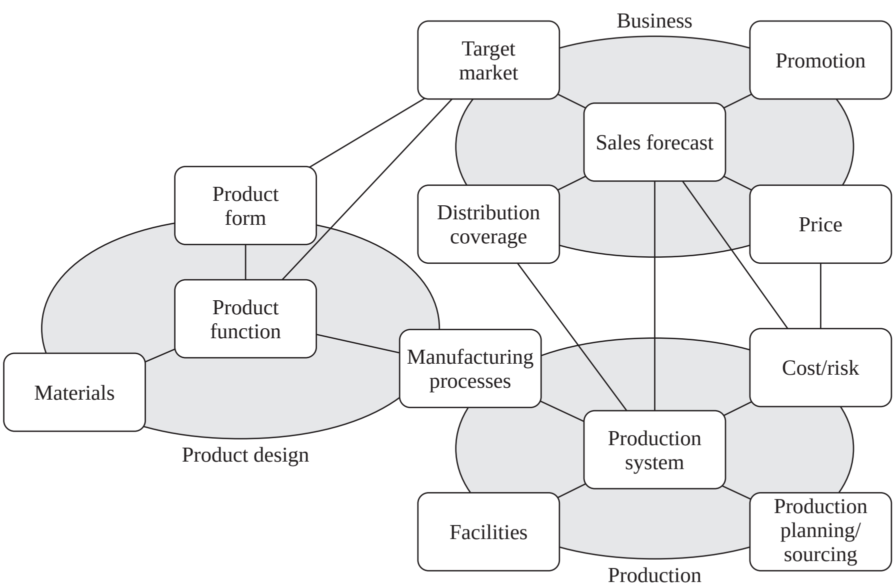

Figure 1.1 Controllable variables in product development.

are of major concern to the designer. This product design oval is further refined in Fig. 9.3.

The product form and function is also important to the business because the customers in the target market judge a product primarily on what it does (its function) and how it looks (its form). The target market is one factor important to the business, as shown in Fig. 1.1. The goal of a business is to make money—to meet its sales forecasts. Sales are also affected by the company's ability to promote the product, distribute the product, and price the product, as shown in Fig. 1.1.

The business is dependent not only on the product form and function, but also on the company's ability to produce the product. As shown in the production oval in Fig. 1.1, the production system is the central factor. Notice how product design and production are both concerned with manufacturing processes. The choice of form and materials that give the product function affects the manufacturing processes that can be used. These processes, in turn, affect the cost and hence the price of the product. This is just one example of how intertwined product design, production, and businesses truly are. In this book we focus on the product design oval. But, we will also pay much attention to the business and production variables that are related to design. As shown in the upcoming sections, the design process has a great effect on product cost, quality, and time to market.

1.2 MEASURING THE DESIGN PROCESS WITH PRODUCT COST, QUALITY, AND TIME TO MARKET

The three measures of the effectiveness of the design process are product cost, quality, and time to market. Regardless of the product being designed—whether it is an entire system, some small subpart of a larger product, or just a small change in an existing product—the customer and management always want it cheaper (lower cost), better (higher quality), and faster (less time).

The actual cost of designing a product is usually a small part of the manufacturing cost of a product, as can be seen in Fig. 1.2, which is based on data from Ford Motor Company. The data show that only 5% of the manufacturing cost of a car (the cost to produce the car but not to distribute or sell it) is for design activities that were needed to develop it. This number varies with industry and product, but for most products the cost of design is a small part of the manufacturing cost.

However, the effect of the quality of the design on the manufacturing cost is much greater than 5%. This is most accurately shown from the results of a detailed study of 18 different automatic coffeemakers. Each coffeemaker had the same function—to make coffee. The results of this study are shown in Fig. 1.3. Here the effects of changes in manufacturing efficiency, such as material cost, labor wages, and cost of equipment, have been separated from the effects of the design process. Note that manufacturing efficiency and design have about the same influence on the cost of manufacturing a product. The figure shows that

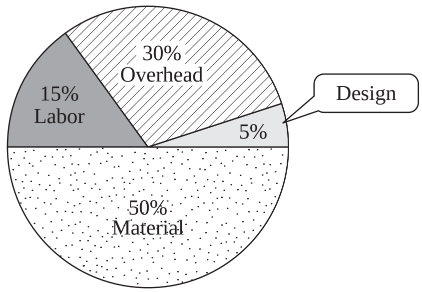

Figure 1.2 Design cost as fraction of manufacturing cost.

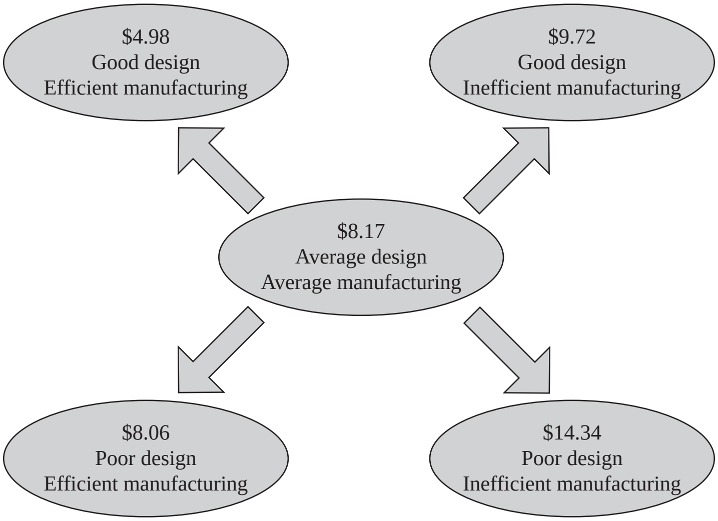

Figure 1.3 The effect of design on manufacturing cost.
(Source: Data reduced from "Assessing the Importance of Design through Product Archaeology," *Management Science*, Vol. 44, No. 3, pp. 352–369, March 1998, by K. Ulrich and S. A. Pearson.)

> Designers cost little, their impact on product cost, great.

good design, regardless of manufacturing efficiency, cuts the cost by about 35%. In some industries this effect is as high as 75%.

Thus, comparing Fig. 1.2 to Fig. 1.3, we can conclude that *the decisions made during the design process have a great effect on the cost of a product but cost very little*. Design decisions directly determine the materials used, the goods

> Product cost is committed early in the design process and spent late in the process.

purchased, the parts, the shape of those parts, the product sold, the price of the product, and the sales.

Another example of the relationship of the design process to cost comes from Xerox. In the 1960s and early 1970s, Xerox controlled the copier market. However, by 1980 there were over 40 different manufacturers of copiers in the marketplace and Xerox's share of the market had fallen significantly. Part of the problem was the cost of Xerox's products. In fact, in 1980 Xerox realized that some producers were able to sell a copier for less than Xerox was able to manufacture one of similar functionality. In one study of the problem, Xerox focused on the cost of individual parts. Comparing plastic parts from their machines and ones that performed a similar function in Japanese and European machines, they found that Japanese firms could produce a part for 50% less than American or European firms. Xerox attributed the cost difference to three factors: materials costs were 10% less in Japan, tooling and processing costs were 15% less, and the remaining 25% (half of the difference) was attributable to how the parts were designed.

Not only is much of the product cost committed during the design process, it is committed early in the design process. As shown in Fig. 1.4, about 75% of the manufacturing cost of a typical product is committed by the end of the conceptual phase process. This means that decisions made after this time can influence only 25% of the product's manufacturing cost. Also shown in the figure is the amount of cost incurred, which is the amount of money spent on the design of the product.

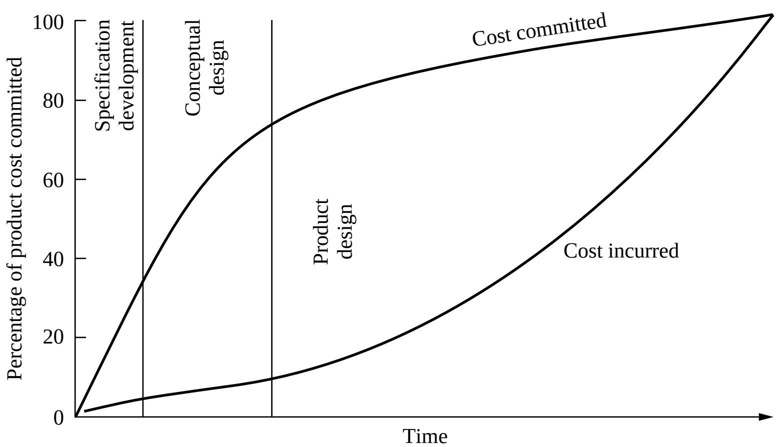

Figure 1.4 Manufacturing cost commitment during design.

Table 1.1 What determines quality

	1989	2002
Works as it should	4.99 (1)	4.58 (1)
Lasts a long time	4.75 (2)	3.93 (5)
Is easy to maintain	4.65 (3)	3.29 (5)
Looks attractive	2.95 (4–5)	3.58 (3–4)
Incorporates latest technology/features	2.95 (4–5)	3.58 (3–4)

Scale: 5 = very important, 1 = not important at all, brackets denote rank.
Sources: Based on a survey of consumers published in *Time,* Nov. 13, 1989, and a survey based on quality professional, R. Sebastianelli and N. Tamimi, "How Product Quality Dimensions Relate to Defining Quality," *International Journal of Quality and Reliability Management,* Vol. 19, No. 4, pp. 442–453, 2002.

It is not until money is committed for production that large amounts of capital are spent.

The results of the design process also have a great effect on product quality. In a survey taken in 1989, American consumers were asked, "What determines quality?" Their responses, shown in Table 1.1, indicate that "quality" is a composite of factors that are the responsibility of the design engineer. In a 2002 survey of engineers responsible for quality, what is important to "quality" is little changed. Although the surveys were of different groups, it is interesting to note that in the thirteen years between surveys, the importance of being easy to maintain has dropped, but the main measures of quality have remained unchanged.

Note that the most important quality measure is "works as it should." This, and "incorporates latest technology/features," are both measures of product function. "Lasts a long time" and most of the other quality measures are dependent on the form designed and on the materials and the manufacturing process selected. What is evident is that the decisions made during the design process determine the product's quality.

Besides affecting cost and quality, the design process also affects the time it takes to produce a new product. Consider Fig. 1.5, which shows the number of design changes made by two automobile companies with different design philosophies. The data points for Company B are actual for a U.S. automobile manufacturer, and the dashed line for Company A is what is typical for Toyota. Iteration, or change, is an essential part of the design process. However, changes occurring late in the design process are more expensive than those occurring earlier, as prior work is scrapped. The curve for Company B shows that the company was still making changes after the design had been released for production. In fact, over 35% of the cost of the product occurred after it was in production. In essence, Company B was still designing the automobile as it was being sold as a product. This causes tooling and assembly-line changes during production and the possibility of recalling cars for retrofit, both of which would necessitate significant expense, to say nothing about the loss of customer confidence. Company A, on the other hand, made many changes early in the design process and finished the design of the car before it went into production. Early design changes require more engineering time and effort but do not require changes in hardware or documentation. A change that would cost $1000 in engineering time if made

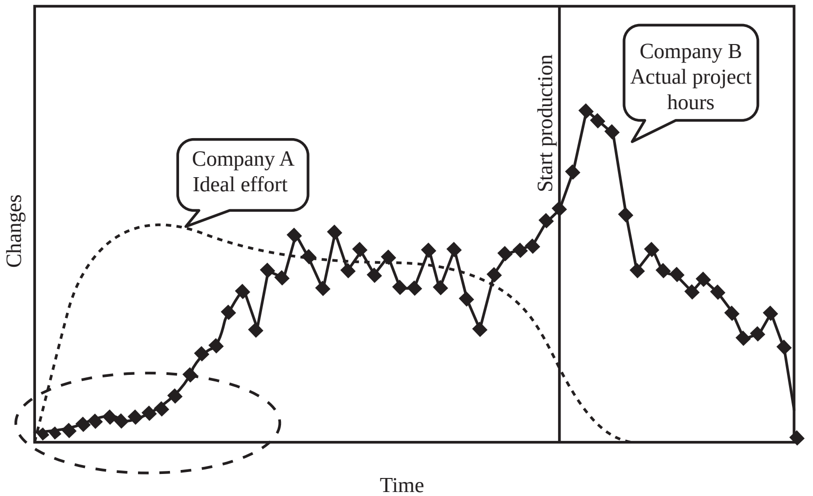

Figure 1.5 Engineering changes during automobile development.
(Source: Data from Tom Judd, Cognition Corp., "Taking DFSS to the Next Level," WCBF, Design for Six Sigma Conference, Las Vegas, June 2005.)

Fail early; fail often.

early in the design process may cost $10,000 later during product refinement and $1,000,000 or more in tooling, sales, and goodwill expenses if made after production has begun.

Figure 1.5 also indicates that Company A took less time to design the automobile than Company B. This is due to differences in the design philosophies of the companies. Company A assigns a large engineering staff to the project early in product development and encourages these engineers to utilize the latest in design techniques and to explore all the options early to preclude the need for changes later on. Company B, on the other hand, assigns a small staff and pressures them for quick results, in the form of hardware, discouraging the engineers from exploring all options (the region in the oval in the figure). The design axiom, *fail early, fail often,* applies to this example. Changes are required in order to find a good design, and early changes are easier and less expensive than changes made later. The engineers in Company B spend much time "firefighting" after the product is in production. In fact, many engineers spend as much as 50% of their time firefighting for companies similar to Company B.

An additional way that the design process affects product development time is in how long it takes to bring a product to market. Prior to the 1980s there was little emphasis on the length of time to develop new products, Since then competition has forced new products to be introduced at a faster and faster rate. During the 1990s development time in most industries was cut by half. This trend has continued into the twenty-first century. More on how the design process has played a major role in this reduction is in Chap. 4.

Finally, for many years it was believed that there was a trade-off between high-quality products and low costs or time—namely, that it costs more and takes more time to develop and produce high-quality products. However, recent experience has shown that increasing quality and lowering costs and time can go hand in hand. Some of the examples we have discussed and ones throughout the rest of the book reinforce this point.

1.3 THE HISTORY OF THE DESIGN PROCESS

During design activities, ideas are developed into hardware that is usable as a product. Whether this piece of hardware is a bookshelf or a space station, it is the result of a process that combines people and their knowledge, tools, and skills to develop a new creation. This task requires their time and costs money, and if the people are good at what they do and the environment they work in is well structured, they can do it efficiently. Further, if they are skilled, the final product will be well liked by those who use it and work with it—the customers will see it as a quality product. *The design process, then, is the organization and management of people and the information they develop in the evolution of a product.*

In simpler times, one person could design and manufacture an entire product. Even for a large project such as the design of a ship or a bridge, one person had sufficient knowledge of the physics, materials, and manufacturing processes to manage all aspects of the design and construction of the project.

By the middle of the twentieth century, products and manufacturing processes had become so complex that one person no longer had sufficient knowledge or time to focus on all the aspects of the evolving product. Different groups of people became responsible for marketing, design, manufacturing, and overall management. This evolution led to what is commonly known as the "over-the-wall" design process (Fig. 1.6).

In the structure shown in Fig. 1.6, the engineering design process is walled off from the other product development functions. Basically, people in marketing communicate a perceived market need to engineering either as a simple, written request or, in many instances, orally. This is effectively a one-way communication and is thus represented as information that is "thrown over the wall."

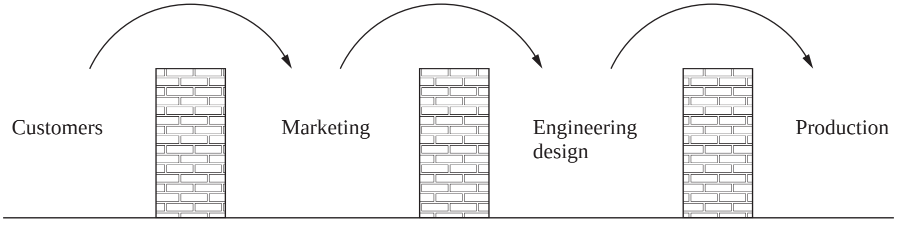

Figure 1.6 The over-the-wall design method.

Engineering interprets the request, develops concepts, and refines the best concept into manufacturing specifications (i.e., drawings, bills of materials, and assembly instructions). These manufacturing specifications are thrown over the wall to be produced. Manufacturing then interprets the information passed to it and builds what it thinks engineering wanted.

Unfortunately, often what is manufactured by a company using the over-the-wall process is not what the customer had in mind. This is because of the many weaknesses in this product development process. First, marketing may not be able to communicate to engineering a clear picture of what the customers want. Since the design engineers have no contact with the customers and limited communication with marketing, there is much room for poor understanding of the design problem. Second, design engineers do not know as much about the manufacturing processes as manufacturing specialists, and therefore some parts may not be able to be manufactured as drawn or manufactured on existing equipment. Further, manufacturing experts may know less-expensive methods to produce the product. Thus, this single-direction over-the-wall approach is inefficient and costly and may result in poor-quality products. Although many companies still use this method, most are realizing its weaknesses and are moving away from its use.

In the late 1970s and early 1980s, the concept of *simultaneous engineering* began to break down the walls. This philosophy emphasized the simultaneous development of the manufacturing process with the evolution of the product. Simultaneous engineering was accomplished by assigning manufacturing representatives to be members of design teams so that they could interact with the design engineers throughout the design process. The goal was the simultaneous development of the product and the manufacturing process.

In the 1980s the simultaneous design philosophy was broadened and called *concurrent engineering,* which, in the 1990s, became *Integrated Product and Process Design (IPPD).* Although the terms *simultaneous, concurrent,* and *integrated* are basically synonymous, the change in terms implies a greater refinement in thought about what it takes to efficiently develop a product. Throughout the rest of this text, the term *concurrent engineering* will be used to express this refinement.

In the 1990s the concepts of *Lean* and *Six Sigma* became popular in manufacturing and began to have an influence on design. Lean manufacturing concepts were based on studies of the Toyota manufacturing system and introduced in the United States in the early 1990s. Lean manufacturing seeks to eliminate waste in all parts of the system, principally through teamwork. This means eliminating products nobody wants, unneeded steps, many different materials, and people waiting downstream because upstream activities haven't been delivered on time. In design and manufacturing, the term "lean" has become synonymous with minimizing the time to do a task and the material to make a product. The Lean philosophy will be refined in later chapters.

Where Lean focuses on time, Six Sigma focuses on quality. Six Sigma, sometimes written as (6σ) was developed at Motorola in the 1980s and popularized in the 1990s as a way to help ensure that products were manufactured to the highest

Table 1.2 The ten key features of design best practice

1.	Focus on the entire product life (Chap. 1)
2.	Use and support of design teams (Chap. 3)
3.	Realization that the processes are as important as the product (Chaps. 1 and 4)
4.	Attention to planning for information-centered tasks (Chap. 4)
5.	Careful product requirements development (Chap. 5)
6.	Encouragement of multiple concept generation and evaluation (Chaps. 6 and 7)
7.	Awareness of the decision-making process (Chap. 8)
8.	Attention to designing in quality during every phase of the design process (throughout)
9.	Concurrent development of product and manufacturing process (Chaps. 9–12)
10.	Emphasis on communication of the right information to the right people at the right time (throughout and in Section 1.4.)

standards of quality. Six Sigma uses statistical methods to account for and manage product manufacturing uncertainty and variation. Key to Six Sigma methodology is the five-step DMAIC process (Define, Measure, Analyze, Improve, and Control). Six Sigma brought improved quality to manufactured products. However, quality begins in the design of products, and processes, not in their manufacture. Recognizing this, the Six Sigma community began to emphasize quality earlier in the product development cycle, evolving DFSS (Design for Six Sigma) in the late 1990s.

Essentially DFSS is a collection of design best practices similar to those introduced in this book. DFSS is still an emerging discipline.

Beyond these formal methodologies, during the 1980s and 1990s many design process techniques were introduced and became popular. They are essential building blocks of the design philosophy introduced throughout the book.

All of these methodologies and best practices are built around a concern for the ten key features listed in Table 1.2. These ten features are covered in the chapters shown and are integrated into the philosophy covered in this book. The primary focus is on the integration of teams of people, design tools and techniques, and information about the product and the processes used to develop and manufacture it.

The use of teams, including all the “stakeholders” (people who have a concern for the product), eliminates many of the problems with the over-the-wall method. During each phase in the development of a product, different people will be important and will be included in the product development team. This mix of people with different views will also help the team address the entire life cycle of the product.

Tools and techniques connect the teams with the information. Although many of the tools are computer-based, much design work is still done with pencil and paper. Thus, the emphasis in this book is not on computer-aided design but on the techniques that affect the culture of design and the tools used to support them.

1.4 THE LIFE OF A PRODUCT

Regardless of the design process followed, every product has a life history, as described in Fig. 1.7. Here, each box represents a phase in the product’s life.

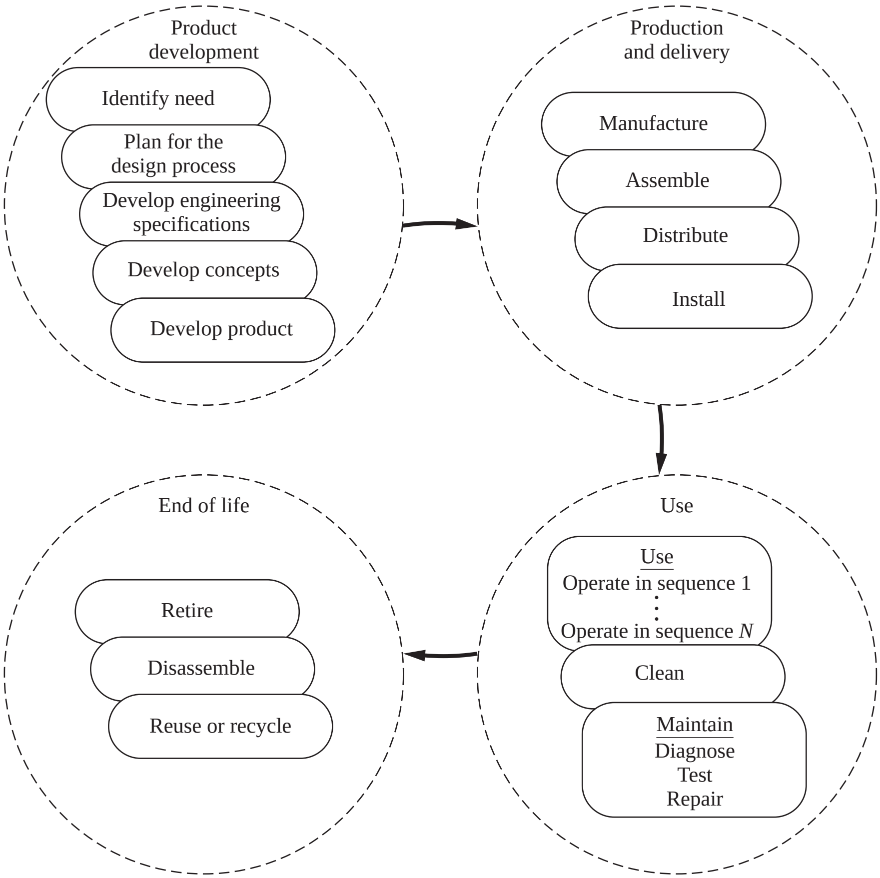

Figure 1.7 The life of a product.

These phases are grouped into four broad areas. The first area concerns the development of the product, the focus of this book. The second group of phases includes the production and delivery of the product. The third group contains all the considerations important to the product's use. And the final group focuses on what happens to the product after it is no longer useful. Each phase will be introduced in this section, and all are detailed later in the book. Note that designers, responsible for the first five phases, must fully understand all the subsequent phases if they are to develop a quality product.

The design phases are:

Identify need. Design projects are initiated either by a market requirement, the development of a new technology, or the desire to improve an existing product.

> The design process not only gives birth to a product but is also responsible for its life and death.

Plan for the design process. Efficient product development requires planning for the process to be followed. Planning for the design process is the topic of Chap. 4.

Develop engineering requirements. The importance of developing a good set of specifications has become one of the key points in concurrent engineering. It has recently been realized that the time spent evolving complete specifications prior to developing concepts saves time and money and improves quality. A technique to help in developing specifications is covered in Chap. 6.

Develop concepts. Chapters 7 and 8 focus on techniques for generating and evaluating new concepts. This is an important phase in the development of a product, as decisions made here affect all the downstream phases.

Develop product. Turning a concept into a manufacturable product is a major engineering challenge. Chapters 9–12 present techniques to make this a more reliable process. This phase ends with manufacturing specifications and release to production.

These first five phases all must take into account what will happen to the product in the remainder of its lifetime. When the design work is completed, the product is released for production, and except for engineering changes, the design engineers will have no further involvement with it.

The production and delivery phases include:

Manufacture. Some products are just assemblies of existing components. For most products, unique components need to be formed from raw materials and thus require some manufacturing. In the over-the-wall design philosophy, design engineers sometimes consider manufacturing issues, but since they are not experts, they sometimes do not make good decisions. Concurrent engineering encourages having manufacturing experts on the design team to ensure that the product can be produced and can meet cost requirements. The specific consideration of *design for manufacturing* and product cost estimation is covered in Chap. 11.

Assemble. How a product is to be assembled is a major consideration during the product design phase. Part of Chap. 11. is devoted to a technique called *design for assembly,* which focuses on making a product easy to assemble.

Distribute. Although distribution may not seem like a concern for the design engineer, each product must be delivered to the customer in a safe and cost-effective manner. Design requirements may include the need for the product to be shipped in a prespecified container or on a standard pallet. Thus, the design engineers may need to alter their product just to satisfy distribution needs.

Install. Some products require installation before the customer can use them. This is especially true for manufacturing equipment and building industry products. Additionally, concern for installation can also mean concern for how customers will react to the statement, "Some assembly required."

The goal of product development, production, and delivery is the use of the product. The "Use" phases are:

Operate. Most design requirements are aimed at specifying the use of the product. Products may have many different operating sequences that describe their use. Consider as an example a common hammer that can be used to put in nails or take them out. Each use involves a different sequence of operations, and both must be considered during the design of a hammer.

Clean. Another aspect of a product's use is keeping it clean. This can range from frequent need (e.g., public bathroom fixtures) to never. Every consumer has experienced the frustration of not being able to clean a product. This inability is seldom designed into the product on purpose; rather, it is usually simply the result of poor design.

Maintain. As shown in Fig. 1.7, to *maintain* a product requires that problems must be *diagnosed*, the diagnosis may require *tests*, and the product must be *repaired*.

Finally, every product has a finite life. End-of-life concerns have become increasingly important.

Retire. The final phase in a product's life is its retirement. In past years designers did not worry about a product beyond its use. However, during the 1980s increased concern for the environment forced designers to begin considering the entire life of their products. In the 1990s the European Union enacted legislation that makes the original manufacturer responsible for collecting and reusing or recycling its products when their usefulness is finished. This topic will be further discussed in Section 12.8.

Disassemble. Before the 1970s, consumer products could be easily disassembled for repair, but now we live in a "throwaway" society, where disassembly of consumer goods is difficult and often impossible. However, due to legislation requiring us to recycle or reuse products, the need to design for disassembling a product is returning.

Reuse or recycle. After a product has been disassembled, its parts can either be reused in other products or recycled—reduced to a more basic form and used again (e.g., metals can be melted, paper reduced to pulp again).

This emphasis on the life of a product has resulted in the concept of Product Life-cycle Management (PLM). The term PLM was coined in the fall of 2001 as a blanket term for computer systems that support both the definition or authoring of product information from cradle to grave. PLM enables management of this information in forms and languages understandable by each constituency in the product life cycle—namely, the words and representations that the engineers understand are not the same as what manufacturing or service people understand.

A predecessor to PLM was Product Data Management (PDM), which evolved in the 1980s to help control and share the product data. The change from "data" in PDM to life cycle in PLM reflects the realization that there is more to a product than the description of its geometry and function—the processes are also important.

As shown in Fig. 1.8, PLM integrates six different major types of information. In the past these were separate, and communications between the communities

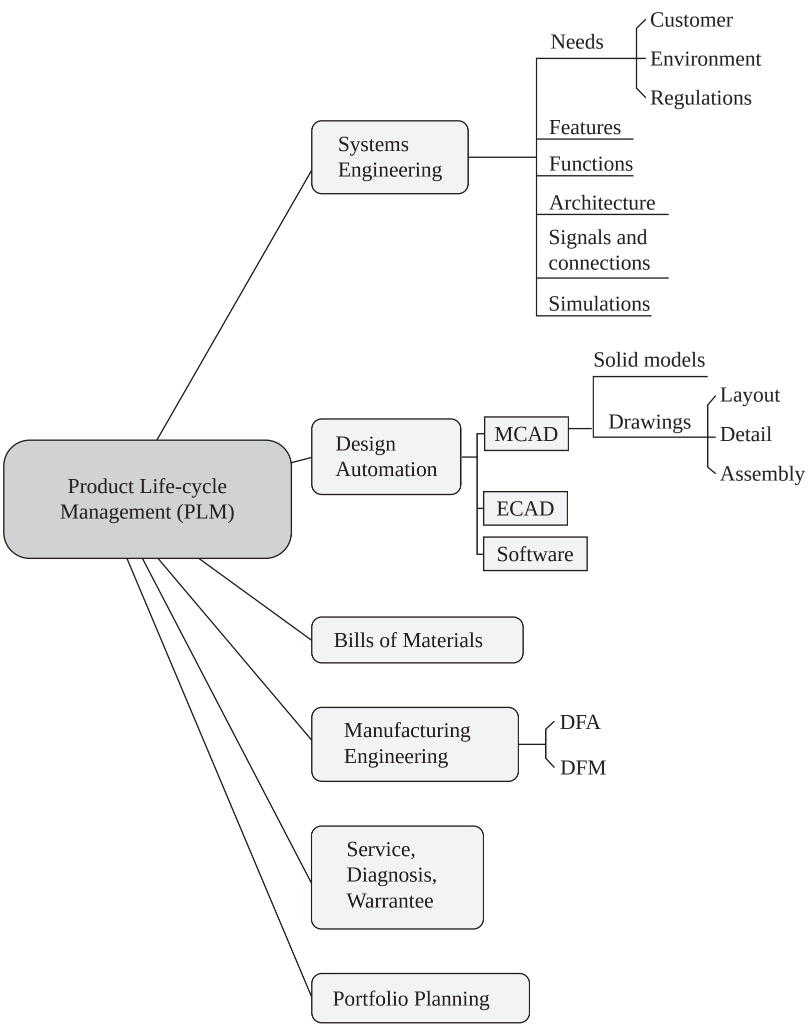

Figure 1.8 Product Life-cycle Management.

was poor (think of the over-the-wall method, Fig. 1.6). Whereas Fig. 1.7 focuses on the activities that happen during a product's life, PLM, Fig. 1.8 focuses on the information that must be managed to support that life. What PLM calls "Systems Engineering" is support for the technical development of the function of the product. The topics listed under Systems Engineering are all covered in this book.

What historically was called CAD (Computer-Aided Design) is now often referred to as MCAD for Mechanical CAD to differentiate it from Electronic CAD (ECAD). These two, along with software are all part of *design automation*. Like most of PLM, this structure grew from the twigs to the root of the tree. Traditional drawings included layout and detailed and assembly drawings. The advent of solid models made them a part of an MCAD system.

Bills Of Materials (BOMs) are effectively parts lists. BOMs are fundamental documents for manufacturing. However, as product is evolving in systems engineering so does the BOM; early on there may be no parts to list. In manufacturing, PLM manages information about Design For Manufacturing (DFM) and Assembly (DFA).

Once the product is launched and in use, there is a need to maintain it, or as shown in Fig. 1.7, diagnose, test, and repair it. These activities are supported by service, diagnosis, and warrantee information in a PLM system. Finally, there is need to manage the product portfolio—namely, of the products that could be offered, which ones are chosen to be offered (the organization's portfolio). Portfolio decisions are the part of doing business that determines which products will be developed and sold.

This description of the life of a product and systems to manage it, gives a good basic understanding of the issues that will be addressed in this book. The rest of this chapter details the unique features of design problems and their solution processes.

1.5 THE MANY SOLUTIONS FOR DESIGN PROBLEMS

Consider this problem from a textbook on the design of machine components (see Fig. 1.9):

> *What size SAE grade 5 bolt should be used to* fasten together two pieces of 1045 sheet steel, each 4 mm thick and 6 cm wide, which are lapped over each other and loaded with 100 N?

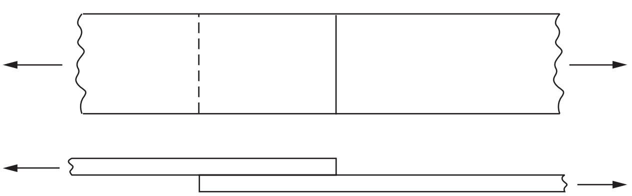

Figure 1.9 A simple lap joint.

> Design problems have many satisfactory solutions but no clear best solution.

In this problem the need is very clear, and if we know the methods for analyzing shear stress in bolts, the problem is easily understood. There is no necessity to design the joint because a design solution is already given, namely, a grade 5 bolt, with one parameter to be determined—its diameter. The product evaluation is straight from textbook formulas, and the only decision made is in determining whether we did the problem correctly.

In comparison, consider this, only slightly different, problem:

> *Design a joint to* fasten together two pieces of 1045 sheet steel, each 4 mm thick and 6 cm wide, which are lapped over each other and loaded with 100 N.

The only difference between these problems is in their opening clauses (shown in italics) and a period replacing the question mark (you might want to think about this change in punctuation). The second problem is even easier to understand than the first; we do not need to know how to design for shear failure in bolted joints. However, there is much more latitude in generating ideas for potential concepts here. It may be possible to use a bolted joint, a glued joint, a joint in which the two pieces are folded over each other, a welded joint, a joint held by magnets, a Velcro joint, or a bubble-gum joint. Which one is best depends on other, unstated factors. This problem is not as well defined as the first one. To evaluate proposed concepts, more information about the joint will be needed. In other words, the problem is not really understood at all. Some questions still need to be answered: Will the joint require disassembly? Will it be used at high temperatures? What tools are available to make the joint? What skill levels do the joint manufacturers have?

The first problem statement describes an analysis problem. To solve it we need to find the correct formula and plug in the right values. The second statement describes a design problem, which is ill-defined in that the problem statement does not give all the information needed to find the solution. The potential solutions are not given and the constraints on the solution are incomplete. This problem requires us to fill in missing information in order to understand it fully.

Another difference between the two problems is in the number of potential solutions. For the first problem there is only one correct answer. For the second there is no correct answer. In fact, there may be many good solutions to this problem, and it may be difficult if not impossible to define what is meant by the "best solution." Just consider all the different cars, televisions, and other products that compete in the same market. In each case, all the different models solve essentially the same problem, yet there are many different solutions. The goal in design is to find a good solution that leads to a quality product with the least commitment of time and other resources. *All design problems have a multitude of satisfactory solutions and no clear best solution.* This is shown graphically

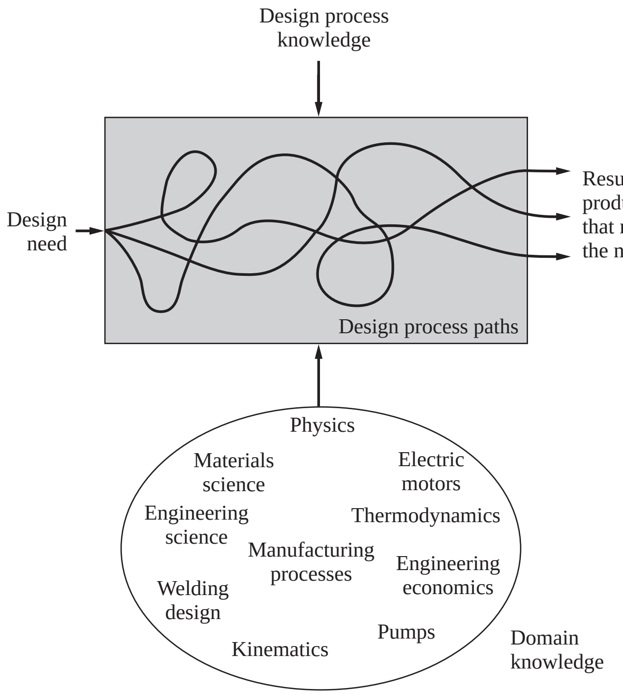

Figure 1.10 The many results of the design process.

in Fig. 1.10 where the factors that affect exactly what solution is developed are noted. Domain knowledge is developed through the study of engineering physics and other technical areas and through the observation of existing products. It is the study of science and engineering science that provides the basis on which the design process is based. Design process knowledge is the subject of this book.

For mechanical design problems in particular, there is an additional characteristic: the solution must be a piece of working hardware—a product. Thus, mechanical design problems begin with an ill-defined need and result in an object that behaves in a certain way, a way that the designers feel meets this need. This creates a paradox. *A designer must develop a device that, by definition, has the capabilities to meet some need that is not fully defined.*

1.6 THE BASIC ACTIONS OF PROBLEM SOLVING

Regardless of what design problem we are solving, we always, consciously or unconsciously, take six basic actions:

1. *Establish* the need or realize that there is a problem to be solved.
2. *Plan* how to solve the problem.

3. *Understand* the problem by developing requirements and uncovering existing solutions for similar problems.
4. *Generate* alternative solutions.
5. *Evaluate* the alternatives by comparing them to the design requirements and to each other.
6. *Decide* on acceptable solutions.

This model fits design whether we are looking at the entire product (see the product life-cycle diagram, Fig. 1.7) or the smallest detail of it.

These actions are not necessarily taken in 1-2-3 order. In fact they are often intermingled with solution generation and evaluation improving the understanding of the problem, enabling new, improved solutions to be generated. This iterative nature of design is another feature that separates it from analysis.

The list of actions is not complete. If we want anyone else on the design team to make use of our results, a seventh action is also needed:

7. *Communicate* the results.

The need that initiates the process may be very clearly defined or ill-defined. Consider the problem statements for the design of the simple lap joint of two pieces of metal given earlier (Fig. 1.9). The need was given by the problem statement in both cases. In the first statement, understanding is the knowledge of what parameters are needed to characterize a problem of this type and the equations that relate the parameters to each other (a model of the joint). There is no need to generate potential solutions, evaluate them, or make any decision, because this is an analysis problem. The second problem statement needs work to understand. The requirements for an acceptable solution must be developed, and then alternative solutions can be generated and evaluated. Some of the evaluation may be the same as the analysis problem, if one of the concepts is a bolt.

Some important observations:

- New needs are established throughout the design effort because new design problems arise as the product evolves. Details not addressed early in the process must be dealt with as they arise; thus, the design of these details poses new subproblems.
- Planning occurs mainly at the beginning of a project. Plans are always updated because understanding is improved as the process progresses.
- Formal efforts to understand new design problems continue throughout the process. Each new subproblem requires new understanding.
- There are two distinct modes of generation: concept generation and product generation. The techniques used in these two actions differ.
- Evaluation techniques also depend on the design phase; there are differences between the evaluation techniques used for concepts and those used for products.
- It is difficult to make decisions, as each decision requires a commitment based on incomplete evaluation. Additionally, since most design problems

are solved by teams, a decision requires consensus, which is often difficult to obtain.

- Communication of the information developed to others on the design team and to management is an essential part of concurrent engineering.

We will return to these observations as the design process is developed through this text.

1.7 KNOWLEDGE AND LEARNING DURING DESIGN

When a new design problem is begun, very little may be known about the solution, especially if the problem is a new one for the designer. As work on the project progresses, the designer's knowledge about the technologies involved and the alternative solutions increases, as shown in Fig. 1.11. Therefore, after completing a project, most designers want a chance to start all over in order to do the project properly now that they fully understand it. Unfortunately, few designers get the opportunity to redo their projects.

Throughout the solution process knowledge about the problem and its potential solutions is gained and, conversely, design freedom is lost. This can also be seen in Fig. 1.11, where the time into the design process is equivalent to exposure to the problem. The curve representing knowledge about the problem is a learning curve; the steeper the slope, the more knowledge is gained per unit time. Throughout most of the design process the learning rate is high. The second curve in Fig. 1.11 illustrates the degree of design freedom. As design decisions are made, the ability to change the product becomes increasingly limited. At the beginning the designer has great freedom because few decisions have been made and little capital has been committed. But by the time the product is in production,

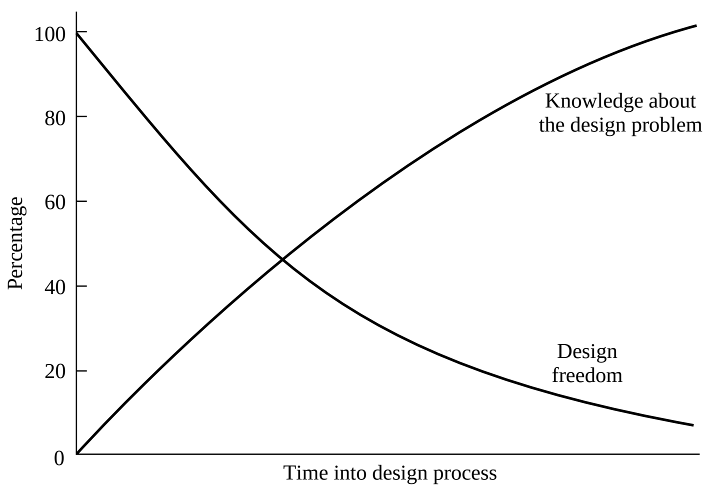

Figure 1.11 The design process paradox.

> A design paradox: The more you learn the less freedom you have to use what you know.

any change requires great expense, which limits freedom to make changes. Thus, *the goal during the design process is to learn as much about the evolving product as early as possible in the design process because during the early phases changes are least expensive.*

1.8 DESIGN FOR SUSTAINABILITY

It is important to realize that design engineers have much control over what products are designed and how they interact with the earth over their lifetime. The responsibility that goes with designing is well summarized in the Hannover Principles. These were developed for EXPO 2000, The World's Fair in Hannover, Germany. These principles define the basics of Designing For Sustainability (DFS) or Design For the Environment (DFE). DFS requires awareness of the short- and long-term consequences of your design decisions.

The Hannover Principles aim to provide a platform on which designers can consider how to adapt their work toward sustainable ends. According to the World Commission on Environment and Development, the high-level goal is "Meeting the needs of the present without compromising the ability of future generations to meet their own needs."

The Hannover Principles are:

1. **Insist on rights of humanity and nature to coexist** in a healthy, supportive, diverse, and sustainable condition.
2. **Recognize interdependence.** The elements of human design interact with and depend on the natural world, with broad and diverse implications at every scale. Expand design considerations to recognizing even distant effects.
3. **Accept responsibility for the consequences of design** decisions on human well-being, the viability of natural systems and their right to coexist.
4. **Create safe objects of long-term value.** Do not burden future generations with requirements for maintenance or vigilant administration of potential danger due to the careless creation of products, processes, or standards.
5. **Eliminate the concept of waste.** Evaluate and optimize the full life cycle of products and processes to approach the state of natural systems in which there is no waste.
6. **Rely on natural energy flows.** Human designs should, like the living world, derive their creative forces from perpetual solar income. Incorporate this energy efficiently and safely for responsible use.
7. **Understand the limitations of design.** No human creation lasts forever and design does not solve all problems. Those who create and plan should practice

> You are responsible for the impact of your products on others.

humility in the face of nature. Treat nature as a model and mentor, not as an inconvenience to be evaded or controlled.

8. **Seek constant improvement by the sharing of knowledge.** Encourage direct and open communication between colleagues, patrons, manufacturers, and users to link long-term sustainable considerations with ethical responsibility, and reestablish the integral relationship between natural processes and human activity.
9. **Respect relationships between spirit and matter.** Consider all aspects of human settlement including community, dwelling, industry, and trade in terms of existing and evolving connections between spiritual and material consciousness.

We will work to respect these principles in the chapters that follow. We introduced the concept of "lean" earlier in this chapter as the effort to reduce waste (Principle 5). We will revisit this and the other principles throughout the book. In Chap. 11, we will specifically revisit DFS as part of Design for the Environment. In Chap. 12, we focus on product retirement. Many products are retired to landfills, but in keeping with the first three principles, and focusing on the fifth principle, it is best to design products that can be reused and recycled.

1.9 SUMMARY

The design process is the organization and management of people and the information they develop in the evolution of a product.

- The success of the design process can be measured in the cost of the design effort, the cost of the final product, the quality of the final product, and the time needed to develop the product.
- Cost is committed early in the design process, so it is important to pay particular attention to early phases.
- The process described in this book integrates all the stakeholders from the beginning of the design process and emphasizes both the design of the product and concern for all processes—the design process, the manufacturing process, the assembly process, and the distribution process.
- All products have a life cycle beginning with establishing a need and ending with retirement. Although this book is primarily concerned with planning for the design process, engineering requirements development, conceptual design, and product design phases, attention to all the other phases is important. PLM systems are designed to support life-cycle information and communication.

- The mechanical design process is a problem-solving process that transforms an ill-defined problem into a final product.
- Design problems have more than one satisfactory solution.
- Design for Sustainability embodied in the Hannover Principles is becoming an increasingly important part of the design process.

1.10 SOURCES

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Ulrich, K. T., and S. A. Pearson: "Assessing the Importance of Design through Product Archaeology," *Management Science,* Vol. 44, No. 3, pp. 352–369, March 1998, or "Does Product Design Really Determine 80% of Manufacturing Cost?" working paper 3601–93, Sloan School of Management, MIT, Cambridge, Mass., 1993. In the first edition of *The Mechanical Design Process* it was stated that design determined 80% of the cost of a product. To confirm or deny that statement, researchers at MIT performed a study of automatic coffeemakers and wrote this paper. The results show that the number is closer to 50% on the average (see Fig. 1.3) but can range as high as 75%.

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1.11 EXERCISES

1.1 Change a problem from one of your engineering science classes into a design problem. Try changing as few words as possible.

1.2 Identify the basic problem-solving actions for

- **a.** Selecting a new car
- **b.** Finding an item in a grocery store
- **c.** Installing a wall-mounted bookshelf
- **d.** Placing a piece in a puzzle

1.3 Find examples of products that are very different yet solve exactly the same design problem. Different brands of automobiles, bikes, CD players, cheese slicers, wine bottle openers, and personal computers are examples. For each, list its features, cost, and perceived quality.

1.4 How well do the products in Exercise 1.3 meet the Hannover Principles?

1.5 To experience the limitations of the over-the-wall design method try this. With a group of four to six people, have one person write down the description of some object that is not familiar to the others. This description should contain at least six different nouns that describe different features of the object. Without showing the description to the others, describe the object to one other person in such a manner that the others can't hear. This can be done by whispering or leaving the room. Limit the description to what was written down. The second person now conveys the information to the third person, and so on until the last person redescribes the object to the whole group and compares it to the original written description. The modification that occurs is magnified with more complex objects and poorer communication. (Professor Mark Costello of Georgia Institute of Technology originated this problem.)

CHAPTER 2

Understanding Mechanical Design

KEY QUESTIONS

- What is the difference between function, behavior, and performance?
- Why does mechanical design flow from function to form?
- What are the languages of mechanical design?
- Are all design problems the same?
- What can you learn from dissecting products?

2.1 INTRODUCTION

For most of history, the discipline of mechanical design required knowledge of only mechanical parts and assemblies. But early in the twentieth century, electrical components were introduced in mechanical devices. Then, during World War II, in the 1940s, electronic control systems became part of the mix. Since this change, designers have often had to choose between purely mechanical systems and systems that were a mix of mechanical and electronic components and systems. These electronic systems have matured from very simple functions and logic to the incorporation of computers and complex logic. Many electromechanical products now include microprocessors. Consider, for example, cameras, office copiers, cars, and just about everything else. Systems that have mechanical, electronic, and software components are often called *mechatronic* devices. What makes the design of these devices difficult is the necessity for domain and design process knowledge in three overlapping but clearly different disciplines. But, no matter how electronic or computer-centric devices become, nearly all products require mechanical functions and a mechanical interface with humans. Additionally, all products require mechanical machinery for manufacture and assembly and mechanical components for housing. Thus, no matter how “smart” products become, there will always be the need for mechanical design.

To explore systems that have significant mechanical components consider two examples that will be used throughout the book, the Irwin Quick-Grip clamp (Fig. 2.1) and the drive wheel assembly for the NASA Mars Exploration Rover (MER) developed by Cal Tech’s Jet Propulsion Laboratory (JPL) (Fig. 2.2).

Figure 2.1 Irwin Quick-Grip clamp. (Reprinted with permission of Irwin Industrial Tools.)

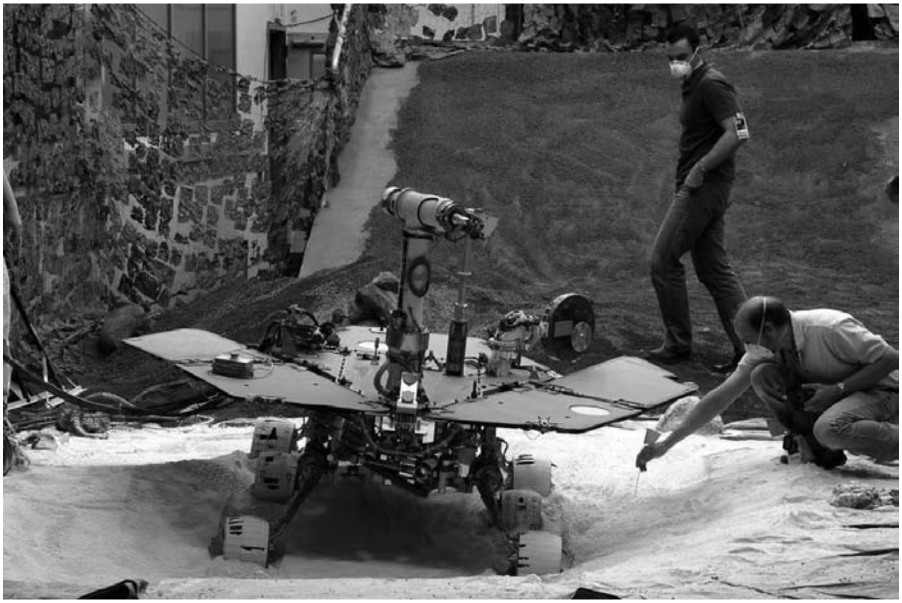


Figure 2.2 The Mars Exploration Rover being tested by JPL engineers. (Reprinted with permission of NASA/JPL.)

Irwin is one of the largest manufacturers of one-handed bar clamps. What makes the model shown in Fig 2.1 unique is that it can generate over 550 lb (250 kg) of force with the strength of only one hand. Irwin introduced this product in 2006 and sells many tens of thousands of them a month. In contrast to the purely mechanical, high-production-volume Quick-Grip, only two MERs were made and they are highly mechatronic.

The two MERs were launched toward Mars on June 10 and July 7, 2003, in search of answers about the history of water on Mars. They landed on Mars January 3 and January 24, 2004. They were designed for 90 Sol (Martian days, about 40 min longer than an Earth day) and were still operating in 2008, over 1300 Sols (over 3.5 years) past their design life. One of the Rovers, *Opportunity,* had traveled over 11 km (7.1 mi) during its five years of life.

Each Rover is a six-wheeled, solar-powered robot that stands 1.5 m (4.9 ft) high and is 2.3 m (7.5 ft) wide and 1.6 m (5.2 ft) long. They weigh 180 kg (400 lb) on Earth, 35 kg (80 lb) of which is the wheel and suspension system. Mars has only 38% the gravitational pull of Earth. So they weigh 68.4 kg (152 lb) on Mars. As shown in Fig. 2.3, a very simplified diagram of the MER's systems, propulsion and steering are two of the subsystems. Later in this chapter, we delve further into the MER, and in later chapters we will detail the wheels.

In general, during the design process the function of the system and its decomposition are considered first. After the function has been decomposed into the finest subsystems possible, assemblies and components are developed to provide these functions. For mechanical devices, the general decomposition is system–subsystem–assembly–component. Figure 2.3 shows the MER propulsion system, within which the motor and transmission are two subsystems. The wheel is a component. Systems, subsystems, and components all have *features,* specific attributes that are important, such as dimensions, material properties, shapes, or functional details. For the MER propulsion system, an important feature is that it can propel the MER at 5 cm/sec. For the transmission, a feature is that it has a 1500:1 reduction ratio. For the MER wheel, some of the important features are its diameter, tread pattern, and flexibility.

We must also note that many systems have both electrical and mechanical subsystems and components. Electrical systems generally provide energy, sensing, and control functions. The function of these electrical systems is fulfilled by circuits (electrical assemblies) that can be decomposed into electrical components (e.g., switches, transistors, and ICs), much as with mechanical objects. Finally, some of the control functions are filled by microprocessors. Physically, these are electric circuits, but the actual control function is provided by software programs in the processor. These programs are assemblies of coding modules composed of individual coding statements. Note that the function of the microprocessor could be filled by an electrical or possibly even a purely mechanical system. During the early phases of the design process, when developing systems is the focus of the effort, it is often unclear whether the actual function will be met by mechanical assemblies, electrical circuits, software programs, or a mix of these elements.

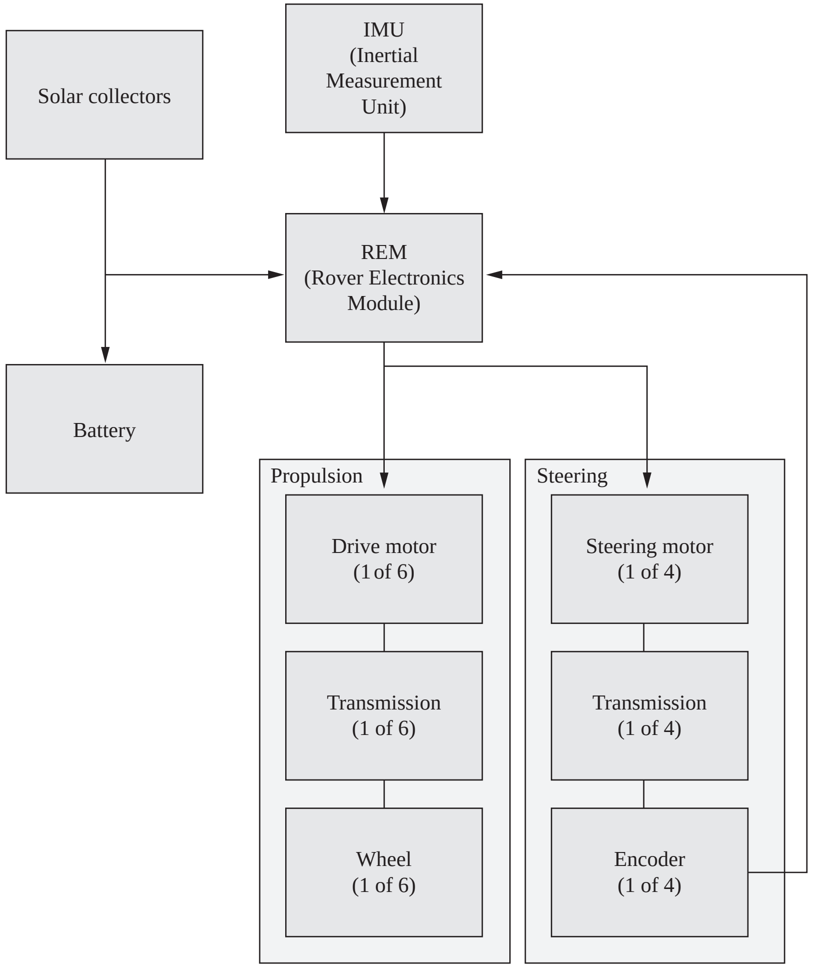


Figure 2.3 The MER Propulsion System showing some of the sub-systems and components.

2.2 IMPORTANCE OF PRODUCT FUNCTION, BEHAVIOR, AND PERFORMANCE

What is the function of the Irwin clamp? How does it behave? Does it have good performance? These three questions revolve around the terms "function," "behavior," and "performance"—similar, but different attributes of the clamp.

There are many synonyms for the word *function*. In mechanical engineering, we commonly use the terms *function*, *operation*, and *purpose* to describe *what* a device does. A common way of classifying mechanical devices is by their *function*. In fact, some devices having only one main function are named for

> Function determines form and form, in turn, enables function.

that function. For example, a screwdriver has the function of enabling a person to insert or remove a screw. The terms *drive, insert,* and *remove* are all verbs that tell what the screwdriver does. In telling what the screwdriver does, we have given no indication of how the screwdriver accomplishes its function. To discover how, we must have some information on the form of the device. The term *form* relates to any aspect of physical shape, geometry, construction, material, or size. As we shall see in Chap. 3, one of the main ways engineers mentally index their knowledge about the mechanical world is by function. Now reread this paragraph and replace the screwdriver example with the Quick-Grip clamp.

In Fig. 2.3, we physically decomposed the Mars Rover propulsion and steering systems into subsystems and components at its physical boundaries. Functional decomposition is often much more difficult than physical decomposition, as each function may use part of many components and each component may serve many functions. Consider the handlebar of a bicycle. The handlebar is a bent piece of tubing, a single component that serves many functions. It enables the rider to "steer the bicycle" ("steer" is a verb that tells what the device does), and the handlebar "supports the rider" (again, a function telling what the handlebar does). Further, it not only "supports the brake levers" but also "transforms (another function) the gripping force" to a pull on the brake cable. The shape of the handlebar and its relationship with other components determine how it provides all these different functions. The handlebar, however, is not the only component needed to steer the bike. Additional components necessary to perform this function are the front fork, the bearings between the fork and the frame, the front wheel, and miscellaneous fasteners. Actually, it can be argued that all the components on a bike contribute to steering, since a bike without a seat or rear wheel would be hard to steer. In any case, the handlebar performs many different functions, but in fulfilling these functions, the handlebar is only a part of various assemblies. Similarly, the steering on the MER cannot actually steer it without the wheels in the propulsion system. The coupling between form and function makes mechanical design challenging.

Many common devices are cataloged by their function. If we want to specify a bearing, for example, we can search a bearing catalog and find many different styles of bearings (plain, ball, or tapered roller, for example). Each "style" has a different geometry—a different form—though all have the same primary function, namely, to reduce friction between a shaft and another object. Cataloging is possible in mechanical design as long as the primary function is clearly defined by a single piece of hardware, either a single component or an assembly. In other words, the form and function are decomposed along the same boundaries. This is true of many mechanical devices, such as pumps, valves, heat exchangers, gearboxes, and fan blades, and is especially true of many electrical circuits and components, such as resistors, capacitors, and amplifier circuits.

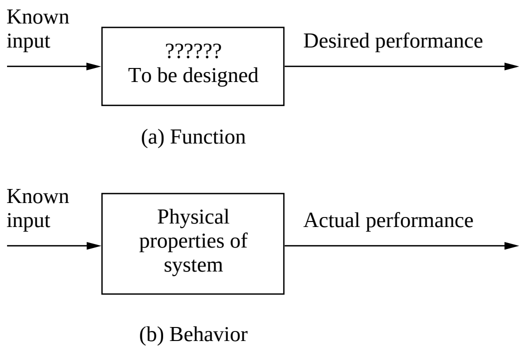


Figure 2.4 Function and behavior.

Two other terms often related to function are *behavior* and *performance. Function* and *behavior* are often used synonymously. However, there is a subtle difference, as shown in Fig. 2.4. In this figure there are two standard system blocks with an input represented by an arrow into the box, the system acted on by the input represented by the box, and the reaction of the system to the input represented by the arrow out of the box. The box in the upper part of the figure shows that *function is the desired output* from a system that is yet to be designed. When we begin to design a device, the device itself is unknown, but what we want it to do is known. If the system is known, as in the second part of the figure, then the behavior of the system can be found. *Behavior is the actual output,* the response of the system's physical properties to the input energy or control. Thus, the behavior can be simulated or measured, whereas function is only a desire.

Performance is the measure of function and behavior—how well the device does what it is designed to do. When we say that one function of the handlebar is to steer the bicycle, we say nothing about how well it serves this purpose. Before designing a handlebar, we must develop a clear picture of its desired performance. For example, one design functional goal is that the handlebar must "support 50 kg," a measurable desired performance for the handlebar. The development of clear performance measures is the focus of Chap. 6. Further, after designing the handlebar we can simulate its strength analytically or measure the strength of a prototype to find the actual performance for comparison to that desired. This comparison is a major focus of Chap. 10.

2.3 MECHANICAL DESIGN LANGUAGES AND ABSTRACTION

Many "languages" or representations can be used to describe a mechanical object. Consider for a moment the difference between a detailed drawing of a component and the actual hardware that *is* the component. Both the drawing and the hardware represent the same object; however, they each represent it in a different language.

A skilled designer speaks many languages.

Extending this example further, if the component we are discussing is a bolt, then the word *bolt* is a textual (semantic or word) description of the component, a third language. Additionally, the bolt can be represented through equations (the final language) that describe its functionality and possibly its form. For example, the ability of the bolt to "carry shear stress" (a function) is described by the equation $\tau = F/A$; the shear stress τ is equal to the shear force F on the bolt divided by the stress area A of the bolt.

Based on this, we can use four different representations or languages to describe the bolt. These four can be used to describe any mechanical object:

Semantic. The verbal or textual representation of the object—for example, the word *bolt*, or the sentence, "The shear stress on the bolt is the shear force divided by the stress area."

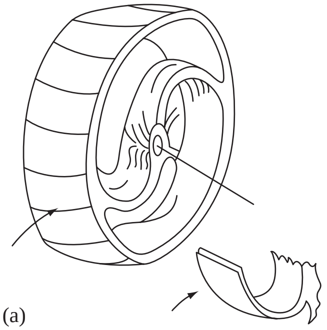
Graphical. The drawings of the object—for example, scale representations such as solid models, orthogonal drawings, sketches, or artistic renderings.

Analytical. The equations, rules, or procedures representing the form or function of the object—for example, $\tau = F/A$.

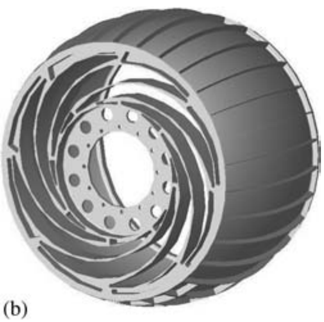
Physical. The hardware or a physical model of the object.

In most mechanical design problems, the initial need is expressed in a semantic language as a written specification or a verbal request by a customer or supervisor. The result of the design process is a physical object. Although the designer produces a graphical representation of the product, not the hardware itself, all the languages will be used as the product is refined from its initial, abstract semantic representation to its final physical form.

Further complicating how we refer to objects being designed, consider two drawings for a MER wheel, as shown in Fig. 2.5. Figure 2.5*a* is a rough sketch, which gives only abstract information about the component. It centers on the



(a)



(b)

Figure 2.5 Abstract sketch and solid model of a MER wheel.

function of the wheel's spokes to act like springs. Figure 2.5*b* is a solid model of the same component, focused on the final form of the wheel. In progressing from the sketch to the solid model, the *level of abstraction* of the device is *refined.*

Some design process techniques are better suited for abstract levels and others for levels that are more concrete. There are no true levels of abstractions, but rather a continuum on which the form or function can be represented. Descriptions of three levels of abstraction in each of the four languages are given in Table 2.1. The object we call a bolt is used as an example in Table 2.2.

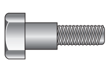
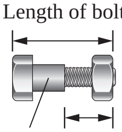
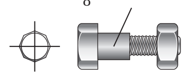
Another term that is often used in describing the analytical row in Table 2.1 is *simulation fidelity*. As analytical models or simulations increase in fidelity, their representation of the actual object or system becomes a more accurate representation of reality. Simulation fidelity will be further refined in Chap. 10.

The process of making an object less abstract (or more concrete) is called *refinement.* Mechanical design is a continuous process of refining the given needs

Table 2.1 Levels of abstraction in different languages

	Level of abstraction		
Language	**Abstract**	⟶	**Concrete**
Semantic	Qualitative words (e.g., *long, fast, lightest*)	Reference to specific parameters or components	Reference to the values of the specific parameters or components
Graphical	Rough sketches	Scale drawings	Solid models with tolerances
Analytical	Qualitative relations (e.g., *left of*)	Back-of-the-envelope calculations	Detailed analysis
Physical	None	Models of the product	Final hardware

Table 2.2 Levels of abstraction in describing a bolt

	Level of abstraction		
Language	**Abstract**	⟶	**Concrete**
Semantic	A bolt	A short bolt	A 1″ 1/4−20 UNC Grade 5 bolt
Graphical			
Analytical	Right-hand rule	$\tau = F/A$	$\tau = F/A$
Physical	—	—	

to the final hardware. The refinement of the bolt in Table 2.4 is illustrated on a left-to-right continuum. In most design situations, the beginning of the problem appears in the upper left corner and the final product in the lower right. The path connecting these is a mix of the other representations and levels of abstractions.

2.4 DIFFERENT TYPES OF MECHANICAL DESIGN PROBLEMS

Traditionally, we decompose mechanical engineering by discipline: fluids, thermodynamics, mechanics, and so on. In categorizing the types of mechanical design problems, this discipline-oriented approach is not appropriate. Consider, for example, the simplest kind of design problem, a selection design problem. Selection design means picking one (maybe more) item from a list such that the chosen item meets certain requirements. Common examples are selecting the correct bearing from a bearings catalog, selecting the correct lenses for an optical device, selecting the proper fan for cooling equipment, or selecting the proper heat exchanger for a heating or cooling process. The design process for each of these problems is essentially the same, even though the disciplines are very different. The goal of this section is to describe different types of design problems independently of the discipline.

Before beginning, we must realize that most design situations are a mix of various types of problems. For example, we might be designing a new type of consumer product that will accept a whole raw egg, break it, fry it, and deliver it on a plate. Since this is a new product, there will be a lot of *original design* work to be done. As the design process proceeds, we will *configure* the various parts. To determine the thickness of the frying surface we will analyze the heat conduction of the frying component, which is *parametric design.* And we will *select* a heating element and various fasteners to hold the components together. Further, if we are clever, we may be able to *redesign* an existing product to meet some or all of the requirements. Each of the italicized terms is a different type of design problem. It is rare to find a problem that is purely one type.

2.4.1 Selection Design

Selection design involves choosing one item (or maybe more) from a list of similar items. We do this type of design every time we choose an item from a catalog. It may sound simple, but if the catalog contains more than a few items and there are many different features to the items, the decision can be quite complex.

To solve a selection problem we must start with a clear need. The catalog or the list of choices then effectively generates potential solutions for the problem. We must evaluate the potential solutions with respect to our specific requirements to make the right choice. Consider the following example. During the process of designing a product, an engineer must select a bearing to support a shaft. The known information is given in Fig. 2.6. The shaft has a diameter of 20 mm (0.787 in.). There is a radial force of 6675 N (1500 lb) on the shaft at the bearing,

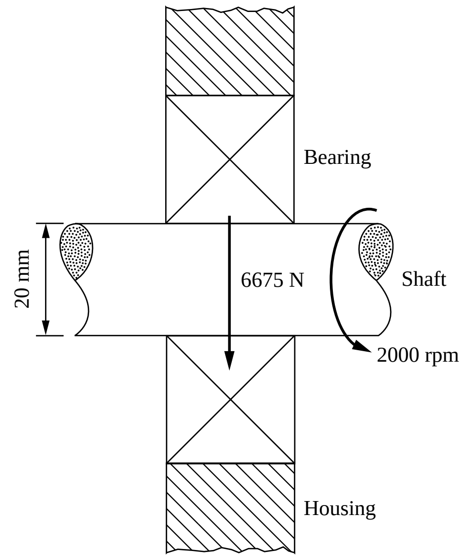


Figure 2.6 Load on a shaft.

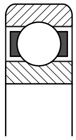
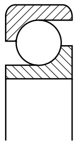
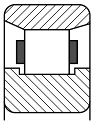
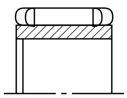
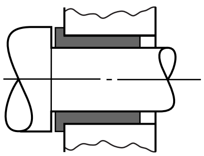
and the shaft rotates at a maximum of 2000 rpm. The housing to support the bearing is still to be designed. All we need to do is select a bearing to meet the needs. The information on shaft size, maximum radial force, and maximum rpm given in bearing catalogs enables us to quickly develop a list of potential bearings (Table 2.3). This is the simplest type of design problem we could have, but it is still incompletely defined. We do not have enough information to select among the five possible choices. Even if a short list is developed—the most likely candidates being the 42-mm-deep groove ball bearing and the 24-mm needle bearing—there is no way to make a good decision without more knowledge of the function of the bearing and of the engineering requirements on it.

2.4.2 Configuration Design

A slightly more complex type of design is called configuration or packaging design. In this type of problem, all the components have been designed and the problem is how to assemble them into the completed product. Essentially, this type of design is similar to playing with an Erector set or other construction toy, or arranging living-room furniture.

Consider packaging of the assemblies in the MER. The body of the MER is made up of a Rover Equipment Deck (RED) where all the experiments are mounted, a Rover Electronics Module (REM), an Inertial Measurement Unit (IMU), a Warm Electronics Box (WEB), a battery, a UHF radio, an X-band telecom HW, and a Solid-State Power Amplifier (SSPA), as shown in Fig. 2.7. Each of these assemblies is of known size and has certain constraints on its position. For example, the RED must be on top and the WEB on the bottom, but

Table 2.3 Potential bearings for a shaft

Type		Outside diameter (mm)	Width (mm)	Load rating (lb)	Speed limit (rpm)	Catalog number
Deep-groove ball bearing		42 47 52	8 14 15	1560 2900 3900	18,000 15,000 9000	6000 6204 6304
Angular-contact ball bearing		47 37	14 9	3000 1960	13,000 34,000	7204 71,904
Roller bearing		47 52	14 15	6200 7350	13,000 13,000	204 220
Needle bearing		24 26	20 12	1930 2800	13,000 13,000	206 208
Nylon bushing		23	Variable	290 ⋮ 8	10 ⋮ 500	4930

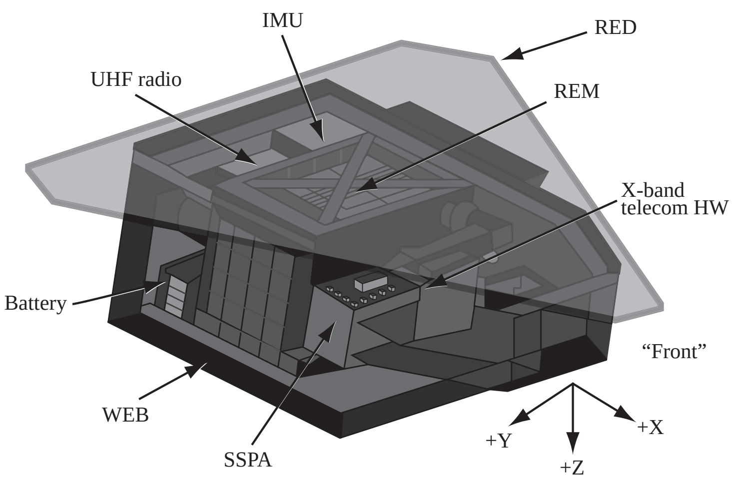


Figure 2.7 The major assemblies in the MER.

many of the other major assemblies can be anywhere inside the envelop defined by these two.

Configuration design answers the question, How do we fit all the assemblies in an envelop? or Where do we put what? One methodology for solving this type of problem is to randomly select one component from the list and position it so that all the constraints on that assembly are met. We could start with the REM in the middle, then we select and place a second component. This procedure is continued until either we run into a conflict or all the components are in the MER. If a conflict arises, we back up and try again. For many configuration problems, some of the components to be fit into the assembly can be altered in size, shape, or function, giving the designer more latitude to determine potential configurations and making the problem solution more difficult. There are other methods to configure assemblies. They will be covered in Chap. 11.

2.4.3 Parametric Design

Parametric design involves finding values for the features that characterize the object being studied. This may seem easy enough—just find some values that meet the requirements. However, consider a very simple example. We want to design a cylindrical storage tank that must hold 4 m^3 of liquid. This tank is described by the parameters r, its radius, and l, its length and its volume is determined by

$$V = \pi r^2 l$$

Given a volume equal to 4 m^3, then

$$r^2 l = 1.273$$

We can see that an infinite number of values for the radius and length will satisfy this equation. To what values should the parameters be set? The answer is not obvious, nor even completely defined with the information given. (This problem will be readdressed in Chap. 10, where the accuracy to which the radius and the length can be manufactured will be used to help find the best values for the parameters.)

Let us extend the concept further. It may be that instead of a simple equation, a whole set of equations and rules govern the design. Consider the instance in which a major manufacturer of copying machines had to design paper-feed mechanisms for each new copier. (A paper feed is a set of rollers, drive wheels, and baffles that move a piece of paper from one location to another in the machine.) Many parameters—the number of rollers, their positions, the shape of the baffles, and the like—characterize this particular design problem, but obviously there are certain similarities in paper feeders, regardless of the relative positions of the beginning and end points of the paper, the obstructions (other components in the machine) that must be cleared, and the size and weight of the paper. The company developed a set of equations and rules to aid designers in developing workable paper paths, and using this information, the designers could generate values for parameters in new products.

2.4.4 Original Design

Any time the design problem requires the development of a process, assembly, or component not previously in existence it calls for an original design. (It can be said that if we have never seen a wheel and we design one, then we have an original design.) Though most selection, configuration, and parametric problems are represented by equations, rules, or some other logical scheme, original design problems usually cannot be reduced to any algorithm. Each one represents something new and unique.

In many ways the other types of design problems—selection, configuration, and parametric—are simply constrained subsets of an original design. The potential solutions are limited to a list, an arrangement of components, or a set of related characterizing values. Thus, if we have a clear methodology for performing original design, we should be able to solve any design problem with a more limited set of potential solutions.

2.4.5 Redesign

Most design problems solved in industry are for the redesign of an existing product. Suppose a manufacturer of hydraulic cylinders makes a product that is 0.25 m long. If the customer needs a cylinder 0.3 m long, the manufacturer might lengthen the outer cylinder and the piston rod to meet this special need. These changes may require only parameter changes, or they may require something more extensive. What if the materials are not available in the needed length, or cylinder fill time becomes too slow with the added length? Then the redesign effort may require much more than parameter changes. Regardless of the change, this is an example of *redesign,* the modification of an existing product to meet new requirements.

Many redesign problems are *routine;* the design domain is so well understood that the method used can be put in a handbook as a series of formulas or rules. The parameter changes in the example of the hydraulic cylinder are probably routine for the manufacturer.

The hydraulic cylinder can also be used as an example of a *mature design,* in that it has remained virtually unchanged over many years. There are many examples of mature designs in our everyday lives: pencil sharpeners, hole punches, and staplers are a few found on the average desk. For these products, knowledge about the design problem is high. There is little more to learn.

However, consider the bicycle. The basic configuration of the bicycle—the two tensioned, spoked wheels of equal diameter, the diamond-shaped frame, and the chain drive—was fairly refined late in the nineteenth century. While the 1890 Humber shown in Fig. 2.8 looks much like a modern bicycle, not all bicycles of this era were of this configuration. The Otto dicycle, shown in Fig. 2.9, had two spoked wheels and a chain; stopping and steering this machine must have been a challenge. In fact, the technology of bicycle design was so well developed by the end of the nineteenth century that a major book on the subject, *Bicycles and Tricycles: An Elementary Treatise on Their Design and Construction, was*

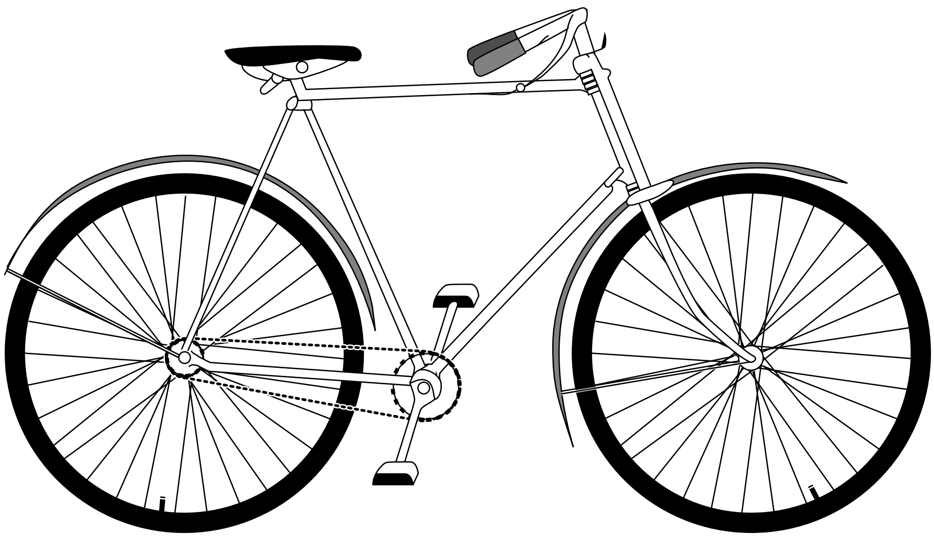


Figure 2.8 1890 Humber bicycle.

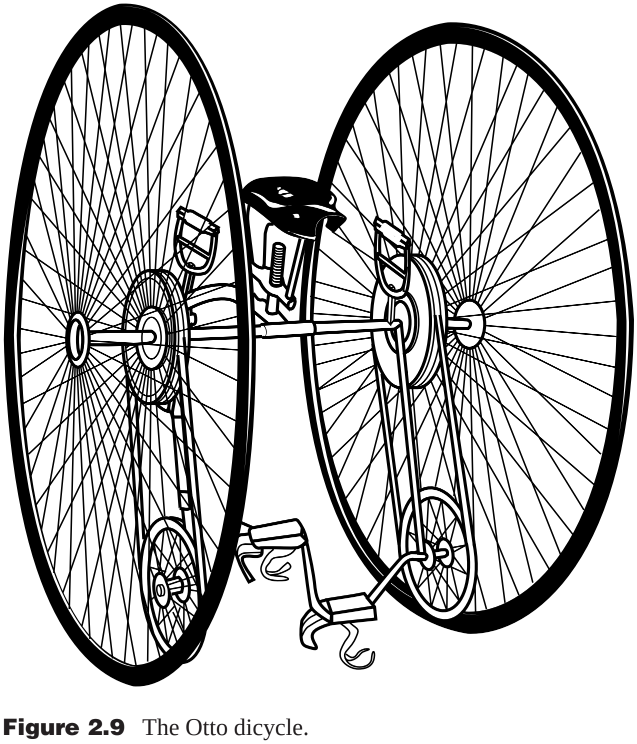


Figure 2.9 The Otto dicycle.

Figure 2.10 The Marin Mount Vision. (Reprinted with permission of Marin Bicycles.)

> Most design problems are redesign problems since they are based on prior, similar solutions. Conversely, most design problems are original as they contain something new that makes prior solutions inadequate.

published in 1896.[1] The only major change in bicycle design since the publication of that book was the introduction of the derailleur in the 1930s.

However, in the 1980s the traditional bicycle design began to change again. For example, the mountain bike shown in Fig. 2.10 no longer has a diamond-shaped frame. Why did a mature design like a bicycle begin evolving again? First, customers are always looking for improved performance. Bicycles of the style shown in Fig. 2.10 are better able to handle rough terrain than traditional bikes. Second, there is improved understanding of human comfort, ergonomics, and suspensions. Third, customers are always looking for something new and exciting even if performance is not greatly improved. Fourth, materials and components have improved.

The point is that even mature designs change to meet new needs, to attract new customers, or to take advantage of new materials. Part of the design of a new bicycle like the Marin Mount Vision is routine, and part is original. Additionally,

[1]The book, written by Archibald Sharp, has recently (1977) been reprinted by the MIT Press, Cambridge, Mass.

many subproblems were parametric problems, selection problems, and configuration problems. Thus, the redesign of a product, even a mature one, may require a wide range of design activity.

2.4.6 Variant Design

Sometimes companies will produce a large number of variants as their products. A variant is a customized product designed to meet the needs of the customer. For example, when you order a new computer from companies such as Dell, you can specify one of three graphics cards, two battery configurations, three communication options, and two levels of memory. Any combination of these is a variant that is specifically tuned to your needs. Also, Volvo trucks estimates that of the 50,000 parts it has in its inventory it annually supplies over 5000 variants, different truck models specifically assembled to meet the needs of the customer.

2.4.7 Conceptual Design and Product Design

Two other terms that will be used throughout the book are *conceptual design* and *product design*. These are catchall terms for two parts of the product development process. First, you must develop a concept and then refine the concept into a product. The activities during the conceptual and product development phases may make use of original, parametric, and selection design and redesign as needed.

2.5 CONSTRAINTS, GOALS, AND DESIGN DECISIONS

The progression from the initial need (the design problem) to the final product is made in increments punctuated by *design decisions.* Each design decision changes the *design state.* The state of a product is a snapshot of all the information known about it at any given time during the process. In the beginning, the design state is just the problem statement. During the process, the design state is a collection of all the knowledge, drawings, models, analyses, and notes thus far generated.

Two different views can be taken of how the design process progresses from one design state to the next. One view is that products evolve by a continuous comparison between the design state and the *goal,* that is, the requirements for the product given in the problem statement. This philosophy implies that all the requirements are known at the beginning of the design problem and that the difference between them and the current design state can be easily found. This difference controls the process. This philosophy is the basis for the methods in Chap. 6.

Another view of the design process is that when a new problem is begun, the design requirements effectively constrain the possible solutions to a subset of all possible product designs. As the design process continues, other *constraints* are added to further reduce the potential solutions to the problem, and potential solutions are continually eliminated until there is only one final design. In other

> Constraints are often opportunities in disguise.

words, design is the successive development and application of constraints until only one unique product remains.

Beyond the constraints in the original problem specifications, constraints added during the design process come from two sources. The first is from the designer's knowledge of mechanical devices and the specific problem being solved. If a designer says, "I know bolted joints are good for fastening together sheet metal," this piece of knowledge constrains the solution to bolted joints only. Since every designer has different knowledge, the constraints introduced into the design process make each designer's solution to a given problem unique. The second type of constraint added during the design process is the result of design decisions. If a designer says, "I will use 1-cm-diameter bolts to fasten these two pieces of sheet metal together," the solution is constrained to 1-cm-diameter bolts, a constraint that may affect many other decisions—clearance for tools to tighten the bolt, thickness of materials used, and the like. During the design process, a majority of the constraints are based on the results of design decisions. Thus, the individual designer's ability to make well-informed decisions throughout the design process is essential. Decision-making techniques are emphasized in Chap. 8.

2.6 PRODUCT DECOMPOSITION

We will conclude this chapter with a method that can is the basis for understanding existing products. As such, it can serve as a starting point whether doing redesign, original design, or some other type of design, whether at the system or subsystem level. This *product decomposition* or "benchmarking" method helps us understand how a product is built, its parts, its assembly, and its function. It cannot be overemphasized how important it is to do decomposition and how it is the starting place for all design. In this chapter, we will decompose to understand the parts and assembly. In Chap. 7, the decomposition begun here will be extended to understand function.

Figure 2.11 shows a template that can be used to organize the decomposition. It is partially filled in for a pre-2003 version of the Irwin Quick-Grip. This version is the starting point for the redesign effort that resulted in the product shown in Fig. 2.1

The template begins with a brief description of the product and how it works—its function. This follows with a section showing each part. Only a selection of the parts is shown for the clamp in Fig. 2.11. Each part is given a name, the number required, its material, and the manufacturing process.

Often it can be hard to determine the material and manufacturing process. For plastics, there is a set of simple experiments for rough identification. Over the last few years, handheld devices have been developed that can identify materials

Product Decomposition

Design Organization: Example for the Mechanical Design Process | **Date:** Aug. 14, 2007

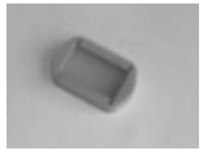
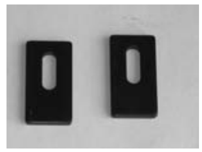
Product Decomposed: Irwin Quick Grip—pre 2007

Description: This is the Quick-Grip Product that has been on the market for many years

How it works: Squeeze the pistol grip repeatedly to move the jaws closer together and increase the clamping force. Squeeze the release trigger to release the clamping force. The foot (the part on the left in the picture that holds the face that is clamped against) is reversible so the clamping force can be made to push apart rather than squeeze together.

Parts:

Part #	Part Name	# Req'd.	Material	Mfg. Process	Image
1	Main body	1	PPO or PVC	Injection molded	
2	Trigger	1	PVC	Injection molded	
4	Face plate, left	1	Polyethylene	Injection molded	

Part #	Part Name	# Req'd.	Material	Mfg. Process	Image
8	Pad	2	??	Injection molded	
13	Power spring	1	Steel	Wound wire	
14	Jam plates	2	Steel	Stamped sheet	

Disassembly:

Step #	Procedure	Part #s removed	Image
1	Take off left face plate	4	
12	Remove jam plates and power spring from main body assembly	13, 14, 1	
13	Remove trigger from main body assembly	2	
14	Pry off pad from main body assembly	8	

The Mechanical Design Process Designed by Professor David G. Ullman

 Form # 1.0

Figure 2.11 Product decomposition samples for an older version of the Irwin Quick-Grip. (Photos reprinted with permission of Irwin Industrial Tools.)

just by pointing the device at a sample of the material. While the main market for these devices is recycling, they are very useful when decomposing a product. Details on these are given in the Sources section at the end of this chapter.

The final section of the template is for the disassembly of the product. To build this section of the Product Decomposition report, remove one part at a time. Document the procedure needed to remove the part and the part numbers for those parts removed. Document what was done with a photograph. Figure 2.11 shows only a couple of the steps. Usually disassembly and part naming occur at the same time. Disassembly step 1 shows the left face plate, Part #4, was removed from the product. The internal parts of the clamp can now be seen in the photo. As this is a digital image in the actual template, it can easily be rescaled and studied as needed. Steps 12–14 are shown using a single image. The first one shows the removal of two parts, #13 and #14, at the same time as they come out together. Note how each procedure begins with a verb or verb phrase to tell what has to be done to remove the parts. Make these as descriptive as possible.

2.7 SUMMARY

- A product can be divided into functionally oriented operating *systems.* These are made-up of mechanical *assemblies,* electronic circuits, and computer programs. Mechanical assemblies are built of various *components.*
- The important form and function aspects of mechanical devices are called *features.*
- Function and behavior tell *what* a device does; form describes *how* it is accomplished.
- Mechanical design moves from function to form.
- One component may play a role in many functions, and a single function may require many different components.
- There are many different types of mechanical design problems: selection, configuration, parametric, original, redesign, routine, and mature.
- Mechanical objects can be described semantically, graphically, analytically, or physically.
- The design process is a continuous constraining of the potential product designs until one final product evolves. This constraining of the design space is made through repeated decisions based on comparison of design alternatives with design requirements.
- Mechanical design is the refinement from abstract representations to a final physical artifact.
- Product dissection is a useful way to understand the structure of a product.

2.8 SOURCES

Good books on designing new products

Clausing, Don, and Victor Fey: *Effective Innovation: Development of Winning Technologies,* ASME Press, 2004.

Cooper, Robert G.: *Winning at New Products,* 3rd ed., Perseus Publishing, 2001.

Vogel, C.M., J. Cagan, and P. Boatwright: *The Design of Things to Come*, Wharton School Publishing, 2005.

Plastics identification

The PHAZIR is a handheld, battery-powered, point-and-shoot plastic identifier. It weighs only 4 lb (1.8 kg) and takes 1–2 sec to determine the makeup of the sample. www.polychromix.com

Metals identification

The iSort is a handheld, battery-powered, point-and-shoot spectrometer for on-site identification and analysis of all common metal alloys. Metal identification just requires pointing the gun-shaped iSort at a clean metal sample. The iSort is fairly expensive. http://www.spectro.com/pages/e/p010101.htm

An inexpensive method uses the color of a chemical deposition to identify the metal. The process requires putting a drop of solution on the sample, then using a battery-powered electric charge through the solution to cause a chemical deposition on a piece of blotter paper. The color of the resulting deposit identifies the metal. http://www.alloyid.com

2.9 EXERCISES

2.1 Decompose a simple system such as a home appliance, bicycle, or toy into its assemblies, components, electrical circuits, and the like. Figures 2.3 and 2.11 will help.

2.2 For the device decomposed, list all the important features of one component.

2.3 Select a fastener from a catalog that meets these requirements:

- Can attach two pieces of 14-gauge sheet steel (0.075 in., 1.9 mm) together
- Is easy to fasten with a standard tool
- Can only be removed with special tools
- Can be removed without destroying either base materials or fastener

2.4 Sketch at least five ways to configure two passengers in a new four-wheeled commuter vehicle that you are designing.

2.5 You are a designer of diving boards. A simple model of your product is a cantilever beam. You want to design a new board so that a 150-lb (67-kg) woman deflects the board 3 in. (7.6 cm) when standing on the end. Parametrically vary the length, material, and thickness of the board to find five configurations that will meet the deflection criterion.

2.6 Find five examples of mature designs. Also, find one mature design that has been recently redesigned. What pressures or new developments led to the change?

2.7 Describe your chair in each of the four languages at the three levels of abstraction, as was done with the bolt in Table 2.2.

2.10 ON THE WEB

A template for the following document is available on the book's website: www.mhhe.com/Ullman4e

- Product Decomposition

CHAPTER 3

Designers and Design Teams

KEY QUESTIONS

- Why is it important to know how people do design?
- How is your ability to design dependent on your cognitive preferences?
- What are the characteristics of creators?
- How do individual cognitive abilities interact with the abilities of others during team activities?
- Why is a team more than a group of people?
- What can you do to help teams be successful?
- How can you measure team health?

3.1 INTRODUCTION

Since the time of the early potter's wheel, mechanical devices have become increasingly complex and sophisticated. This sophistication has evolved without much concern for how humans solve design problems. Throughout history people who were just naturally good at design were trained, through an apprentice program, to be masters in their art. The design methods they used and the knowledge of the domain in which they worked was refined through their personal experiences and passed, in turn, to their apprentices. Much of this experience was gained through experiments, through building prototypes and then going "back to the drawing board" to iterate toward the next product. The results of these experiments taught the designers what worked and what did not and pointed the way to the next refinement. With this methodology, products took many generations to be refined to the point of mature design.

However, as systems grew more complex and the world community grew more competitive, this mode of design became too time-consuming and too expensive. Designers recognized the need to find ways to deal with larger, more complex systems; to speed the design process; and to ensure that the final design be reached with a minimum use of resources and time. In this book we discuss design techniques that meet these goals. To understand how these techniques help streamline the design process, it is important to understand how designers and design teams progress from abstract needs to final, detailed products.

To put this chapter in context, it is important to realize that design is the confluence of technical processes, cognitive processes, and social processes. We begin our discussion of how humans design mechanical objects by describing a cognitive model of how memory is structured in the individual designer. The types of information that are processed in this structure are explored, and the term *knowledge* is defined. Once we understand the information flow in human memory, we develop the different types of operations that a designer must perform in memory during the design process, and we explore creativity.

Based on this model of the individual's cognitive process, the chapter moves to the social aspect of design—working in teams. First, the structure of design teams is developed. This includes descriptions of the members of teams and how they are managed. Further, beyond the formal titles that people have, there is a more subtle, cognitive role that people play on teams. Second, an entire section is devoted to building and maintaining a design team. This includes how to start a team, inventory its health, and resolve problems as they develop. Supporting this chapter is a series of templates available at the book's website.

3.2 THE INDIVIDUAL DESIGNER: A MODEL OF HUMAN INFORMATION PROCESSING

The study of human problem-solving abilities is called *cognitive psychology.* Although this science has not yet fully explained the problem-solving process, psychologists have developed models that give us a pretty good idea of what happens inside our heads during design activities. A simplification of a generally accepted model is shown in Fig. 3.1. This model, called the *information-processing system* and developed in the late 1950s, describes the mental system used in the solution of any type of problem. In discussing that system here, we give special emphasis to the solution of mechanical design problems.

Information processing takes place through the interaction of two environments: the *internal environment* (information storage and processing inside the human brain) and the *external environment.* The external environment comprises paper and pencil, catalogs, computer output, and whatever else is used outside the human body to extend the internal environment.

In the internal environment, that is, within the human mind, there are two different types of memory: *short-term memory,* which is similar to a computer's operating memory (its random access memory or RAM), and *long-term memory,* which is like a computer's disk storage. Bringing information into this system from the external environment are *sensors,* such as the eyes, ears, and hands. Taste and smell are less often used in design. Information is output from the body with the use of the hands and the voice. There are other means of output, such

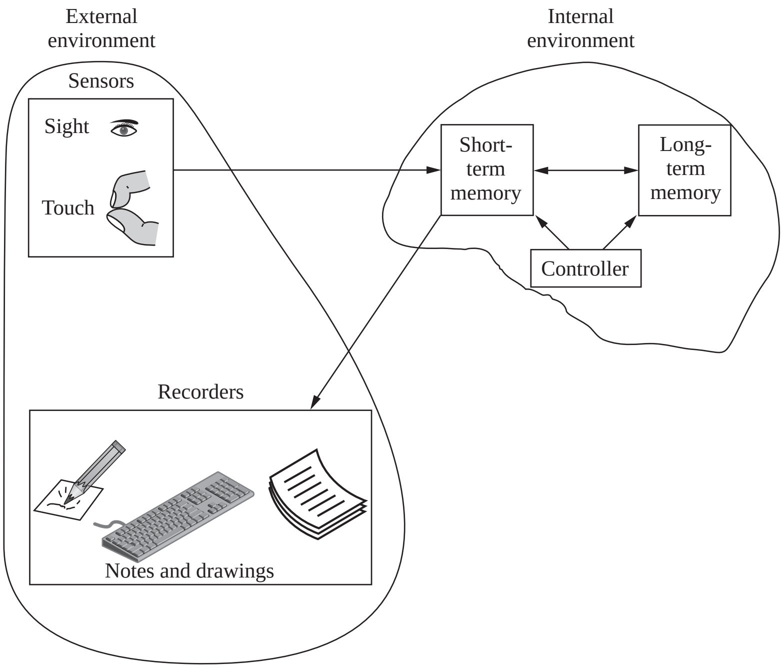


Figure 3.1 The human problem solver.

as body position, that are less often used in design. Additionally, as part of the internal processing capability, there is a *controller* that manages the information flow from the sensors to the short-term memory, between the short-term and the long-term memory, and between the short-term memory and the means of output.

Before describing short-term and long-term memory and the control of information flow, we need to describe the *information* that is processed in this system. In a computer the information is in terms of bits, or binary digits (0s and 1s), but in the human brain, information is much more complex.

In recent experiments, an orthographic drawing of a power transmission system consisting of shafts, gears, and bearings was shown to mechanical engineering students and professional engineers. The students were lower-level undergraduates who had not studied power transmission systems. The drawing was shown briefly and then removed, and the subjects were asked to sketch what they had seen. The students tended to reconstruct the drawings from the line segments and simple shapes they had seen in the original drawing. Not understanding the complexities of geared transmissions, they could not remember anything more complicated. They remembered and drew only the basic form of the components. On the other hand, the professional engineers were able to remember components grouped together by their function. In recalling a gear set, for example, the experts knew that two meshed gears and their associated shafts and bearings provide the function of changing the rpm and torque in the system. They also knew what geometry or line segments were needed to represent the form of a gear set. Thus, the experienced engineers using functional groupings were able to include substantially more information than the students in their sketches.

The line segments remembered by the students and the functional groupings remembered by the experienced designers are called *chunks of information* by cognitive psychologists. The greater the expertise of the designer, the more content there is in the chunks of information processed. Exactly what types of information are in these chunks, however, is not always clear. Types of knowledge that might be in a chunk include

- ***General knowledge,*** information that most people know and apply without regard to a specific domain. For example, red is a color, the number 4 is bigger than the number 3, an applied force causes a mass to accelerate—all exemplify general knowledge. This knowledge is gained through everyday experiences and basic schooling.
- ***Domain-specific knowledge,*** information on the form or function of an individual object or a class of objects. For example, all bolts have a head, a threaded body, and a tip; bolts are used to carry shear or axial stresses; the proof stress of a grade 5 bolt is 85 kpsi. This knowledge comes from study and experience in the specific domain. It is estimated that it takes about ten years to gain enough specific knowledge to be considered an expert in a domain. Formal education sets the foundation for gaining this knowledge.
- ***Procedural knowledge,*** the knowledge of what to do next. For example, if there is no answer to problem X, then decomposing X into two independent easier-to-solve subproblems, X1 and X2, would illustrate procedural knowledge. This knowledge comes from experience, but some procedural knowledge is also based on general knowledge and some on domain-specific knowledge. We must often make use of procedural knowledge to solve mechanical design problems.

In mechanical engineering the term *feature* is synonymous with *chunks of information.* Since a design feature is some important aspect of a component, assembly, or function, the gear set discussed in the preceding example is both a chunk and a feature.

The exact language in which chunks of information are encoded in the brain is unknown. They might be dealt with as semantic information (text), graphical information (visual images), or analytical information (equations or relationships). Psychologists believe that most mechanical designers process information in terms of visual images and that these images are three-dimensional and are readily manipulated in the short-term memory.

> All design and decision making is limited by human cognitive capabilities.

3.2.1 Short-Term Memory

The short-term memory is the main information processor in the human brain. It has no known specific anatomic location, yet it is known to have very specific attributes.

One important attribute of the short-term memory is its quickness. Information chunks can be processed in the short-term memory in about 0.1 second. The term *processed* implies such actions as comparing one chunk of information to another, modifying a chunk by decomposing it into smaller parts, combining two or more chunks into one new one, changing a chunk's size or distorting its shape, and making a decision about the chunk. It is unknown how much of the short-term memory is actually used to process the information. We do know that the harder it is to solve the problem, the more short-term memory is used for processing.

The capacity of the short-term memory was first described in a paper titled "The Magical Number Seven, Plus or Minus Two" (see Section 3.8), which reported that the short-term memory is effectively limited to seven chunks of information (plus or minus two). This is like having a computer RAM with only seven memory locations. These approximately seven chunks—these seven unique things—are all that a person can deal with at one time. For example, let us say we are working on a design problem and have an idea (a chunk of information, maybe just a word or maybe a visual image) that we want to compare to some constraints on the design (other chunks of information). How many constraints can we compare to the idea in our head? Only two or three at a time, since the idea itself takes one slot in the short-term memory and the constraints take two or three more. That does not leave much memory to do the processing necessary for comparison. Add any more constraints and the processing stops; the short-term memory is simply too full to make any progress on solving the problem.

A couple of quick experiments are convincing about the limits of the short term memory. Open a phone book and randomly choose a phone number in which the seven digits are unrelated to each other. (A number such as 555-2000 is not acceptable because the last four digits can be lumped together as a single chunk—two thousand.) After looking at the number briefly, close the phone book, walk across the room, and dial the number. Most people can manage to do this task if they are not interrupted or do not think about anything else. The same experiment can be tried with two unrelated phone numbers. Few people are able to remember them long enough to dial them both since they require dialing 14 pieces of information, which is beyond the capacity of the short-term memory. Granted, these 14 digits can be memorized, or stored in long-term memory, but that would take some study time.

Another example of the size limitations of short-term memory is more mechanical in nature. Consider the four-bar linkage of Fig. 3.2. It is made up of four elements: the driver A–B, the link B–C, the follower C–D, and the base D–A.

It is not difficult for most engineers to visualize the follower C–D rocking back and forth as the driver A–B is rotated. Point B makes a circle, and point C moves in an arc about point D. An expert on linkages would only use a single

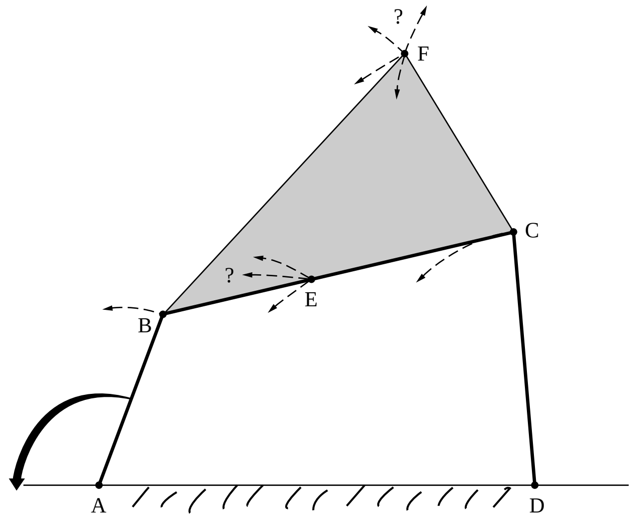


Figure 3.2 A four-bar linkage.

chunk to encode this mechanism. But a novice in the domain of four-bar linkages would need to visualize four line segments, using four chunks plus others for processing the motion. To make the task more difficult, trace the path of point E on the link. This requires more short-term memory. Harder still is tracing the path of point F. In fact, this requires so many different parameters to track that only a few linkage experts can visualize the path of point F.

Another feature of the short-term memory is the fading of information stored there. The phone number remembered earlier is probably forgotten within a few minutes. To keep from forgetting short-term information, like the phone number, many people keep repeating the information over and over. With such continuous refreshing, it is possible to retain certain objects or parts of objects within the short-term memory and to let only the unimportant information fade to make room for the processing of new chunks of information.

Last, it is impossible for us to be aware of what is happening in our short-term memory while we are solving problems. To follow our own thoughts, we need to use some of that memory to monitor and understand the problem-solving process, making that space no longer available for problem solving. Thus, you can not really observe what you are doing during problem solving without affecting what you are trying to observe.

3.2.2 Long-Term Memory

The long-term memory was earlier compared with the disk storage in a computer; like disk storage, it is for permanent retention of information. Let us look at the four major characteristics of long-term memory. First, long-term memory has seemingly unlimited capacity. Despite the cartoon in Fig. 3.3, there is no

"Mr. Osborne, may I be excused? My brain is full."

Figure 3.3 Long-term memory problems.

documented case of anybody's brain becoming "full," regardless of head size. It is hypothesized that as we learn more we unconsciously find more efficient ways to organize the information by reorganizing the chunks in storage. Reconsider the difference between the student's and the expert's ways of remembering information about the power transmission system. The expert's information storage was more efficient than the student's.

The second characteristic of the long-term memory is that it is fairly slow in recording information. It takes 2 to 5 min to memorize a single chunk of information. This explains why studying new material takes so long.

The third characteristic is the speedy recovery of information from long term memory. Retrieval is much quicker than storage, the time depending on the complexity of the information and the recentness of its use. It can be as fast as 0.1 sec per chunk of information.

The fourth characteristic is that the information stored in the long-term memory can be retrieved at different levels of abstraction, in different languages, and with different features. For example, consider the knowledge an average engineer can retrieve about a car (Fig. 3.4). The sample data ranges from images of entire vehicles to semantic rules and equations for diagnosing problems. Human memory is very powerful in matching the form of the data retrieved to that which is needed for processing in the short-term memory.

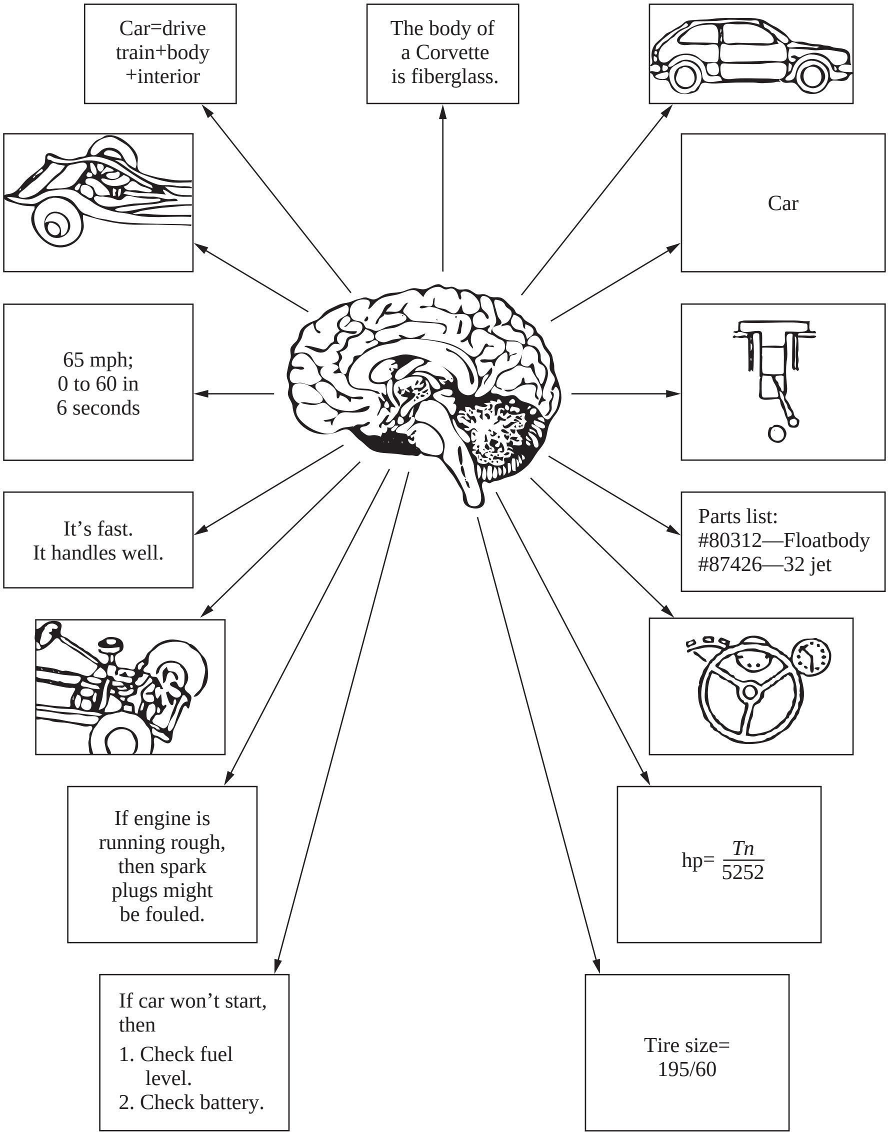


Figure 3.4 Knowledge stored in memory about cars.

3.2.3 Control of the Information-Processing System

During problem solving, the controller (Fig. 3.1) enables us to encode outside information obtained through our senses or retrieve information from long-term memory for processing in the short-term memory. Some of the information in the short-term memory is allowed to fade, and new information is input as it is needed and becomes available. Additionally, the controller can help extend the short-term memory by making notes and sketches; these need to be done quickly so that they do not bog down the problem-solving process. When we have completed manipulating the information, the controller can store the results in long-term memory, or in the external environment by describing it in text, verbally, or in graphic images.

3.2.4 External Environment

The external environment—paper and pencil, computers, books—plays a number of roles in the design process: it is a source of information; it is an analytical capability; it is a documentation/communication facility; and, most importantly for designers, it is an extension for the short-term memory. The first three of these roles seem evident; however, the last role, as an extension for the short-term memory, needs some discussion.

Because the short-term memory is a space-limited central processor, human problem solvers utilize the external environment as a short-term memory extension, much as a computer extends RAM by using cache memory. This is accomplished by making notes and sketches of ideas and other information needed in problem solving. In order to be useful to the short-term memory, any extension must share the characteristics of being very fast and having high information content. Watch any design engineer trying to solve a problem. He or she will make sketches even when not trying to communicate. These sketches serve as aids in generating and evaluating the ideas by serving as additional chunks of information to be processed. Sketches are fast to make and are information-rich.

3.2.5 Implications of the Model

One of the implications of the information-processing model of human problem solving is that the size of the short-term memory is a major limiting factor in the ability to solve problems. To accommodate this limitation we break down problems into finer and finer subproblems until we can "get our mind around it"—in other words, manage the information in our short-term memory. Typically, these fine-grained subproblems are worked on for about 1 minute before going to the next one. Thus, design of even a simple problem is the solution of many thousands of subproblems. Further, our thinking process has evolved so that, as we solve problems, our expertise about the constraints and potential solutions increases and our configuration of chunks becomes more efficient. This helps offset the "magic number" seven, but human designers are still quite limited. It would almost seem that these limitations would preclude our ability to solve

> If you try to think about what you are doing while you are doing it, you stop doing it. If you don't reflect on what you just did, you are doomed to repeat it.

complex problems. As discussed in the upcoming sections, processing speed and flexibility of information storage and recovery enable designers to develop very complex products.

3.3 MENTAL PROCESSES THAT OCCUR DURING DESIGN

We can now describe what happens when a designer faces a new design problem. The problem may be the design of a large, complex system or of some small feature on a component. We will focus on how a designer understands new information such as the problem statement, how ideas are generated, and how they are evaluated.

In Section 1.6 we introduced seven basic actions of problem solving. The core actions—understand, generate, evaluate, and decide—are refined here.

3.3.1 Understanding the Problem

Consider what happens when a new problem is broached. If we think of its design state as a blackboard on which is written or drawn everything known about the device being designed, then the blackboard is initially blank, i.e., the design state is empty. Let us return to the fastening problem presented in Chap. 1 (see Fig. 1.9):

> Design a joint to fasten together two pieces of 1045 sheet steel, each 4 mm thick and 6 cm wide, that are lapped over each other and loaded with 100 N.

Before any information about the problem is put on the design-state blackboard, the problem statement must be understood. If the problem is outside the realm of experience (the designer does not know what the term *lapped* means, for example), then the problem cannot be understood.

But how do we "understand" a problem? Most likely in this way: As the problem is read, it is "chunked" into significant packets of information. This happens in the short-term memory, where we naturally parse the sentence into phrases like "design a joint," "to fasten together," and so on. These chunks are compared with long-term memory information to see if they make sense, and then most are allowed to fade. The goal of this first pass through the problem is to try and retain only the major functions of the needed device. Usually a problem will be read or sensed a number of times until the major function(s) is identified. Unfortunately there is no guarantee that, from the usually incomplete data that exist at the beginning of a design problem, the most important functions will be identified. In our example there is no ambiguity. The prime function is to transfer a load from one sheet of steel to another through a lapped joint.

What is important to realize is that a problem is "understood" by comparing the requirements on the desired function to information in the long-term memory. Thus, every designer's understanding of the problem is different, because each designer has different information stored in the long-term memory. (In Chap. 6 we develop a method to ensure that the problem is fully understood with minimal bias from the designer's own knowledge.)

3.3.2 Generating Solutions

We have seen that in trying to understand a design problem, we compare the problem to information from the long-term memory. In order to retrieve information from the long-term memory, we need a way to index the knowledge stored there. We can index that information in many ways (Fig. 3.4). As in the gearbox example at the beginning of this chapter, the most efficient indexing method is by function. What are recalled and downloaded to the short-term memory are specific (usually abstract) visual images from past experience. Thus, we search by function and recall form or graphical representations. This is not always true: we can also index our memory by shape, size, or some other form feature. However, in solving design problems, function is usually the primary index. For some problems the information recalled meets all the design requirements and the problem is solved.

If, in understanding a problem, we must recall images of previous designs, we have a predisposition to use these designs. Some designers get stuck on these initially recalled images and have difficulty evaluating them objectively and generating other, potentially better ideas. Many of the techniques discussed in Chaps. 7 and 11 are specifically designed to overcome this tendency.

On the other hand, what happens if the problem being solved is new and we find no solution to it in the long-term memory? We then use a three-step approach: decompose the problem into subproblems, try to find partial solutions to the subproblems, and finally recombine the subsolutions to fashion a total solution. The subproblems are generally functional decompositions of the total problem. The creative part of this activity is in knowing how to decompose and recombine cognitive chunks.

3.3.3 Evaluating Solutions

Often people generate ideas but have no ability to evaluate them. Evaluation requires comparison between generated ideas and the laws of nature, the capability of technology, and the requirements of the design problem itself. Comparison, then, necessitates modeling the concept to see how it performs with respect to these measures. The ability to model is usually a function of knowledge in the domain. We will address evaluation techniques in Chaps. 8, 10, and 11.

3.3.4 Deciding

At the end of each problem-solving activity, a decision is made. It may be to accept an idea that was generated and evaluated, or more likely, it will be to address another topic that is related to the problem. The rationale for how decisions are made is not well understood, but Sections 3.3.5 and 3.3.6 should help clarify what is known.

3.3.5 Controlling the Design Process

To understand how designers progress through a design problem, subjects were videotaped as they worked. In the study of these videotapes, it became evident that the path from initial problem presentation to solution was not very straightforward. It seemed like an almost random process—efforts on a subproblem made the designer aware of another subproblem, and the designer then focused attention on this second problem without having solved the first. No model for the control of focus was found. However, it was clear that the process for some designers is so chaotic that they never find solutions to their problems, while other designers rapidly proceed through the design effort. The techniques discussed in this book are intended to give structure to the design process so that the path from problem statement to solution is as controlled and direct as possible.

3.3.6 Problem-Solving Behavior

Everybody has a unique manner of problem solving. A person's problem-solving behavior affects how decisions are made individually and has a significant impact on team effectiveness. The following discussion is centered around five personal problem-solving dimensions. These five are useful for describing how an individual solves a design problem because they describe an individual's information management and decision-making preferences. Since all the team members bring their individual problem-solving processes to team activities, it is the interaction of all the individuals' solution processes that determines the team's health. For each of the five dimensions, suggestions for how to counteract extreme behavior are given. Some of these are useful to the individual working alone, and all are important in team situations and will be referenced later in the chapter when we talk about team health. A template for easily evaluating your problem-solving behavior is available.

The first personal problem-solving dimension describes an individual's **energy source** or **extraversion.** It is a measure of whether you are an *internal* or *external* problem solver. For a rough estimate of your, or a colleague's, energy source, answer five questions. If scoring a colleague, pretend you are that person. The five questions are shown in Figs. 3.5–3.9, screen shots from the template. In each of the five questions are shown with two potential responses. In Fig. 3.5 the top responses indicate an internal energy source and the bottom responses indicate an external energy source. For the example here, internal is

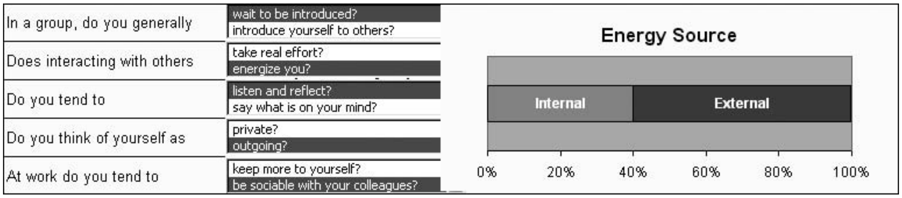


Figure 3.5 Energy source personal problem-solving dimension.

selected for the first and third questions and so the person is 2/5 or 40% internal and 60% external. In the template, the bar chart updates as you select the responses.

If a person is reflective, is a good listener, thinks and then speaks, and enjoys solving problems alone, then she is an internal problem solver. If the person's energy comes from outside through interactions with others (i.e., the person is sociable and tends to speak and then think) she is an external problem solver. About 75% of all Americans and 48% of engineering students and top executives are external problem solvers. There is no right or wrong style; this is merely the way people operate. They may show slightly different styles in different situations, but will generally not deviate very far from type.

In team settings both internals and externals have characteristics that are essential to the team but may cause difficulty—the externals tend to overwhelm the internals, who are reluctant to share their ideas. Here are some suggestions to keep the externals productive but not domineering:

- Externals need to allow others time to think. Point out to them that it is not necessary to fill in all the pauses with words.
- Externals need to practice listening to the ideas and suggestions of others and pausing before they react. Brainstorming or another creativity-support activity can help here (see Section 7.4).
- Encourage externals to recap what has been said to make sure they have heard the contributions of others.
- Externals need to realize that silence does not always mean consent. Sometimes an external will overwhelm the internals, who will become quiet rather than argue the point.

Here are some suggestions to assist internals in getting their ideas out for consideration:

- Encourage internals to share more than their final response. There is value in thinking out loud, as even the most trivial idea may be part of a good solution. The process will judge the value of the ideas.
- Try suggesting techniques that enable internals to have an equal say in selecting ideas and plans, such as the techniques in Chaps. 5–12.

- Encourage internals to develop some nonverbal, body-language signals that indicate assent or dissent. Make sure that these signals are understood by other team members.
- Encourage internals to restate their ideas. This restating signifies to the internal that his or her ideas count and forces the externals to listen.
- Get internals to push externals for more clarity and meaning.

The second dimension reflects your preference for an **information management style** or **originality.** It is a measure of whether you like working with *facts* or *possibilities*. For an estimate of your or a colleague's information management style, answer the questions in Fig. 3.6. For the example shown, the individual operates on both facts and possibilities with a slight tendency for possibilities.

People who prefer facts and details are literal, practical, and realistic; they appreciate the here and now. Those who think in terms of possibilities, patterns, concepts, and theories are looking for relationships between pieces of information and the meaning of the information. About 75% of Americans are fact-oriented, as are 66% of top executives; yet only 34% of all engineering students are fact-oriented. This is interesting in light of the heavy emphasis on math and science that is the focus of an engineering education. Other labels that could be placed on the scale are *Preserver* and *Explorer,* where the Preservers maintain the system, the Explorers are the boat rockers.

To solve most problems it is important to have a balance between the two extremes. When solving a problem alone, fact-oriented people have trouble getting started, whereas possibility-oriented people have trouble doing the details.This problem-solving dimension is the cause of most miscommunication, misunderstanding, and team problems. Design requires working with both facts and possibilities. Thus, both types of thinking are essential on a design team. However, individuals with a strong tendency toward either extreme may need help in the team setting. Some suggestions for fact-oriented team members are as follows:

- Encourage fact-oriented team members to fantasize, think wildly, and allow others to think wildly. Wild ideas can lead to good ideas. Brainstorming (Section 7.4) and thinking out loud (rambling) bring out such ideas.
- Encourage fact-oriented team members to allow the team to set goals rather than dive right into the problem and tackle the details.

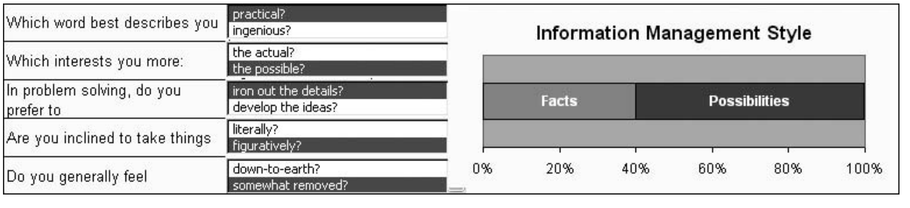


Figure 3.6 Information management style problem-solving dimension.

Here are some suggestions for team members who think in terms of possibilities:

- Encourage possibility-oriented team members to deal with details. The best idea will never reach maturity if the details are not attended to. It is frustrating to them but possibly worthwhile to have them take on the responsibility of a detail task.
- Force possibility-oriented team members to be specific and avoid generalities. They should be encouraged to try to enumerate the exact items they want to address instead of making sweeping general statements.
- Remind possibility-oriented team members to stick to the issues. Other team members can control the flow of the problem solving by clearly stating the issues being addressed. Other issues that arise during discussion should be recorded and then shelved for later consideration.

The third dimension measures which **information language** a person prefers to use, *verbal* or *visual*. For a rough idea of your or a colleague's information language style, answer the questions in Fig. 3.7. The example individual is primarily a visual problem solver, but can work verbally.

Visual information includes pictures, diagrams, graphs, and hardware. Verbal information includes written or spoken words and mathematical formulas. It is interesting to note that most people favor visual information, yet most classes in school are presented in a verbal language. This mismatch is especially striking in science and engineering classes.

When you are working alone, the language you use is not an important consideration. In teams, however, the preferred languages greatly affect the development of a shared vision of the problem and alternative solutions. Some guidelines on how to manage the two types of communication language in team situations follow.

- Help identify information that needs to be communicated, regardless of language.
- Help identify differences in team members' mental models, encouraging extra effort by both visual and verbal people to communicate clearly with other members to develop a shared understanding.

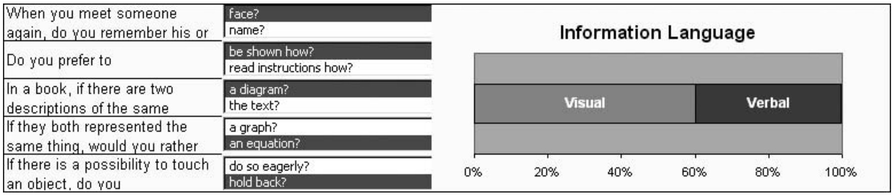


Figure 3.7 Information language personal problem-solving dimension.

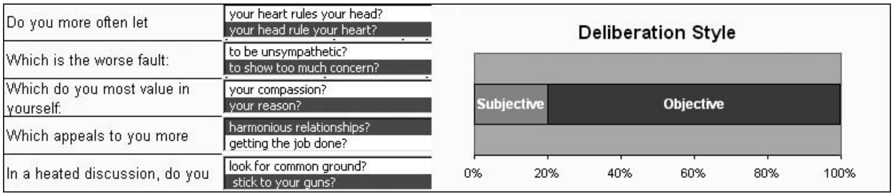


Figure 3.8 Deliberation style personal problem-solving dimension.

- If words and equations aren't working, try a diagram or picture. If the picture isn't working, try words and equations.

The fourth dimension reflects the **deliberation style** or **accommodation,** the *objectivity* or *subjectivity* with which problems are solved. To get an estimate of your or a colleague's deliberation style, answer the five questions in Fig. 3.8. In the example, the person is primarily an objective problem solver.

Some team members take a subjective approach, others an objective one. People who rely on interpersonal involvement, circumstances, and the "right thing to do" take a subjective approach to design. These team members can be referred to as "adaptors." Conversely, team members who are logical, detached, and analytical take an objective approach to problems. They challenge others when their logic tells them that they are right. About 51% of Americans are objective decision-makers, as are 68% of engineering students and 95% of top executives.

As it is important to have a variety of information-collection approaches on a design team, it is equally important to have a range of deliberation styles. Although engineers are trained to make decisions based on objective measures, the greatest number of decisions faced in every design problem have incomplete, inconsistent, qualitative information requiring subjective evaluation. For objective designers the following may help in working with the team:

- Encourage objective team members to pay attention to the feelings of others. Gut feelings are often right, and sometimes a lack of information forces one to rely on these feelings.
- Help objective team members understand that how the team functions is as important as what is accomplished. If there is acrimony, no decisions will be made.
- Remind objective team members that not everyone likes to discuss a topic merely for the sake of argument. Others may drop out from exhaustion and be taken to be conceding the point.
- Encourage objective team members to express how they feel about the outcome once in a while. Objective decision-makers may have trouble expressing feelings.

Subjective people are in a minority on most design teams. Thus, they must develop techniques to get their opinions heard and not get their sensitivities hurt.

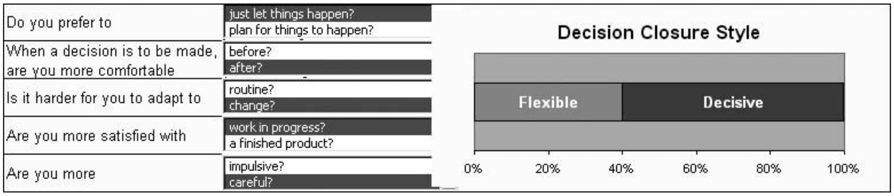


Figure 3.9 Decision closure style personal problem-solving dimension.

Here are some ideas:

- Help subjective team members to realize that it is all right to disagree and argue.
- Reassure subjective team members that while harmony is important, not every resolved issue will satisfy everyone even if consensus is reached.
- Reinforce to subjective team members that discussions about ideas are not personal attacks.

The fifth and final personality dimension relates to the need to actually come to a conclusion during decision making. **Decision closure style** ranges from **flexible** to **decisive.** For a rough estimate of your or a colleague's decision closure style, answer the questions in Fig. 3.9.

Some people are flexible and others are decisive. If a person goes with the flow; is flexible, adaptive, and spontaneous; and finds it difficult to make and stick with decisions, he is considered flexible. If, on the other hand, he makes decisions with a minimum of stress and likes an environment that is ordered, scheduled, controlled, and deliberate, then he is decisive. About half of all Americans are decisive, as are 64% of engineering students and 88% of top executives. One characteristic of flexible decision makers is that they have a tendency to procrastinate because they want to remain adaptive. This can make working with them difficult. The following are some suggestions for flexible decision-makers on the team:

- Give flexible decision-makers plans in advance so that they can think about them in their own time.
- Acknowledge the flexible decision-maker's contribution as a step toward moving to closure. Remind them that problems are solved one step at a time.
- Set clear decision deadlines in advance.
- Encourage feedback from flexible decision-makers so that they can think about the direction of their thoughts.
- Encourage flexible decision-makers to settle on something and live with it a while before redesigning. Encourage them to take a clear position and stick to it. This may be difficult for them to do.

A contrary characteristic of decisive people is that they tend to jump to conclusions. This too can adversely affect teamwork, as many ideas may be generated and consensus may be needed to reach a decision. Here are some suggestions for slowing down decisive people:

- Ask decisive people questions about their decision process. Remind them that most problems need to be subdivided into smaller problems to be solved.
- Let decisive people organize the data collection and review process.
- Utilize techniques, such as brainstorming, that suppress judgment. Do not let them settle on the first good idea they hear.
- Remind decisive people that they are not always right.

This discussion may seem like a lot of detail for an engineering book. Research has shown, however, that paying attention to the psychological makeup of a team is critical.

3.4 CHARACTERISTICS OF CREATORS

Some people seem naturally more creative than others. Before describing the characteristics of a creative design engineer, let us clarify what we mean by "creative." A creative solution to a problem must meet two criteria: it must solve the problem in question, and it must be original. Solving a problem involves understanding it, generating solutions for it, evaluating the solutions, deciding on the best one, and determining what to do next. Thus, creativity is more than just coming up with good ideas. The second criterion, originality, depends on the knowledge of the designer and of society as a whole. What is new and original to one person may be old hat to another. If someone who has never before experienced a wheel designs one, then it is original for that person. But it is society that assesses "originality" and labels a solution or a person "creative."

As discussed earlier, all humans have the same cognitive, or problem-solving, structure. Why is it, then, that some engineers can generate ingenious ideas while others, who may be brilliant at complex analysis, cannot come up with new concepts no matter how hard they try? There has been a lot of research on creativity, yet this trait is still not very well understood. The best way to understand the results of the research to date is in terms the relationship of creativity to other attributes.

Creativity and intelligence. There appears to be little correlation between creativity and intelligence.

Creativity and visualization ability. Creative engineers have good ability to visualize, to generate and manipulate visual images in their heads. We have seen before that people represent information in their minds in three ways: as semantic information (words), as graphical information (visual images), and as analytical information (equations or relationships). Words and equations convey serial information. They are generally understood on the basis of word order or the order of variables and constants. Pictures, or visual images, on the other hand, contain parallel information—you can see many different

> The odds are greatly against you being immensely smarter than everyone else.
> —John R. Page, *Rules of Engineering*

things in a single image. Some people are very good at decomposing and manipulating visual images in their heads, whereas others are not. It appears, however, that the ability to manipulate complex images of mechanical devices can be improved with practice. This may be related to the formation of more information-rich chunks having functional information or to some other mechanism.

Creativity and knowledge. The model of the information-processing system implies that all designers start with what they know and modify this to meet the specific problem at hand. At every step of the way, the process involves small movements away from the known, and even these small movements are anchored in past experience. Since creative people form their new ideas out of bits of old designs, they must retain a storehouse of images of existing mechanical devices in their long-term memory. Thus, in order to be a creative mechanical designer, a person must have knowledge of existing mechanical products.

Additionally, part of being creative is being able to evaluate the viability of ideas. Without knowledge about the domain, the designer cannot evaluate the design. Knowledge about a domain is only gained through hard work in that domain. Thus, a firm foundation in engineering science is essential to being a creative designer of mechanical devices. For example, during World War II many people sent ideas for weapons to the Department of War. Some were very far-fetched ideas for death rays or for building 5-mile-high walls or domes over Europe to stop the bombers. These were very original but unworkable and were therefore not creative. The "inventors" had good intentions but lacked the knowledge to develop creative solutions to the war problems.

Creativity and partial solution manipulation. Since new ideas are born from the combination of parts of existing knowledge, the ability to decompose and manipulate this knowledge seems to be an important attribute of a creative designer. This attribute, more than any other so far discussed, appears to become stronger with exercise. Although there is no scientific evidence to support this contention, anecdotal evidence does support it.

Creativity and risk taking. Another attribute of creative engineers is the willingness to take an intellectual chance. Fear of making a mistake or of spending time on a design that in the end does not work is characteristic of a noncreative individual. Edison tried hundreds of different lightbulb designs before he found the carbon filament.

Creativity and conformity. Creative people also tend to be nonconformists. There are two types of nonconformists: constructive nonconformists and obstructive nonconformists. Constructive nonconformists take a stand because they think they are right. Obstructive nonconformists take a stand just to have an opposing view. The constructive nonconformist might generate a good idea; the obstructive nonconformist will only slow down the design progress. Creative engineers are constructive nonconformists who may be hard to manage since they want to do things their own way.

Creativity and technique. Creative designers have more than one approach to problem solving. If the process they initially follow is not yielding solutions, they turn to alternative techniques. A number of books listed in Section 3.7 give methods to enhance creativity. Many of the techniques covered in these are woven into the mechanical design techniques presented in the remainder of this book. This is especially true in the chapters on concept and product generation (Chaps. 7 and 9).

Creativity and environment. If the work environment allows risk taking and nonconformity and encourages new ideas, creativity will be higher. Further, if teammates and other colleagues are creative, the environment for creativity is greatly enhanced. In the discussion of teams in Section 3.5, it is stated that, on a team, the sum is greater than the parts. This is especially true for creativity.

Creativity and practice. Creativity comes with practice. Most designers find that they have creative phases in their careers—periods when they have many good ideas. During these times the environment is supportive and one good idea builds on another. However, even with a supportive environment, practice enhances the number and quality of ideas.

To summarize, the creative designer is generally a visualizer, a hard worker, and a constructive nonconformist with knowledge about the domain and the ability to dissect things in his or her head. Even designers who do not have a strong natural ability can develop creative methods by using good problem-solving techniques to help decompose the problem in ways that maximize the potential for understanding it, for generating good solutions, for evaluating the solutions, for deciding which solution is best, and for deciding what to do next.

One final comment: There are many design tasks that require talents very different from those used to describe a creative person. Design requires much attention to detail and convention and demands strong analytic skills. Therefore, there are many good designers who are not particularly creative individuals; a design project requires people with a variety of skills and talents.

3.5 THE STRUCTURE OF DESIGN TEAMS

The material already covered describes an individual designer. However, because of the complexity of most products, design work is generally done by design teams. As shown in Fig. 3.10, the complexity of mechanical devices has grown rapidly over the last 200 years. Gone are the days when a single individual could design an entire product. Even Edison had a team of others that worked with

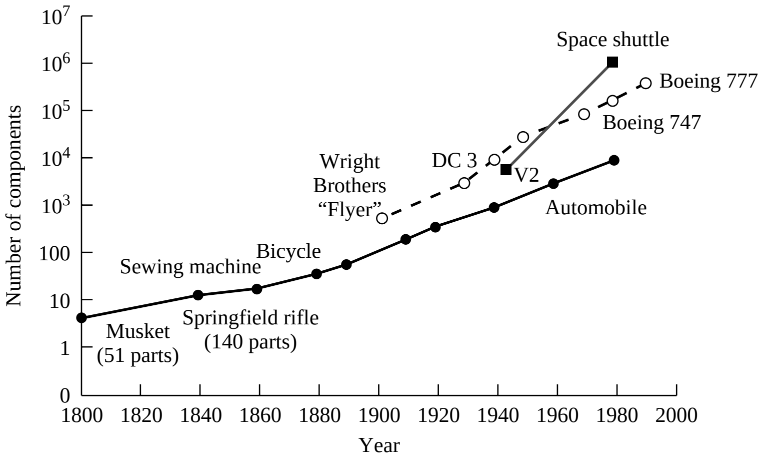


Figure 3.10 Increasing complexity in mechanical design.

him. For example, the Boeing 777 aircraft, which has over 5 million components, required over 10 thousand person-years of design time. Thousands of designers worked over a three-year period on the project. Obviously, a single designer could not approach this effort.

Modern design problems require a design *team*—a small number of people with complementary skills who are committed to a common purpose, common performance goals, and a common approach for which they hold themselves mutually accountable.

A team is a group of people with complementary skills who are committed to a common purpose, performance goals, and approach for which they hold themselves mutually accountable. A group is not necessarily a team. Groups that interact primarily to share information and to help each individual perform within his or her area of responsibility is not a team. An effective team is more than the sum of it parts. Important points about teams are the following:

1. Teamwork is central to success in engineering as most problems are made of many interdependent subparts, all of which must be solved concurrently. Teams bring together complementary skills and experiences, which are needed to solve many engineering problems.
2. Management takes risks in forming teams as a team must be empowered to make decisions, removing this responsibility from the management.
3. Teams establish communication to support real-time problem solving.
4. Teams develop decisions by consensus rather than by authority. This leads to more robust decisions.

In the most basic sense, teams solve design problems in the same way an individual does—understanding, generating, evaluating, and decision making.

> A team is a group of people in search of a common understanding.

However, there are some important differences.

- Team members must learn how to *collaborate* with each other. Collaboration means more than just working together—it means getting the most out of other team members. The suggestions that follow help develop a collaborative team.
- Teams are generally empowered to make decisions. Since these are team decisions, members must *compromise* to reach them. Empowering teams to make these decisions means that management takes a risk in giving up responsibility for them. Further, developing decisions by *consensus* rather than by authority leads to more robust decisions.
- Team members must establish *communication* to support real-time problem solving. Further, members need to ensure that the others have the same understanding of design ideas and evaluations that they have. It is very difficult for people with different areas of expertise to develop a shared vision of the problem and its potential solutions. Developing this shared vision requires the development of a rich understanding of the problem.
- It is important that team members and management be *committed* to the good of the team. If they are not, it will be difficult reaching the other team goals.

To address what is special about teams, in this chapter we first itemize the different technical roles people play on teams and then, in Section 3.6, we address building teams and maintaining team health.

3.5.1 Members of Design Teams

In this section, we list the individuals who might fill a role on a product design team. The roles on a design team will vary with product development phase and from product to product, and the titles will vary from company to company. Each position on the team is described as if filled by one person. In a large design project, there may be many persons filling that role, whereas in a small project one individual may fill many roles.

Product design engineer. The major design responsibility is carried by the product design engineer (hereafter referred to as the *design engineer*). This individual must be sure that the needs for the product are clearly understood and that engineering requirements are developed and met by the product. This usually requires both creative and analytical skills. The design engineer must bring knowledge about the design process and knowledge about specific technologies to the project. The person who fills this position usually has a four-year engineering degree. In smaller companies he or she may be a nondegreed designer who has extensive experience in the product area. For most product design projects, more than one design engineer will be involved.

Product manager. In many companies, this individual has the ultimate responsibility for the development of the product and represents the major link between the product and the customer. Because the product manager is accountable for the success of the product in the marketplace, he or she is also often referred to as the *marketing manager* or the *product marketing manager.* The product manager is often from the sales or customer service department.

In order to initiate a design project, management must appoint the nucleus of a design team—at a minimum, a design engineer and a product manager.

Manufacturing engineer. Design engineers generally do not have the necessary breadth or depth of knowledge about various manufacturing processes to fully support the design of most products. This knowledge is provided by the manufacturing or industrial engineer, who must have a grasp not only of in-house manufacturing capabilities but also of what the industry as a whole has to offer.

Designer. In many companies, the design engineer is responsible for specification development, planning, conceptual design, and the early stages of product design. The project is then turned over to *designers,* who finish detailing the product and developing the manufacturing and assembly documentation. Designers are often CAD experts with two-year technology degrees. At some companies designers are the same as design engineers.

Technician. The technician aids the design engineer in developing the test apparatus, performing experiments, and reducing data in the development of the product. The insights gained from the technician's hands-on experience are usually invaluable.

Materials specialist. In some products, the choice of materials is forced by availability. In others, materials may be designed to fit the needs of the product. The more a product moves away from the use of known, available materials, the more a materials specialist is needed as a member of the design team. This individual is usually a degreed materials engineer or a materials scientist. Often the materials specialist will be a vendor's representative who has extensive knowledge about the design potential and limitations of the vendor's materials. Many vendors actually provide design assistance as part of their service.

Quality control/quality assurance specialist. A quality control (QC) specialist has training in techniques for measuring a statistically significant sample to determine how well it meets specifications. This inspection is done on incoming raw materials, incoming products from vendors, and products produced in-house. A quality assurance (QA) specialist makes sure that the product meets any pertinent codes or standards. For example, for medical products, there are many FDA (Food and Drug Administration) regulations that must be met. Often QC and QA are covered by one person.

Analyst. Many engineers work as analysts. Analysts usually perform complex mathematical studies of design performance using finite-element methods, thermal system modeling, or other advanced software. They are generally specialists who focus on one type of system or method.

Industrial designer. Industrial designers are responsible for how a product looks and how well it interacts with consumers; they are the stylists who have a background in fine arts and in human factors analysis. They often design the envelope within which the engineer has to work.

Assembly manager. Where the manufacturing engineer is concerned with making the components from raw materials, the assembly manager is responsible for putting the product together. As you will see in Chap. 11, concern for the assembly process is an important aspect of product design.

Vendor's or supplier's representatives. Very few products are made entirely in one factory. In fact, many manufacturers outsource (i.e., have suppliers provide) 70% or more of their product. Usually there will be many suppliers of both raw and finished goods. There are three types of relationships with suppliers: (1) partnership—the supplier takes part in the process beginning with requirements and concept development; (2) mature—the supplier relies on the parent company's requirements and concepts to develop needed items; and (3) parental—the supplier builds only what the parent company specifies. Often it is important to have critical suppliers on the design team, as the success of the product may be highly dependent on them.

As Fig. 3.11 illustrates, having a design team made up of people with varying views may create difficulties, but teams are essential to the success of a product.

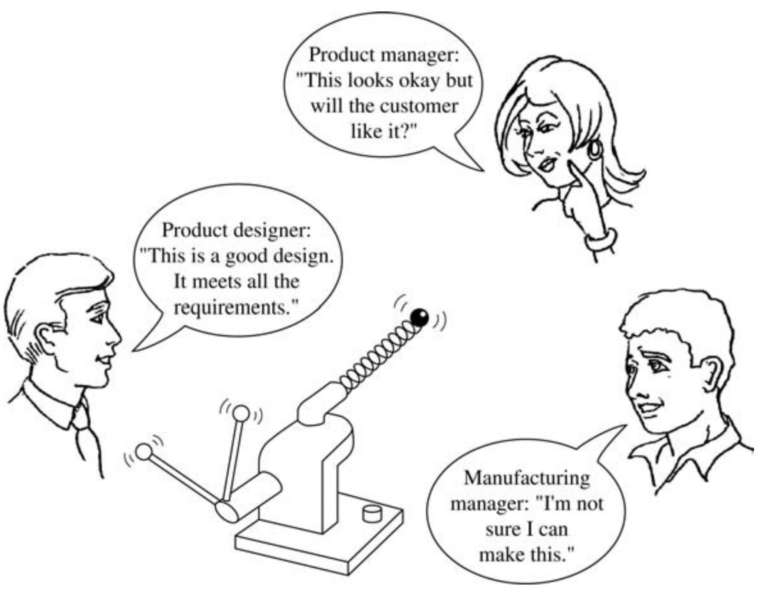


Figure 3.11 The design team at work.

The breadth of these views helps in developing a quality design. Part of the promise of PLM is to help all these different contributors communicate in a consistent and productive manner.

3.5.2 Design Team Management

Since projects require team members with different domains of expertise, it is valuable to look at the different structures of teams in an organization. This is important because product design requires coordination across the functions of the product and across the phases in the product's development process. Listed next are the five types of project structures. The number in parentheses is the percentage of development projects that use that type. These results are from a study of 540 projects in a wide variety of industries.

Functional organization (13%). Each project is assigned to a relevant functional area or group within a functional area. A functional area focuses on a single discipline. For aircraft manufacturers, Boeing, for example, the main functions are aerodynamics, structures, payload, propulsion, and the like. The project is coordinated by functional and upper levels of management.

Functional matrix (26%). A project manager with limited authority is designated to coordinate the project across different functional areas or groups. The functional managers retain responsibility and authority for their specific segments of the project.

Balanced matrix (16%). A project manager is assigned to oversee the project and shares with the functional managers the responsibility and authority for completing the project. Project and functional managers jointly direct many work-flow segments and jointly approve many decisions.

Project matrix (28%). A project manager is assigned to oversee the project and has primary responsibility and authority for completing the project. Functional managers assign personnel as needed and provide technical expertise.

Project team (16%). A project manager is put in charge of a project team composed of a core group of personnel from several functional areas or groups, assigned on a full-time basis. The functional managers have no formal involvement. Project teams are sometimes called "Tiger teams," "SWAT teams," or some other aggressive name, because this is a high-energy structure and the team is disbanded after the project is completed.

What is important about these structures is that some of them are more successful than others. Structures focused on the project are more successful than those built around the functional areas in the company (Fig. 3.12). Here the balanced matrix, project matrix, and project teams resulted in a higher percentage of success across all measures. Thus, when planning for a design project, organize the talent around the project whenever possible.

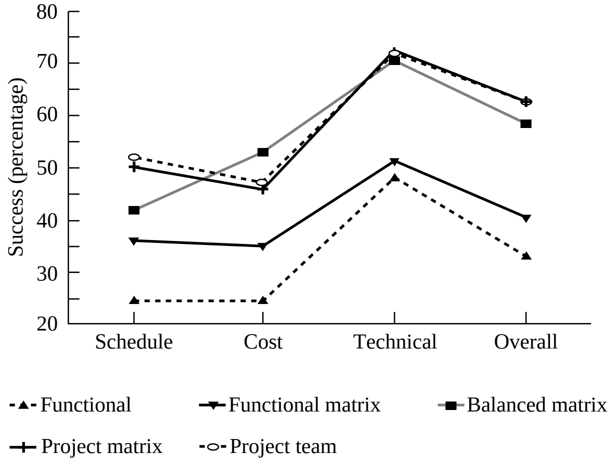


Figure 3.12 Project successes versus team structure.

3.6 BUILDING DESIGN TEAM PERFORMANCE

It can be very exciting being part of a team that is productive and is making good use of all the members. Conversely, it can be hellish working on a team that is not functioning very well. So the goal of this section is to help you build and maintain successful teams. To help ensure success, we will use *Team Contracts, Team Meeting Minutes,* and *Team Health Assessments*. Each of these encourages behavior that leads to a successful team experience.

According to a leading book on teams, there are ten characteristics of a successful team. Included in the description of each of these characteristics is a guide to where this text presents material to help make teams successful.

1. **Clarity in goals.** The process developed in this book focuses on goals during process planning in Chap. 4 and for the product itself in Chap. 6. Further, the Team Contract suggested later in this section encourages documenting the immediate team goals.
2. **Plan of action.** Chapter 4 is all about project planning.
3. **Clearly defined roles.** We have already discussed roles, and documenting them is part of the Team Contract.
4. **Clear communication.** Team Contracts, Team Meeting Minutes, and Team Health Assessments (all in this chapter) plus virtually all the process methods in this book are designed to help with communication.
5. **Beneficial team behaviors.** As with communication, the material in this book is designed to result in beneficial behaviors.
6. **Well-defined decision process.** The decision process is introduced in Chap. 4 and is the focus of Chap. 8.

7. **Balanced participation.** Equal division of work is very important for a successful team. This is further discussed later in this chapter.
8. **Established ground rules.** This is discussed later in this chapter.
9. **Awareness of team process.** This is what we are talking about in this entire chapter.
10. **Use of sound generation/evaluation approach.** As introduced in Chap. 1, the seven activities of the design process are: *Establish* the Need, *Plan, Understand, Generate, Evaluate, Decide, and Document.* Generate and Evaluate are covered in Chaps. 7–12.

To set the foundation for future work, the remainder of this chapter covers Team Contracts, Team Meeting Minutes, and Team Health Assessments.

3.6.1 Team Contract

A good starting point for a team is with a team contract. Team contracts are seldom done in industry because the basics of it are assumed in the employment contract, and it is further assumed that people know how to work to make a team successful. Here we will use a contract as both a learning tool and as a way to increase the odds of team success.

Figure 3.13 shows an example Team Contract. The first section is for the assignment of roles on the team and goals for the team. As suggested in the list of characteristics for a successful team, the goals and roles need to be known and agreed to. Roles can be developed from the list in Section 3.5 and make the goals be as specific as possible. Much in Chaps. 4 and 5 focuses on goals.

In the second section the team members sign, indicating they agree to a list of performance expectations that are shown in the example. Additionally, the form has room for other expectations to which the team may want to agree. The final section on the form is for strategies for conflict resolution. Hopefully these won't be needed, but, like any other contract, methods for problem resolution need to be addressed at the beginning to prevent difficulties later. Suggested strategies are shown in the example.

3.6.2 Team Meeting Minutes

Before a meeting begins, it is essential to have an agenda. Without an agenda, meetings wander and it is often not clear whether anything was accomplished. Thus, the purpose of the first section in the team meeting minutes (Fig. 3.14) is to itemize the agenda. Agendas should be written in terms of the goals of the meeting. Agenda items such as "Present the results of the stress analysis" are not sufficient. Why are the results being presented? What is to be accomplished by telling others the results? It is better to state this in terms of what is to be accomplished: "Decide how the stress affects the assembly's performance" or "Determine if the stress is low enough to meet the requirements of the system."

The second section itemizes the high points of the discussion. To understand why taking notes about the high points is so important, consider the results of an

Team Contract

Design Organization: The B Team	**Date:** Jan. 2, 2009

Team Member	Roles	Signature
Jason Smathers	Lead designer	Jason Smathers
Brittany Spars	Structural engineer	Brittany Spars
Deon Warner	Systems engineer	Deon Warner

Team Goals	Responsible Member
1. Develop layout and initial input to solid model.	JS
2. Analyze for fatigue and other failures.	BS
3. Detail latching mechanism.	JS
4. Develop wiring plan.	DW
5.	

Team Performance Expectations	Initial			
• Strive to complete all assigned tasks before or by deadlines.	JS	BS	DW	
• Complete all tasks to the best of ability.	JS	BS	DW	
• Listen carefully and attentively to all comments at meetings.	JS	BS	DW	
• Accept and give criticism in a professional manner.	JS	BS	DW	
• Focus on results before the fact, rather than excuses after.	JS	BS	DW	
• Provide as much notice as possible of commitment problems.	JS	BS	DW	
• Attend and participate in all scheduled group meetings.	JS	BS	DW	

Strategies for Conflict Resolution

- Amend contract with deadlines for agreed to tasks.
- Reward entire team for goals met with some treat or social gathering.
- As a team, go to a higher authority for assistance with a team problem.
- Don't kill messengers. Seek to encourage the airing of problems.

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Figure 3.13 Example team contract.

Team Meeting Minutes

Design Organization: The C Team	**Date:** Jan. 30, 2009

Agenda

1. Finalize the plan for the exotherm system.
2. Decide on the final shape for the housing.
3. Resolve how to complete task 3.
4. Plan the postproject party.
5.
6.

Discussion: Jason, Brittany, and Deon attended. The meeting lasted an hour. The agenda was fully covered and new issues were added to the list for the next meeting.

Decisions Made

1. Exotherm plan finalized. See Attachment A.
2. Housing alternative 3 was chosen.
3.

Action Items	Person Responsible	Deadline
Jason details Housing alternative 3	JS	Thursday
Brittany to plan party	BS	2/10
Deon will assist Brittany to get Task 3 completed by Thursday	BS	Thursday

Team member: Jason Smathers	Date for next meeting: Thursday
Team member: Brittany Spars	
Team member: Deon Warner	
Team member:	

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 Form # 3.0

Figure 3.14 Team meeting minutes.

experiment where a group was asked 2 weeks after a meeting to recall specific details of that meeting. In recounting the meeting they

- Omitted 90% of the specific points that were discussed.
- Recalled half of what they did remember incorrectly.
- Remembered comments that were not made.
- Transformed casual remarks into lengthy orations.
- Converted implicit meanings into explicit comments.

Recording the decisions made is even more important. Often decisions are clear. For example, "Choose to use 5056-T6 aluminum for the brace" or "The potential difference on anode and cathode of the X-ray tube will be 140 keV." However, if you listen carefully to unstructured meetings, you find that they wander from topic to topic. When one topic gets difficult because some of the parties disagree or more information is needed, the conversation moves to another topic with no resolution of the initial topic. If stuck, decide what to do to get unstuck and record that call for action. For example, "A decision was made to gather more information on material x" or "We will use Belief Maps to help the team work toward agreement." These decisions lead directly to the most important item in the meeting minutes, the action items—an itemized list of what is to happen next. State each action item as a clear deliverable, assign the responsible party, and determine by when it is to be done.

3.6.3 Team Health Assessment

One of the most important activities is assessing the team's heath. A form for assessing team health is shown in Fig. 3.15. This form includes 17 measures (with room for more) to be assessed periodically by the team to measure how it is doing. For each measure, the response ranges from strongly agree to strongly disagree, with attention needed to remedy problems in areas where at least *one person* does not agree with the measure. The team needs to devise remedies for these "problem areas." Not doing so allows problems to fester and worsen.

This assessment should be used periodically and especially when any team members experience one of the following:

- A loss of enthusiasm
- A sense of helplessness
- A lack of purpose or identity
- Meetings in which the agenda is more important than the outcome
- Cynicism and mistrust
- Interpersonal attacks made behind peoples backs
- Floundering
- Overbearing or reluctant team members

Team Health Assessment

Team Assessed:							**Date:**

SA = Strongly Agree, A = Agree, N = Neutral, D = Disagree, SD = Strongly Disagree, NA = Not Applicable

	Measure	SA	A	N	D	SD	NA
1	Team mission and purpose are clear, consistent and attainable.	☐	☐	☐	☐	☐	☐
2	I feel that I am part of a team.	☐	☐	☐	☐	☐	☐
3	I feel good about the team's progress.	☐	☐	☐	☐	☐	☐
4	Respect has been built within the team for diverse points of view.	☐	☐	☐	☐	☐	☐
5	Team environment is characterized by honesty, trust, mutual respect, and team work.	☐	☐	☐	☐	☐	☐
6	The roles and work assignments are clear.	☐	☐	☐	☐	☐	☐
7	Team treats every member's ideas as having potential value.	☐	☐	☐	☐	☐	☐
8	Team encourages individual differences.	☐	☐	☐	☐	☐	☐
9	Conflicts within the team are aired and worked to resolution.	☐	☐	☐	☐	☐	☐
10	Team takes time to develop consensus by discussing the concerns of all members to arrive at an acceptable solution.	☐	☐	☐	☐	☐	☐
11	Decisions are made with input from all in a collaborative environment.	☐	☐	☐	☐	☐	☐
12	The environment encourages communication and does not "kill the messenger" when the news is bad.	☐	☐	☐	☐	☐	☐
13	When one team member has a problem others jump in to help.	☐	☐	☐	☐	☐	☐
14	Dysfunctional behavior is dealt with in an appropriate manner.	☐	☐	☐	☐	☐	☐
15	When someone on the team says they are going to do something, the team can count on it being done.	☐	☐	☐	☐	☐	☐
16	There is no "them and us" on the team.	☐	☐	☐	☐	☐	☐
17	Our team cultivates a "what we can learn" attitude when things do not go as expected.	☐	☐	☐	☐	☐	☐
18		☐	☐	☐	☐	☐	☐
19		☐	☐	☐	☐	☐	☐
20		☐	☐	☐	☐	☐	☐

Remedies for improving the Neutral (N), Disagree (D) and Strongly Disagree(SD) responses:

Assessor:

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Figure 3.15 Team health assessment.

3.7 SUMMARY

- The human mind uses the long-term memory, the short-term memory, and a controller in the internal environment when problem solving.
- Knowledge can be considered to be composed of chunks of information that are general, domain-specific, or procedural in content.
- The short-term memory is a small (seven chunks, features, or parameters) and fast (0.1-sec) processor. Its properties determine how we solve problems. We use the external environment to augment the size of the short-term memory.
- The long-term memory is the permanent storage facility in the brain. It is slow to remember, it is fast to recall (sometimes), and it never gets full.
- Creative designers are people of average intelligence; they are visualizers, hard workers, and constructive nonconformists with knowledge about the problem domain. Creativity takes hard work and can be aided by a good environment, practice, and design procedures.
- Because of the size and complexity of most products, design work is usually accomplished by teams rather than by individuals.
- Working in teams requires attention to every team member's problem-solving style (including yours)—introverted or extroverted, fact or possibility, verbal or visual, objective or subjective, or decisive or flexible.
- It is important to have team goals and roles, keep meeting minutes, and assess team health.
- Many activities can help build team health.

3.8 SOURCES

Adams, J. L.: *Conceptual Blockbusting,* Norton, New York, 1976. A basic book for general problem solving that develops the idea of blocks that interfere with problem solving and explains methods to overcome these blocks; methods given are similar to some of the techniques in this book.

Larson, E., and D. Gobeli: "Organizing for Product Development Projects," *Journal of Product Innovation Management,* No. 5, pp. 180–190, 1988. The study in Section 3.5.2 on design team management is from this paper.

Koberg, D., and J. Bagnall: *The Universal Traveler: A Systems Guide to Creativity, Problem Solving and the Process of Reaching Goals,* Kaufman, Los Altos, Calif., 1976. A general book on problem solving that is easy reading.

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The next five titles are all good books on developing and maintaining teams.

Belbin, R. M.: *Management Teams,* Heinemann, New York, 1981.

Cleland, D. I., and H. Kerzner: *Engineering Team Management,* Van Nostrand Reinhold, New York, 1986.

Johansen, R., et al.: *Leading Business Teams,* Addison-Wesley, New York, 1991.

Katzenbach, J. R., and D. Smith: *The Wisdom of Teams,* Harvard Business School Press, 1993.

Scholtes, P. R., et al.: *The Team Handbook*, 3rd edition, Oriel Inc, 2003.

The problem-solving dimensions in Section 3.3.5 are based on the Myers-Briggs Type Indicator. These titles give more details on this method.

Keirsey, D., and M. Bates: *Please Understand Me,* 5th ed., Prometheus Nemesis, 1978.

Kroeger, O., and J. M. Thuesen: *Type Talk at Work,* Delta, 1992.

Kroeger, O., and J. M. Thuesen: *Type Talk*, Delta, 1989.

3.9 EXERCISES

3.1 Develop a simple experiment to convince a colleague that the short-term memory has a capacity of about seven chunks.

3.2 Think of a simple object, write about it, and sketch it in as many ways as possible. Refer to Table 2.1 and Fig. 3.4 to encourage a range of language and abstraction.

3.3 Describe a mechanical design problem to a colleague. Be sure to describe only its function. Have the colleague describe it back to you in different terms. Did your colleague understand the problem the same way as you? Was the response in terms of previous partial solutions?

3.4 During work on a team, identify the secondary roles each person is playing. Can you identify who fills each role?

3.5 For a new team begin with these team-building activities.

a. *Paired introductions.* Get to know each other by asking questions such as

- What is your name?
- What is your job (class)?
- Where did you grow up (go to school)?
- What do you like best about your job (school)?
- What do you like least about your job (school)?
- What are your hobbies?
- What is your family like?

b. *Third-party introductions.* Have one member of the team tell another the information in (a). Then the second member introduces the first member to the rest of the team using all the information that he or she can remember. It makes no difference if the team heard the initial introduction.

c. *Talk about first job.* Have each member of the team tell the others about his or her first job or other professional experience. Information such as this can be included:

- What did you do?
- How effective was your manager?
- What did you learn about the real world?

   d. *"What I want for myself out of this."* Have each member of the team tell the others for 3 to 5 min what his or her goals are for participation in the project. What do they want to learn or do, and why? Consider personal goals such as getting to know other people, feeling good about oneself, learning new skills, and other nontask goals.

   e. *Team name.* Have each person write down as many potential team names as possible (at least five). Discuss the names in the team, and choose one. Try to observe who plays which secondary role.

3.6 Pick an item from the team health assessment. For that item, one member of a four-person team checks "Strongly Disagrees." Develop a list of actions you would take as a team leader or team member.

3.10 ON THE WEB

Templates for the following documents are available on the book's website: www.mhhe.com/Ullman4e

- Personal Problem Solving Dimensions
- Team Contract
- Team Meeting Minutes
- Team Health Assessment

CHAPTER 4

The Design Process and Product Discovery

KEY QUESTIONS

- What are the six phases of the mechanical design process?
- What are the three prime sources for new products?
- What does it mean for a product to be “mature”?
- How can a SWOT analysis help choose which products to develop?
- How did Benjamin Franklin contribute to decision making?
- What are the six basic decision-making activities?

4.1 INTRODUCTION

In this chapter, we introduce the major phases in the design process and tackle the first of them, discovering the need. The six-phase design process established here sets the structure for the rest of this book. Since design is fundamentally the effort to fulfill a need, discovering the need is always the first phase in the process. Because there are always more needs than there are resources to meet them, key here is deciding which product ideas to develop. Thus, in this chapter we also introduce the basics of decision making. Making good decisions is probably the most important and least studied engineering skill. We will refine decision making when choosing a concept and again when making Product Development decisions.

4.2 OVERVIEW OF THE DESIGN PROCESS

Regardless of the product being developed or changed, or the industry, there is a generic set of phases that must be accomplished for all projects. These are listed

> Design is a process—not just building hardware.
> —Tim Carver, OSU student, 2000

in Fig. 4.1. They are a refinement of the phases in a product's life cycle (Fig. 1.8) that are of concern to the designer. For each phase, there are a series of activities that need to be accomplished. The phases and activities are briefly introduced in this chapter and refined throughout the rest of the book. After this introduction, the first phase, Product Discovery, is explained in detail.

This design process, as shown, applies to design of systems, subsystems, assemblies, and components. It applies to new, innovative products and to changes in existing products. Of course, the detail and emphasis will change with the level of decomposition and with the amount of change needed. To help introduce the phases and how they are used at all levels in a product's decomposition consider the design of a General Electric CT Scanner.

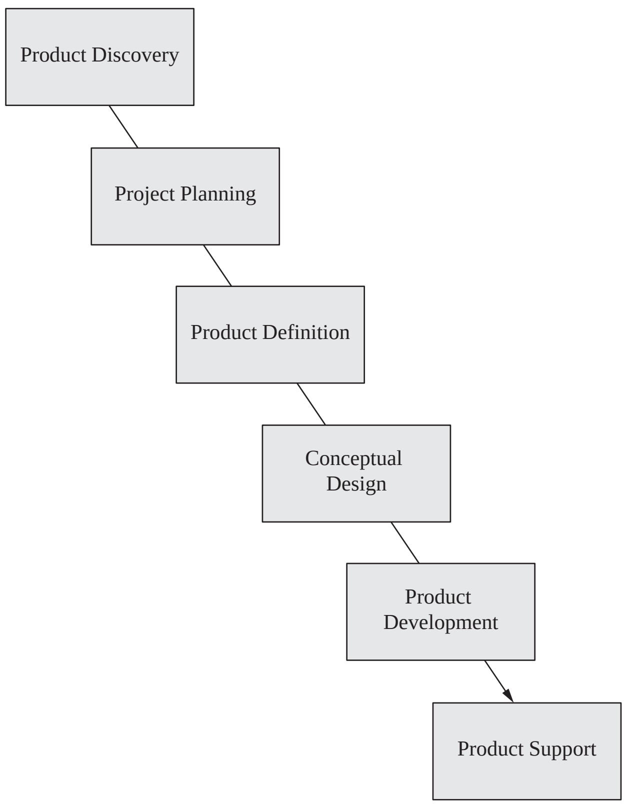

Figure 4.1 The mechanical design process.

General Electric designs and manufactures many different types of products including home appliances, lightbulbs, jet engines, and a host of medical products. One of the products developed by GE's healthcare business is the CT Scanner shown in Fig, 4.2. The full name of the technology used in this scanner is X-ray Computed Tomography (CT). CT is a diagnostic imaging technique that can produce solid images of the organs inside patients. A CT system consists of a patient table that can be positioned and moved through the bore of the gantry. Beneath the sleek outer casing, the gantry houses a frame that holds an X-ray tube and a detector. The X-ray tube is on the top at the 1 o'clock position in Fig. 4.3 and the arc-shaped detector is on the bottom at the 7 o'clock position. The frame, X-ray tube, and detector rotate around the patient at 120 rpm. This means that there is a centrifugal acceleration on the components of more than 10*g*s. Thus, the X-ray tube components experience very large radial body loads and covey centrifugal loading to the gantry support of approximately 2000 N of radial force.

In order to generate images of organs the tube emits rays that pass through the patient, are sensed by the detector, and are processed by a computer, as shown in Fig. 4.4. To accomplish this, the X-ray tube emits bursts of X-rays. During emission, the tube requires 60–100 kW of power. This power must be transmitted to the rotating tube, where the majority of the power is converted into waste heat that must be transferred out of the gantry. Making the design task even more

Figure 4.2 GE CT Scanner. (Source: Reprinted with permission of GE Medical.)

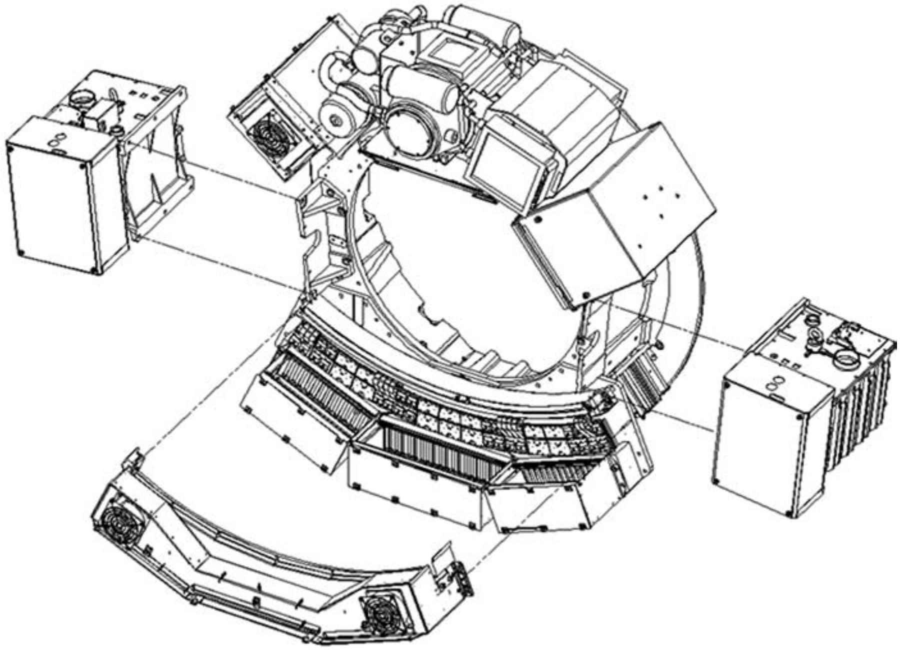

Figure 4.3 The insides of a CT gantry. (Source: Reprinted with permission of GE Medical.)

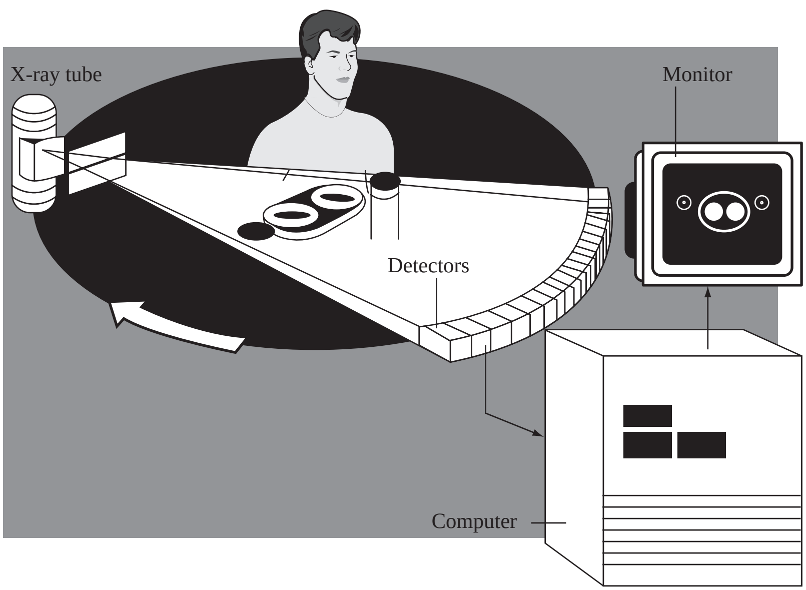

Figure 4.4 How a CT works.

difficult, the anode in the X-ray tube is rotating on an axis perpendicular to the plane of the gantry at 7000–10,000 rpm. The bearings for the anode are operating in a vacuum at a temperature of 450°C.

The design of the X-ray tube is a tremendous undertaking requiring hundreds of design and manufacturing engineers, materials scientists, technicians, purchasing agents, drafters, and quality-control specialists, all working over several years. To recap:

- The *system* is the CT Scanner.
- Major *subsystems* are the patient table and the gantry.
- A major *assembly* in the gantry is the frame with the X-ray tube and detector.
- The X-ray tube itself is a *subsystem* in the frame assembly.
- Two *components* in the X-ray tube are the anode and its bearings.

Regardless of which of these are being designed or changed, there will be a Plan, Product Definition, and Conceptual Design before there are products. These phases, itemized in Fig. 4.1, are common to the design of every system, subsystem, assembly, and component. Let's expand each of the phases.

4.2.1 Product Discovery

Before the original design or redesign of a product can begin, the need for it must be established. As shown in Fig. 4.5, there are three primary sources for design projects: technology, market, and change. We will delve into these sources later in this chapter. Regardless of the source, a common activity at most companies is maintaining a list of potential projects. Since companies have limited people and money, the second activity, after identifying the products, is choosing which

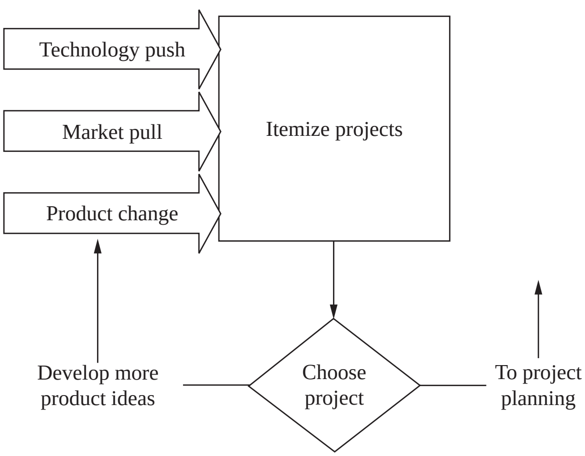

Figure 4.5 The Discovery phase of the mechanical design process.

of them to work on. Sometimes this decision comes before Project Planning as structured in this book, and sometimes it is postponed until later, after Planning, Product Definition, and Conceptual Design has been done and more is known about each of the options. The ordering of work on these phases will be further discussed in Chap. 5.

The GE CT Scanner is a mature product, but new products are advancing the state of the art at a rapid rate. For mature products, design changes focus on improved reliability, cost, and supply chain management. New products are pulled by new imaging applications and performance capability. For the X-ray tube itself, changes are usually in response to market pull for more detailed X-rays and faster times. These system-level needs are projected down as projects to redesign the X-ray tube. Within these projects, the needs are communicated as specifications for higher power, more rotational speed, better heat removal, and other technical changes.

4.2.2 Project Planning

The second phase is to plan so that the company's resources of money, people, and equipment can be allocated and accounted for (Fig 4.6). Planning needs to precede any commitment of resources; however, as with much design activity, this requires speculating about the unknown—and that makes the planning for a product that is similar to an earlier product easier than planning for a totally new one. Since planning requires a commitment of people and resources from all parts of the company, part of the planning is forming the *design team*. As discussed in Chap. 3, few products or even subsystems of products are designed by one person. Additionally, much planning work goes into developing a schedule and estimating the costs. The final goal of the activities in this phase is generating a set of tasks that need to be performed and a sequence for them. Planning is covered in detail in Chap. 5.

The plan for redesigning the X-ray tube is very complex as it is usually only a small part of the plan to redesign the entire CT Scanner to create the next model. Thus, the tasks, schedule, and budget must integrate with many other similar plans.

4.2.3 Product Definition

During the product definition phase (Fig. 4.7), the goal is to understand the problem and lay the foundation for the remainder of the design project. Understanding the problem may appear to be a simple task, but since most design problems are poorly defined, finding the definition can be a major undertaking. In Chap. 6, we will look at a technique to accomplish this. Using this technique, the first activity will be to *identify the customers* for the product. This activity serves as the basis to *generate the customers' requirements.* These requirements are then used to *evaluate the competition* and to *generate engineering specifications,* measurable behaviors of the product-to-be that, later in the design process, will help in

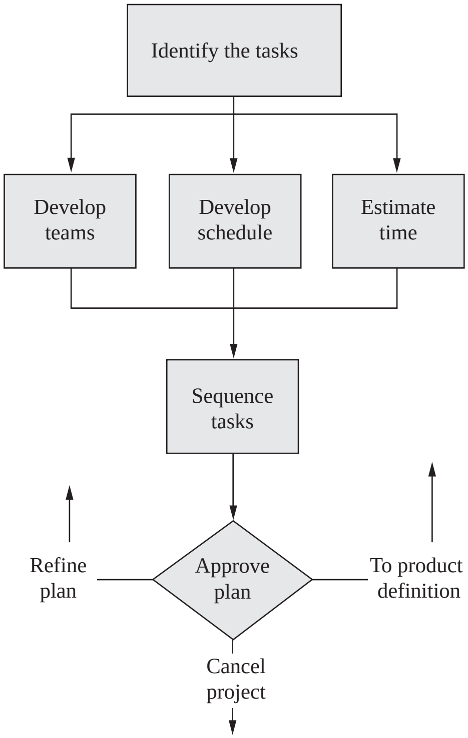

Figure 4.6 The Project Planning phase of the mechanical design.

determining product quality. Finally, in order to measure the "quality" of the product, we *set targets for its performance.*

Often, the results of the activities in this phase determine how the design problem is decomposed into smaller, more manageable design subproblems. Sometimes not enough information is yet known about the product, and decomposition occurs later in the design process.

In redesigning the X-ray tube, the needs are translated into realizable targets for power, rotational speed, heat removal, and other technical specifications. These specifications are developed in concert with other design teams that need to supply the power, structurally support and power the rotating X-ray tube, and dispose of the waste heat.

4.2.4 Conceptual Design

Designers use the results of the Planning and Product Definition phases to generate and evaluate concepts for the product or product changes (Fig 4.8). When we *generate concepts,* the customer's requirements serve as a basis for developing a

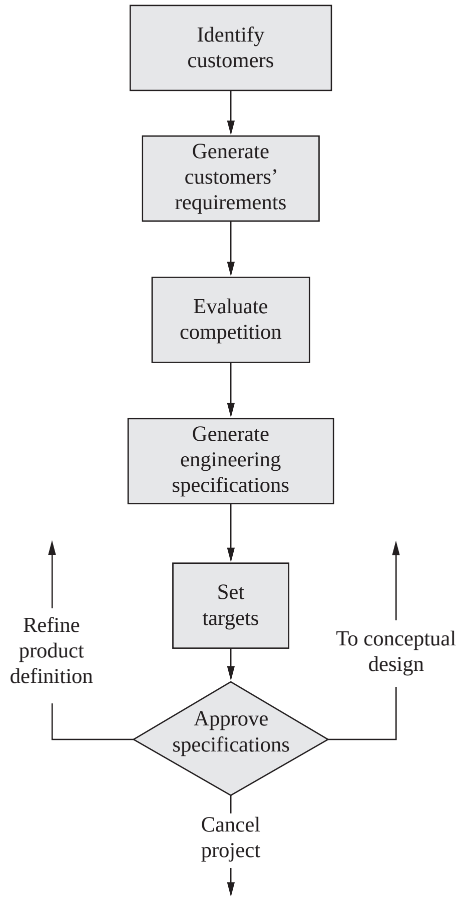

Figure 4.7 The Product Definition phase of the mechanical design.

> Developing a concept into a product without prior effort on the earlier phases of the design process is like building a house with no foundation.

functional model of the product. The understanding gained through this functional approach is essential for developing concepts that will eventually lead to a quality product. Techniques for concept generation are given in Chap. 7.

After we *evaluate concepts,* the goal is to compare the concepts generated to the requirements developed during Product Definition and make decisions.

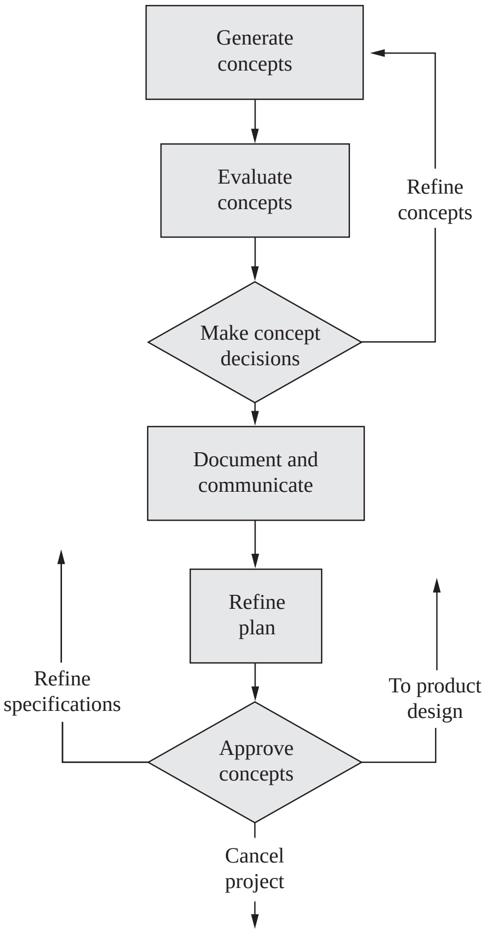

Figure 4.8 The Conceptual Design phase of the mechanical design process.

Concept decisions are made with limited knowledge. As shown in Fig. 1.11 knowledge increases with time and effort. One goal in Conceptual Design is choosing the best alternatives with the least expenditure of time and other resources needed to gain knowledge. Techniques helpful in concept evaluation and decision making are in Chap. 8.

During projects to redesign the X-ray tube, concepts are small changes to existing products, and the X-ray design team at GE uses detailed analytical models to evaluate them. However, for the Mars Rover, introduced in Chap. 2, new wheel concepts were dramatically different from those previously used and concept evaluation was much less analytical than at GE.

4.2.5 Product Development

After concepts have been generated and evaluated, it is time to refine the best of them into actual products (see Fig. 4.9). The Product Development phase is discussed in detail in Chaps. 9–11. Unfortunately, many design projects are begun here, without benefit of prior specification or concept development. This design approach often leads to poor-quality products and in many cases causes costly changes late in the design process. It cannot be overemphasized: *Starting a project by developing product, without concern for the earlier phases, is poor design practice.*

At the end of the Product Development phase, the product is released for production. At this time, the technical documentation defining manufacturing,

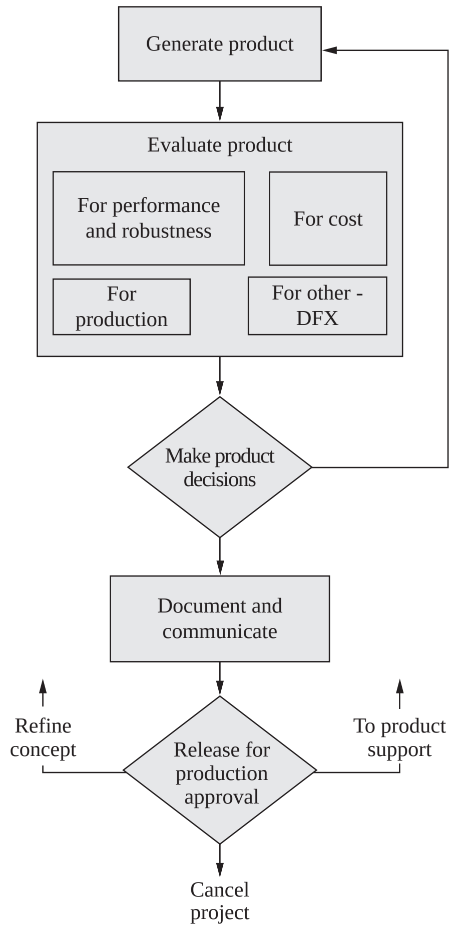

Figure 4.9 The Product Development phase of the mechanical design process.

assembly, and quality control instructions must be complete and ready for the purchase, manufacture, and assembly of components.

The GE design team used refined analytical models and component system testing during Product Development. Their final prototypes generally use actual production processes and production lines to fabricate final prototypes. This helps to ensure they capture the expected product quality and not be misled by “laboratory” produced prototypes.

4.2.6 Product Support

The design engineer’s responsibility may not end with release to production. Often there is continued need for manufacturing and assembly support, support for vendors, and help in introducing the product to the customer (see Fig. 4.10). Additionally, design engineers are usually involved in the engineering change process. This is the process where changes made to the product, for whatever reason, are managed and documented. This is one of the Product Support topics discussed in Chap. 12.

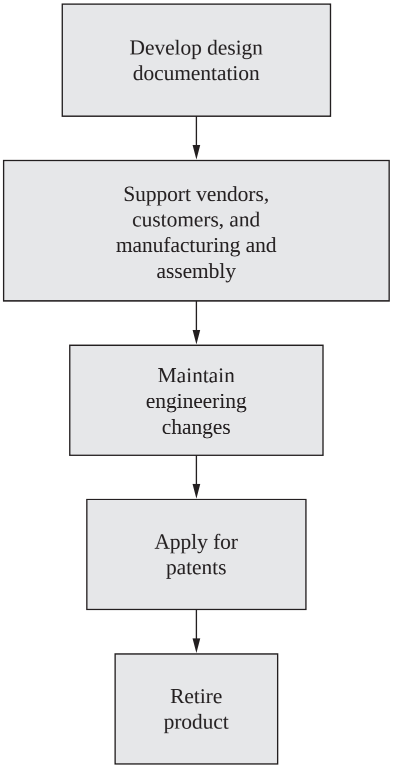

Figure 4.10 The Product Support phase of the mechanical design process.

Finally, the designers may be involved in the retirement of the product. This is especially true for products that are designed for specialized short-term use and then decommissioning. But, as pointed out in the Hannover Principles, this should be a concern regardless of the product throughout the design process.

Whereas the GE team must continue to support the X-ray tubes that are in use, a better example of postproduction support is the Mars Rover. The two Rovers were designed for 90 Mars days of operation. As of this writing, they have both lasted over 3.5 years. One of the Rovers is operating with only five of its original six legs providing power as one drive motor has ceased to function. The other has lost one of its four steering motors. In both cases, the engineers had to figure out how to change the Rovers from Earth to compensate for the failures. This is an extreme example of postproject Product Support.

Before refining the first phase, Product Discovery, later in the chapter, some justification is in order for why a product needs to be developed carefully through these six phases.

4.3 DESIGNING QUALITY INTO PRODUCTS

A good design process will support designing quality into the product. Traditionally, quality has been the concern of Quality Control (QC) or Quality Assurance (QA). QC/QA specialists inspect products as they are being manufactured and assembled. They check for conformance with the technical documentation (i.e., drawings, material properties, and other specifications) developed during design. They check dimensions, material properties, surface finishes, and other factors that are critical for form and function. This is often referred to as "inspecting quality into a product."

It is less expensive and much more effective to *design quality into a product.* This implies not only designing a product that works as it should, lasts a long time, and meets the other customer desires listed in Table 1.1, but it also means designing the components and assemblies so they are easy to make, they have few or no tightly toleranced dimensions, and they have few critical (i.e., prone to failure) features. Finally, designing quality into a product also implies designing the product so that it is easy and foolproof to assemble.

Many engineering best practices help design quality into a product. Table 4.1 itemizes techniques generally considered as best practice and discussed in this text. They appear in the order in which they are generally applied to a typical design problem. However, each design problem is different, and some techniques may not be applicable to some problems. Additionally, even though the techniques are described in an order that reflects sequential and specific design phases, they

> Quality cannot be manufactured or inspected into a product,
> it must be designed into it.

Table 4.1 Best practices presented in this text

Project Planning (Chap. 5)	**Product Development**
Generating a product development plan	**Product generation (Chap. 9)**
Managing the project	Form generation from function
	Form representation
Specification Development (Chap. 6)	Materials and process selection
Understanding the design problem	Vendor development
Developing customer's requirements	**Product evaluation (Chaps. 10 and 11)**
Assessing the competition	Functional evaluation
Generating engineering specifications	Evaluating performance
Establishing engineering targets	Tolerance analysis
	Sensitivity analysis
Conceptual Design	Robust design
Generating concepts (Chap. 7)	Design for cost
Functional decomposition	Design for value
Generating concepts from functions	Design for manufacture
Evaluating concepts (Chap. 8)	Design for assembly
Judging feasibility	Design for reliability
Assessing technology readiness	Design for test and maintenance
Using the decision matrix	Design for the environment
Robust decision making	
	Product Support (Chap. 12)
	Developing design documentation
	Maintaining engineering changes
	Applying for a patent
	Design for end of product life

are often used in different order and in different phases. Understanding the techniques and how they add quality to the product aids in selecting the best technique for each situation.

The techniques described in this text comprise a design strategy that will help in the development of a quality product that meets the needs of the customer. Although these techniques will consume time early in the design process, they may eliminate expensive changes later. The importance of this design strategy is clearly shown in Fig. 4.11, a reprint of Fig. 1.5.

Figure 4.11 shows that Company A structures its design process so that changes are made early, while Company B is still refining the product after it has been released to production. At this point, changes are expensive, and early users are subjected to a low-quality product. The goal of the design process is not to eliminate changes but to manage the evolution of the design so that most changes come through iterations early in the process. The techniques listed in Table 4.1 also help in developing creative solutions to design problems. This may sound paradoxical, as lists imply rigidity and creativity implies freedom, however, creativity does not spring from randomness. Thomas Edison, certainly one of the most creative designers in history, expressed it well: "Genius," he said, "is 1% inspiration and 99% perspiration." The inspiration for creativity can only occur if the perspiration is properly directed and focused. The techniques presented here

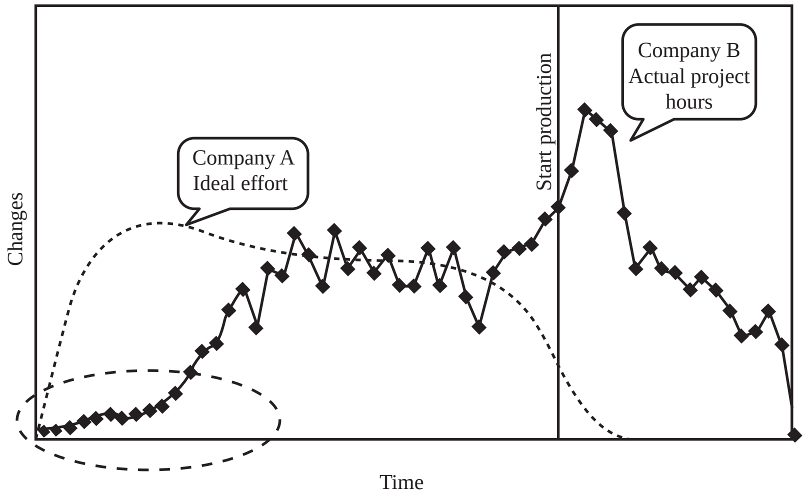

Figure 4.11 Engineering changes during automobile development.

help the perspiration occur early in the design process so that the inspiration does not occur when it is too late to have any influence on the product. Inspiration is still vital to good design. The techniques that make up the design process are only an attempt to organize the perspiration.

These techniques also force documentation of the progress of the design, requiring the development of notes, sketches, informational tables and matrices, prototypes, and analyses—records of the design's evolution that will be useful later in the design process.

In the 1980s, it was realized that the process was as important as the product. One result of this realization is that Product Development is now often referred to as integrated product and process development or IPPD. Note that the term *process* is on equal footing with the *product.* Note also that IPPD implies that the product and process are under development. They are evolving.

Another result of this awareness is the increasing use of the International Standard Organization's ISO 9000, the quality management system. ISO 9000 was first issued in 1987 and now has been adopted by most countries. There are millions of companies with ISO-9000 certification worldwide. All major manufacturing companies are ISO-9000 certified and, regardless of size, any company involved in international Product Development or manufacturing is also.

Prior to 2000 there were five standards numbered 9000 through 9005. In 2000, these were reduced to: ISO 9000, fundamentals and vocabulary; ISO 9001, requirements; and ISO 9004, guidance for performance improvement. ISO-9000 registration means that the company has a quality system that

1. Standardizes, organizes, and controls operations.
2. Provides for consistent dissemination of information.

3. Improves various aspects of the business-based use of statistical data and analysis.
4. Enhances customer responsiveness to products and service.
5. Encourages improvement.

Companies decide to seek ISO-9000 certification because they feel the need to control the quality of their products and services, to reduce the costs associated with poor quality, or to become more competitive. Also, they may choose this path simply because their customers expect them to be certified or because a regulatory body has made it mandatory.

In order to receive the certification, they must first develop a process that describes how they develop products, handle product problems, and interact with customers and vendors. Among the materials that must be prepared are written procedures that

- Describe how most work in the organization gets carried out (i.e., the design of new products, the manufacture of products, and the retirement of products).
- Control distribution and reissue of documents.
- Design and implement a corrective and preventive action system to prevent problems from recurring.

Once this material is developed the company invites an accredited external auditor (registrar) to evaluate the effectiveness of the process. If the auditors like what they see, they will certify that the quality system has met all of the ISO's requirements. They will then issue an official certificate. The company can then announce to the world that the quality of their products and services is managed, controlled, and assured by a registered ISO-9000 quality system. The certification typically expires after three years. Also, the registration agency typically requires surveillance audits at six-month intervals to maintain the currency of the certificate.

It must be made clear that ISO 9000 does not give a plan or process for developing products. It only requires a company to have a documented Product Development process on which the plan for a particular product can be based. The certification is not on the quality of the process itself, but that it exists, is maintained, and is used. Thus, a company can have a very poor methodology for developing products and still be certified. However, it is assumed that if a company is going to go to the trouble to get certified and wants to remain competitive in its markets, it will work to make this process and its Product Development plans as good as it can.

4.4 PRODUCT DISCOVERY

The goal of Product Discovery (Fig. 4.12), the first phase in the design process, is to develop a list of design projects that includes new products and product changes, and to choose which projects to work on. The term "discovery" may sound odd,

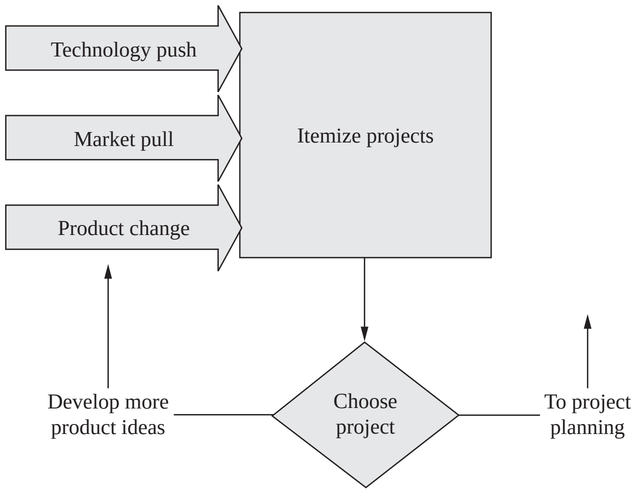

Figure 4.12 The Product Discovery phase of the mechanical design process.

but every design effort begins with the discovery of a need for product. There are three prime sources for new products: *market pull, technology push*, and *product change*.

Market pull occurs when there is customer demand for new products or product features. About 80% of new product development is market-driven. Without a customer for the product, there is no way to recover the costs of design and manufacture. Conversely, technology push is when a new technology is developed before there is customer demand. Let us refine these two product sources.

To manage market pull, the sales and marketing departments of most companies have a long list of new products or product improvements that they would like. When they see customers purchase a competitor's product, they wish their products had the unique features found on that product. Further, if they are doing a good job, they project the customer demand into the future. If sales and marketing had their way, there would be a continuous flow of product improvements and new products so that all potential customers could be satisfied. In fact, this is the direction that product development has been taking for the last few years—near-custom products with short development time.

At the same time, engineers and scientists have ideas for new products and product improvements based on technology. Rather than being driven by the customer, these ideas are driven by new technologies and what is learned during the design process. In fact, most product-producing companies spend from 2% to 10% of their revenue on research and development. And, since design is learning, by the time a designer finishes with a project, she or he knows enough to improve it. Most engineers would like to have a second chance at each project so they can, based on their new understanding, do it better the second time.

When a company wants to develop a product without market demand, utilizing a new technology, they are forced to commit capital investment and possibly years of scientific and engineering time. Even though the resulting ideas may be innovative and clever, they are useless unless they can be matched to a market need or a new market can be developed for them. Of course, devices such as sticky notes and many other products serve as examples of products that have been successfully introduced without an obvious market need. While these types of products have high financial risk, they can reap a large profit because of their uniqueness.

4.4.1 Product Maturity

Let's explore the need for new products further by examining the technology maturity "S" curve shown in Fig. 4.13. This shows the stages a technology matures through as it goes from a new product to a mature product. Products are often introduced to the market while some of the technologies it uses are still in the "make it work properly" stage, some even sooner. Product changes and improvements occur as technologies mature over time. Think of each of these improvements as redesign projects—they are. By the time a technology begins to reach maturity, the market is saturated with competition and companies need to decide if they are going to continue to develop using the existing technologies or innovate, develop new technologies, and begin the "S" curve again, as shown in Fig. 4.14.

If companies stay with the current technologies and further refine them, they probably have much competition and little room for improvement. If they innovate, they are taking a risk as the product matures.

4.4.2 Kano's Model of Customer Satisfaction

Another way to look at the need for product development is to examine Kano's Model of Customer Satisfaction. The Kano model was developed by Dr. Noriaki Kano in the early 1980s to describe customer satisfaction. This model will help us understand how and why features mature. Kano's model plots customer

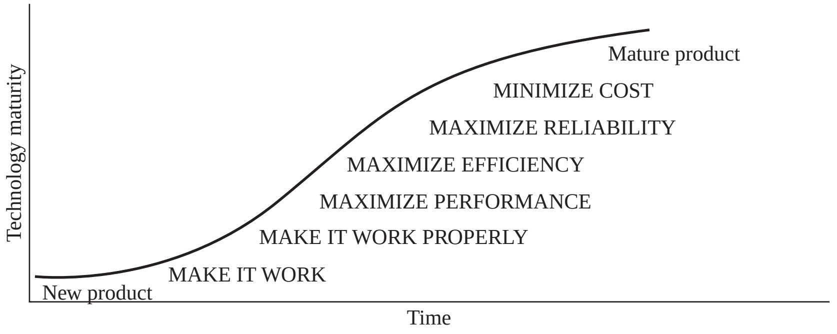

Figure 4.13 Product maturity "S" curve.

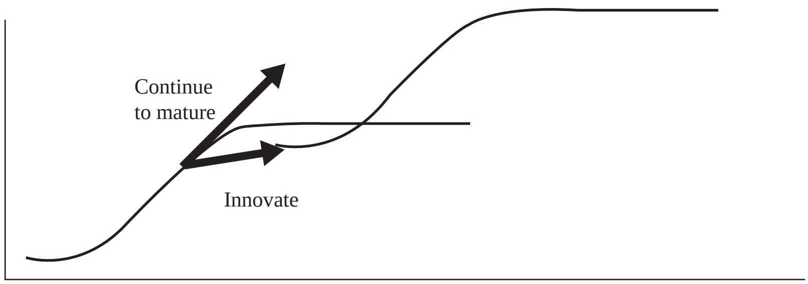

Figure 4.14 A decision point on the "S" curve.

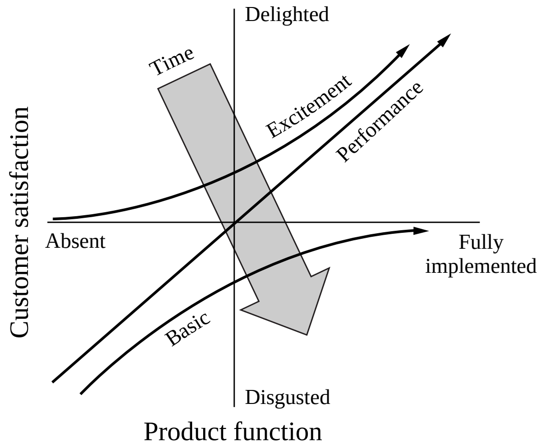

Figure 4.15 The Kano diagram for customer satisfaction.

satisfaction, from disgusted to delighted, versus product function, from absent to fully implemented, as shown in Fig. 4.15. This plot shows three lines representing basic features, performance features, and excitement features.

Basic features refer to customers' requirements that are not verbalized as they specify assumed functions of the device. The only time a customer will mention them is if they are missing. If they are absent in the final product, the customer will be disgusted with it. If they are included, the customer will be neutral. An example is the requirement that a car should have brakes. If there are no brakes, then the customer is going to be disgusted with the product (and may be injured also). Brakes are expected on cars and so, just being there is not a cause for delight, just a neutral reaction from the customer. However, how well the brakes perform is a concern.

Requirements for *performance* features are verbalized in the form that the better the performance, the better the product. For example, a requirement on brake stopping distance is clearly a performance requirement. Generally, the shorter the distance, the more delighted the customer.

But what if your car would apply the brakes when you said so? What if you said, “Slow down” and the car gently decelerated, and when you yelled, “STOP!” it braked hard? This capability is unexpected. If it is absent, the customers are neutral because they don’t expect it anyway. However, if customers’ reactions to the final product are surprise and delight at the additional functions, then the product’s chance of success in the market is high. Requirements for excitement-quality features are often called “wow requirements.” If you went to a car showroom and test-drove a car with voice-activated brakes, this would be unexpected. Your reaction to the system would be “wow.” If the system worked well, you would be delighted, if it were not there at all, you wouldn’t know the difference and so would be neutral. Excitement-level features on a product generally require new technologies.

Over time, excitement-level features become performance-level features and, ultimately, basic features. This is true for most features of home entertainment systems, cars, and other consumer products. When first introduced, a new feature is special in one brand and consumers are surprised and delighted. The next year, as the technology matures, every brand has the feature and some perform better than others. Companies then work the “S” curve to improve performance, efficiency, reliability, and cost. After a few years, the feature is not even mentioned in advertising because it is an expected feature of the product.

The Kano model is just another view of technology maturity. Companies need to make decisions about whether to invest in innovation to “wow” customers or improve performance, efficiency, reliability, and cost and work their way farther up the “S” curve.

In addition to market pull and technology push, the third source of design projects is in response to the need for a change. There are three major sources for product changes:

- A vendor can no longer supply materials or components used in the product or has recommended improved ones. This may require the development of new plans, specifications, and concepts.
- Manufacturing, assembly, or another downstream phase in the product’s life cycle has identified a quality, time, or cost improvement that results in a cost-effective change in the product.
- The product fails in some way and the design needs to be changed. This type of change can be very costly. Reflect back to Fig. 4.11, where the automobile manufacturer was still making design changes after release for production. As discussed there, these changes are very expensive.

Change-driven projects are so important that an entire section will be devoted to them in Chap. 12.

4.4.3 Product Proposal

Regardless of the source, one deliverable from this phase of the design process is the product proposal. A template for developing such a proposal is available and is shown with a simplistic example in Fig. 4.16.

Note in this example that there is sufficient information to at least initiate discussions about how much resources should be allocated to following up on this proposal. In a real situation, much more documentation would be needed on each of these items.

Product Proposal	
Design Organization: xxxxxxxx	**Date:** June 23, 2010
Proposed Product Name: The Toastalator	
Summary: Customers who live in small spaces and have the need in the morning to both make coffee and cook toast. The concept here is for a device that combines these two products in a small space.	
Background of the Product: Observations of people living in small apartments have revealed an opportunity to minimize the space used when preparing breakfast. Since we manufacture both coffee makers and toasters this seems like a reasonable opportunity to pursue.	
Market for the Product: Although there is no firm evidence, there is anecdotal demand for this product. Studies of space availability and market size are needed. An initial survey shows the potential for up to 10 million customers.	
Competition: There is no known product such as this on the market today. And an initial patent survey has shown no recent activity with similar products.	
Manufacturing Capability: XXXXX currently manufactures similar products independently.	
Distribution Details: XXXX as distribution channels for similar products.	
Proposal Details: Task 1: Develop better market numbers. Task 2: Develop project plans through the Conceptual Design phase. Task 3: Develop product definition. Task 4: Develop and evaluate a proof-of-concept prototype.	
Team member:	Prepared by:
Team member:	Checked by:
Team member:	Approved by:
Team member:	
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Figure 4.16 The product proposal template.

4.5 CHOOSING A PROJECT

The hard part of this phase of the design process is deciding which projects to undertake and which to leave for later. We all think we make good decisions. It has been estimated, however, that over half of all decisions fail! A failed decision is later remade or the results ignored altogether. Failed decisions result in lost time and cost money. Any time you revisit a decision, all the work, tooling, prototypes, and CAD models made in the interim have little value.

During the Product Definition phase, there are usually more product ideas than there are time, people and money to do them all. The goal here is to choose which projects to undertake and which to leave for later or not attempt at all. This effort is commonly called *project portfolio management*, where a portfolio is a list of potential projects and the goal is to decide which of them to undertake.

To choose the best we need to know how to make decisions. We will introduce good decision-making practice and then specifically address portfolio decisions, the key decision needed during discovery. We will revisit decision making in Conceptual Design and then again during Product Development, adding to what we learn here.

In the remainder of this section, three methods will be presented that can help in choosing a project from the portfolio. The first two are simple, but somewhat limited. The third sets the foundation for decision-making processes that will be developed later in the book.

4.5.1 SWOT Analysis

The first decision support method we will use to help us choose a project is called a SWOT analysis. SWOT stands for Strengths, Weaknesses, Opportunities, and Threats. This method is commonly used in business, can be applied to the evaluation of single projects, and is easy to do. The basics of the method are to list the four SWOT items on a quadchart (each of four quadrants filled in with SWOT entries), as shown in Fig. 4.17 and then informally weigh the strengths versus the weaknesses and the opportunities versus the threats. As an example in the figure, a bicycle manufacturing company is considering adding a tandem bicycle to its product line.

Filling out a SWOT analysis makes it easier to judge whether or not a single potential project should be undertaken. Although this method does lay out the major points to consider when for decision making, it does not actually help in making the decision. It is still not clear whether or not BURL should undertake building a tandem bicycle.

> Design is the technical and social evolution of information punctuated by decision making.

SWOT Analysis	
Design Organization: BURL Bicycles	**Date:** Nov. 11, 2007
Topic of SWOT Analysis: Explore the potential for adding a tandem bicycle to the product line in 2008.	
Strengths: • BURL has the technology to design a top quality tandem bicycle. • BURL's engineers want to do this project. • It will expand the product line. • Market for tandems is growing, although no exact market numbers have been collected. • For the most part, they can be made with current equipment and processes. • We can use our patented suspension to differentiate BURL's tandem from the rest.	Weaknesses: • Market for tandems is small, <1% of all bicycle sales. • The profit margin may be smaller than on traditional bikes. • Cost to develop may exceed $40,000. • Pay back time is estimated at 3 years. • It will take 6 months to get to market, missing the current sales season. • A tandem is just different enough to need unique marketing and shipping.
Opportunities: • A tandem will open BURL into new markets. • A tandem might allow bike shops that carry BURL to expand business and order more bikes.	Threats: • The product is not unique enough to attract customers. • We can't get bike shops to carry them. • It will cost more than $40,000 to develop. • Engineering can't get it to ride like a CLIEN.
Team member: Fred Flemer	Prepared by: Fred Flemer
Team member: Bob Ksaskins	Checked by: Bob Ksaskins
Team member:	Approved by: Betty Booper
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Figure 4.17 SWOT diagram example.

4.5.2 Pro-Con Analysis

To take the SWOT analysis one step further, consider a pro-con analysis. An early, recorded use of this type of analysis is by Ben Franklin. Besides being a statesman, he was a designer of stoves, bifocals and many other inventions. In a 1772 letter to Joseph Priestly (the discoverer of oxygen), Franklin explained how he analyzed his problems when intuition failed him.

Dear Sir:

In the affair of so much importance to you, where in you ask my advice, I cannot, for want of sufficient premises, advise you what to determine, but if you please I will tell you how. When those difficult cases occur, they are difficult, chiefly because while we have them under consideration, all the reasons pro and con are not present to the mind at the same time; but sometimes one set present themselves, and at other times another, the first being out of sight. Hence the various purposes or information that alternatively prevail, and the uncertainty that perplexes us.

To get over this, my way is to divide a sheet of paper by a line into two columns; writing over the one Pro, and over the other Con. Then, during three or four days consideration, I put down under the different heads short hints of the different motives, that at different times occur to me, for or against the measure.

When I have thus got them all together in one view, I endeavor to estimate their respective weights; and when I find two, one on each side, that seem equal, I strike them both out. If I find a reason pro equal to some two reasons con, I strike out the three. If I judge some two reasons con, equal to three reasons pro, I strike out the five; and thus proceeding I find at length where the balance lies; and if, after a day or two of further consideration, nothing new that is of importance occurs on either side, I come to a determination accordingly.

And, though the weight of the reasons cannot be taken with the precision of algebraic quantities, yet when each is thus considered, separately and comparatively, and the whole lies before me, I think I can judge better, and am less liable to make a rash step, and in fact I have found great advantage from this kind of equation . . .

Franklin considers whether to accept or reject a single alternative. This is really a choice between two alternatives: do this or do something else (including nothing). Franklin advises five steps for making a decision:

Step 1: Make two columns on a sheet of paper and label one “Pros” and the other “Cons.”

Step 2: Fill in the columns with all the pros and cons of an alternative.

Step 3: Estimate the importance of each pro and each con.

Step 4: Eliminate pros and cons this way:

- **a.** When two are of about equal importance, cross them both out and
- **b.** Find other importance equalities of pros and cons—for example, the importance of two pros equals three cons—and then strike them out.

Step 5: When one or the other column becomes dominant, then “come to the determination accordingly.”

You can extend the idea of using pro-con lists to include more than one alternative, but the balancing step quickly becomes complex. Still, NASA frequently uses this approach to help organize experts when evaluating multiple project proposals. For each proposal, the experts list the pros and cons. They then informally balance the pros and cons to differentiate among the alternatives. This helps to tease out the good and bad points.

Pro-Con Analysis

Design Organization: BURL Bicycles	**Date:**

Topic of Pro-Con Analysis: Should BURL market a tandem bicycle?

Pro:

- BURL has the technology to design a top-quality tandem bicycle.
- BURL's engineers want to do this project.
- It will expand the product line.
- Market for tandems is growing, although no exact market numbers have been collected.
- For the most part they can be made with current equipment and processes.
- We can use our patented suspension to differentiate BURL's tandem from the rest. A tandem will open BURL into new markets.
- A tandem might allow bike shops that carry BURL to expand business and order more bikes.

Con:

- Market for tandems is small, <1% of all bicycle sales.
- The profit margin may be smaller than for traditional bikes.
- Cost to develop may exceed $40,000.
- Pay-back time is estimated at 3 years.
- It will take 6 months to get to market, missing the current sales season.
- A tandem is just different enough to need unique marketing and shipping.
- The product is not unique enough to attract customers.
- We can't get bike shops to carry them.
- It will cost more than $40,000 to develop.
- Engineering can't get it to ride like a BURL.

Team member: Fred Flemer	Prepared by: Fred Flemer
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Team member:	Approved by: Betty Booper

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Figure 4.18 Pro-con analysis example.

If you look back at the SWOT analysis, the statements there are all an argument either for or against designing and marketing a tandem bicycle. In Fig. 4.18, these are reordered on Pro-Con Analysis Template. Thus, we have already completed steps 1 and 2 of Franklin's method.

Step 3 forces you to put a value on how important each of the pro and con statements is to the success of the project in preparation for step 4. For example, in looking down the list, it appears that

> Market for tandems is growing although no exact market numbers have been collected.

is about as important as

> A tandem is just different enough to need unique marketing and shipping.

So, according to step 4, they need to be crossed out. Then,

BURL has the technology to design a top-quality tandem bicycle.
and
BURL's engineers want to do this project.

is about as important as

Engineering can't get it to ride like a BURL.

So they too need to be crossed out. Continuing this way BURL ultimately sees that the cons outweigh the pros and decides not to undertake a tandem project.

4.5.3 Basics of Decision Making

Although the two methods just presented begin to get the information organized for good decision making, they are both limited to one alternative. In this section, we will formalize the entire decision-making process and make a protocol decision.

The basic structure of decision making is the same, whether addressing discovery issues or concept selection or choosing product details. In each case, there are six basic activities. Let's look at these activities in more detail:

1. **Clarify the issue** that needs a satisfactory solution.
2. **Generate alternatives**—itemize the potential solutions for the issue.
3. **Develop criteria** as they measure a satisfactory solution for the issue.
4. **Identify criteria importance** of each criterion relative to the others.
5. **Evaluate** the value of the alternatives by comparing them to the criteria.
6. Based on the evaluation results, **decide what to do next.** This decision will direct the process to
   - **a.** Add, eliminate, or refine alternatives.
   - **b.** Refine criteria.
   - **c.** Refine evaluation—work to gain consensus and reduce uncertainty.
   - **d.** Choose an alternative—you've made a decision, document it and address other issues.

These are shown in a flow diagram in Fig. 4.19.

We will reuse this list of activities and this diagram numerous times throughout the book.

Comparing the SWOT analysis to this ideal flow, SWOT is limited to activities 1, 2, and 5. It addresses only a single alternative and never actually itemizes the criteria for evaluation, even though they are inherent in the SWOT statements. (As we shall see in a moment.) SWOT focuses informally on the evaluation and never really gets to "what to do next." Thus, it is not really a decision-making method by our definition, even though it supports some of the activities.

The pro-con method adds concern for the importance (activity 4) of the statements and gives a limited idea of "what to do" to the process (activity 6).

4.5.4 Making a Portfolio Decision

Here we will apply the activities listed in the previous section to the bicycle example.

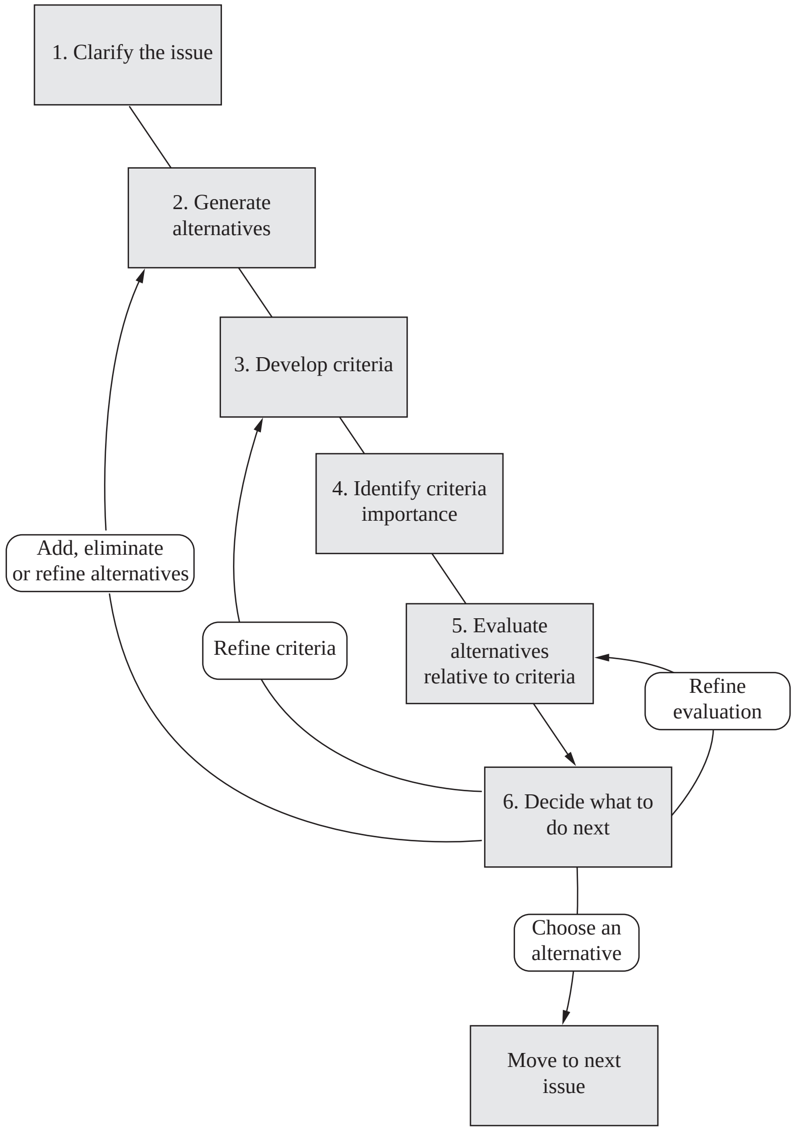

Figure 4.19 The decision-making flow.

Activity 1. BURL clarifies the issue. This was already done earlier, but we will make it broader here: "Choose, from a list of alternative product development projects, which one should be undertaken first?" In general, an issue is a question that needs to be addressed with some object or course of action chosen to answer the question and resolve the issue.

Activity 2. BURL itemizes the alternatives to be considered. This list can be as few as two items or in the hundreds, and spans all the way from minor product changes to new models of existing products to innovative new products. For our bicycle company example, the options are

- Upgrade the current road bike.
- Introduce a tandem (as already considered).
- Add a front suspension to a soft-tail mountain bike product.

Activity 3. BURL develops criteria that are the basis for evaluating the alternatives. This is such an important activity that all of Chap. 6 is devoted to developing engineering specifications, the criteria for evaluating concepts and products. For many types of issues, those that are commonly repeated, a generic set of criteria can be used, at least as a starting place. For portfolio issues, the following list of criteria have evolved over time and can be used here:

- Acceptable program complexity: The complexity of the effort is within the experience of the organization or vendors. People are available with the skill sets needed to do the work.
- Clear market need: There is an established need in a market. (If evaluating innovative products, this may not be important.)
- Acceptable competitive intensity: The competitive intensity is reasonable and the alternative is not so new to the organization to impede commercialization.
- Acceptable five-year cash flow: The cash needed or generated over a five-year period is within reason.
- Reasonable payback time: The payback period for the needed investment and costs is acceptable.
- Acceptable start-up time: The time to realize cash flow is within the means of the organization.
- Good company fit: The newness or impact on the organization is acceptable—the new product or improvement fits the organization's image.
- Strong proprietary position: The ability to withstand the competition's efforts to erode the unique features that discriminate is good.
- Good platform for growth: The effort leads to future products or services.

In the SWOT analysis, we can see that the strengths, weaknesses, opportunities, and threats listed are evaluations of the criteria just listed. For example, the SWOT statements: "Market for tandems is growing although no exact market numbers have been collected" and "Market for tandems is small, $<1\%$ of all bicycle sales" are qualitative evaluation statements for "Clear market need."

One way to develop a list of criteria is to begin with a SWOT or pro-con analysis and then group the statements in categories. In fact, the list of protocol criteria was developed by examining many different protocol decisions, SWOT analyses and pro-con lists to find the common measures.

Activity 4. BURL decides what is most important. Not all of the nine criteria listed above are of equal importance. Complicating this is that the importance is in the eye of the beholder. For example, BURL's financial people think that

Table 4.2 The portfolio scoring by BURL

	Alternatives					
	Upgrade road bike		Tandem		Front suspension for mountain bike	
Criteria	**Agreement**	**Certainty**	**Agreement**	**Certainty**	**Agreement**	**Certainty**
Acceptable program complexity complexity	SA	C	N	C	D	VU
Clear market need	N	VC	D	U	SA	VC
Acceptable competitive intensity	A	C	A	N	N	N
Acceptable five-year cash flow	D	C	D	C	A	C
Reasonable payback time	N	C	D	U	A	U
Acceptable start-up time	A	VC	A	VC	N	C
Good company fit	A	C	D	C	N	C
Strong proprietary position	SD	C	SA	C	A	C
Good platform for growth	D	C	A	U	A	C

"acceptable five-year cash flow" and "reasonable payback time" are most important, and marketing wants to see "Good company fit." Engineering wants a "Strong proprietary position" and a "Good platform for growth."

For now, we will assume they are all equally important and address this activity further in Chap. 8.

Activity 5. BURL evaluates the alternatives relative to the criterion. These evaluations can range from qualitative assessments to the results of analytical simulations. For now, we will work with the qualitative statements made in the SWOT analysis and use a very simplified method to evaluate and decide what to do next. This will be refined as the product matures and more numerical analyses and simulation become possible.

To support this evaluation BURL used a *Decision Matrix*, a table with the alternatives in columns and the criteria in rows (Table 4.2). The cells of the matrix contain the evaluation results. For this qualitative assessment, BURL evaluated each alternative relative to each criterion using two measures. The first is how well the alternative meets the criterion in terms of level of agreement with the statement "I <X> that the <alternative> has <criterion>" where <X> equals

- Strongly agree (SA)
- Agree (A)
- Neutral (N)
- Disagree (D)
- Strongly disagree (SD)

For example "I <disagree> that the <Introduce tandem> has <clear market need>."

Further, a second score will also be used, the level of certainty with which the evaluation is made. This is in terms of

- Very certain (VC)
- Certain (C)

- Neutral (N)
- Uncertain (U)
- Very uncertain (VU)

Certainty is a measure of how much you know or how much variation you expect. From an engineering standpoint the program complexity range is from disagree to strongly agree. However, for the development of the front suspension, the disagree assessment is very uncertain. Thus, in considering this alternative it will be hard to make use of the program complexity to judge whether or not to undertake a project to develop the front suspension. Further, note that only the front suspension option has an acceptable five-year cash flow. This implies that from a financial viewpoint none of these projects may be acceptable. We will do much more with tables of this type as the book evolves.

Activity 6. Based on the evaluation results, BURL must decide what to do next. It seems clear that none of these alternatives are outstanding. The financial picture of the first two alternatives looks weak. The complexity of the third alternative is questionable but knowledge about it is uncertain. So, one activity should be to develop other alternatives that overcome the drawbacks of the current portfolio. Additionally, it may be worthwhile to better understand the program complexity for the front suspension system.

Although the decision matrix has not given BURL a definitive decision, it has provided them a window on which to base a decision and has directed them about what to do next. This methodology will be refined as the book progresses.

4.6 SUMMARY

- There are six phases of the mechanical design process: Product Discovery, Project Planning, Product Definition, Conceptual Design, Product Development, and Product Support.
- The design process focuses effort on early phases, when the major decisions are made and quality is initiated. Additionally, a good process encourages communication, forces documentation, and encourages data gathering to support creativity.
- There are specific design process best practices that have been proven to improve product quality.
- New products originate from technology push, market pull, and product change.
- Products mature over time and new products emerge during maturation.
- A SWOT analysis can help choose which products to develop.
- Benjamin Franklin developed one of the earliest examples of using a pro-con analysis to make simple decisions.
- There are six basic decision-making activities: clarify the issue, generate alternatives, develop criteria, identify criteria importance, evaluate the value of the alternatives, and decide what to do next.
- The decision matrix can help in deciding what to do next.

4.7 SOURCES

"Letter to Joseph Priestley," *Benjamin Franklin Sampler*, New York, Fawcett, 1956.

Ullman, David: *Making Robust Decisions*, Trafford, 2006. A complete book on design decision making.

4.8 EXERCISES

4.1 Develop a list of original design problems that you would like to do (at least 3). Choose one to work on that is within the time and knowledge available.

4.2 Make a list of features you don't like about products you use. One way to develop this list is to note every time a device you use does not have a feature that is easy to use, doesn't work like you think it should, or is missing as you go through your day. If you pay attention, a list like this will be easy to develop. Once the list has at least five items on it, choose one to improve through a redesign project.

4.3 Do a SWOT analysis on

- The idea of taking Philosophy 101.
- Buying an electric car.
- Adding solar hot water heater to your parent's house.
- Adding a new feature to your backpack or briefcase.

4.4 Use Ben Franklin's pro-con method to decide

- Whether or not to go to coffee with the person next to you.
- Whether or not to buy a new cell phone (pick the latest and greatest).
- If the fix on your latest idea (e.g., bookcase, car repair, code, etc.) is worth pursuing.

4.5 Use a decision matrix to decide what to do next for

- Purchasing one of three specific bicycles (or cars, electronic equipment) that you are interested in.
- Choosing a ball bearing, a bronze bushing, or a nylon bearing for a pivot on the rear suspension of a bicycle.
- Specifying a heating system for a house you are designing. The options are an air-to-air heat pump, air-to-water heat pump, or water-to-water heat pump.

4.9 ON THE WEB

Templates for the following documents are available on the book's website: www.mhhe.com/Ullman4e

- Product Proposal
- Pro-Con Analysis
- SWOT Analysis

CHAPTER 5

Planning for Design

KEY QUESTIONS

- How does planning help in completing the five phases of the mechanical design process in a timely, cost-effective manner?
- Does one type of plan fit all design projects?
- What is the difference between a waterfall and a spiral plan?
- Why are deliverables so important?
- How can a plan be developed when the future is so uncertain?

5.1 INTRODUCTION

The goal of project planning is to formalize the process so that a product is developed in a timely and cost-effective manner. Planning is the process used to develop a scheme for scheduling and committing the resources of time, money, and people, as shown in Fig. 5.1. Planning results in a map showing how product design process activities are scheduled. The phases shown in Fig. 4.1—specification definition, conceptual design, and product development—must be scheduled and have resources committed to them. The flow shown in the figure is only schematic; it is not sufficient for allocating resources or for developing a schedule.

Planning generates a procedure for developing needed information and distributing it to the correct people at the correct time. Important information includes product requirements, concept sketches, system functional diagrams, solid models, drawings, material selections, and any other representation of decisions made during the development of the product.

The activity of planning results in a blueprint for the process. The terms *plan* and *process* are often used interchangeably in industry. Most companies have a generic process (i.e., a master plan) that they customize for specific products. This

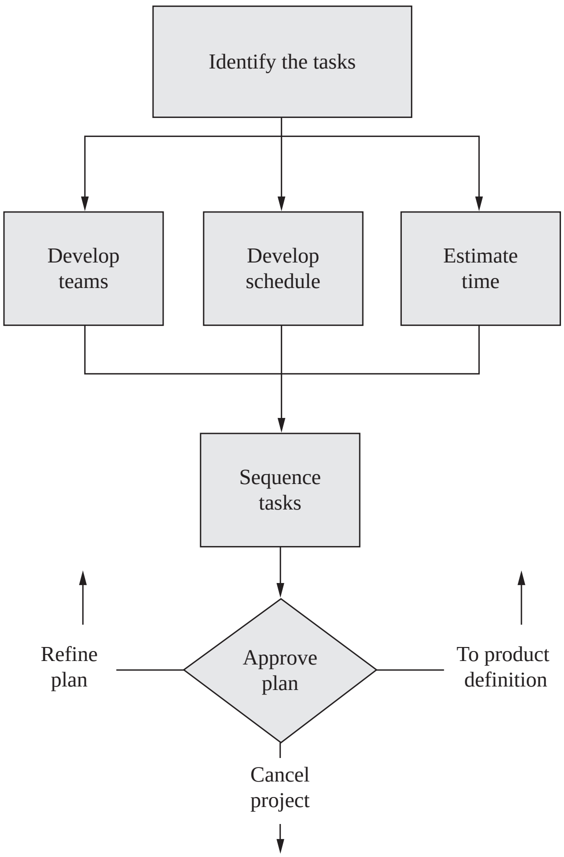

Figure 5.1 Project planning activities.

master plan is called the product development process, product delivery process, new product development plan, or product realization plan. In this book, we will refer to this generic process as the Product Development Process and use the acronym PDP.

Changing the design process in a company requires breaking down the way things have always been done. Although it can be quite difficult, many companies have accomplished it during recent decades. Generally, companies that have enjoyed good markets for their products and have begun to see these markets erode begin to look at their product development process as part of their effort to reengineer themselves to meet the competition. Most successful companies put emphasis on the continuous improvement of both the product and the process for developing the product.

> If you do not know where you are going, you can not know when you get there. (Modernized from "Our plans miscarry because they have no aim. When a man does not know what harbor he is making for, no wind is the right wind" Lucius Annaeus Seneca [4 BC–AD 65].)

5.2 TYPES OF PROJECT PLANS

There are many different types of project plans. The simplest is the Stage-Gate or Waterfall plan. As shown in Fig. 5.2, work done in each stage is approved at a decision gate before progressing to the next stage. In its simplest form, the stage-gate methodology is very simple: Stage 1 = Product discovery, Stage 2 = Develop concepts, Stage 3 = Evaluate concepts, and so on. More likely, the stages are focused on specific systems or subsystems. Further, each stage may contain a set of concurrent activities executed in parallel, not in sequence.

The Stage-Gate Process can also be represented as a waterfall (Fig. 5.3) with each stage represented like a flat area where the water pools before falling to the next pool. The Stage-Gate method was formalized by NASA in the 1980s for managing massive aerospace projects.

The gates are often referred to as *design reviews*, formal meetings during which the members of the design team report their progress to management. Depending on the results of the design review, management then decides to either continue the development of the product, perform more work in the previous stage, or to terminate the project before any more resources are expended.

A major assumption in stage-gate or waterfall plans is that work can be done sequentially. This means that the product definition can be determined early in the process and that it will flow through concept to product. This is true for most mature types of products. A good example is the process used by Irwin in the design of new tools such as the Quick-Grip Clamp introduced in Chap. 2. Figure 5.4 shows the process used for the development of the clamp. At each stage, Irwin refines the definition into the objective and the deliverables. For example, the objective of "MS2-Design" is "Concept feasibility and robust business case." In order to know that the objective has been achieved, there must be a set of deliverables. These include

- Concept development
- Technical feasibility
- Cost targets and financials
- Concept validation by consumers
- Legal assessment of intellectual property

The gate that follows Design is refined with the decisions made, who makes the decisions, and the criteria for the decisions. At Irwin, for example, the decisions made at the gate following MS 2 are select concept, approve business cases, accept

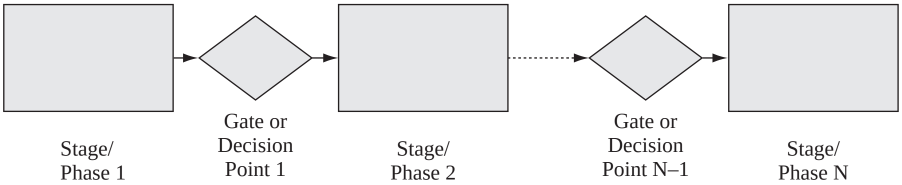

Figure 5.2 The Stage-Gate process.

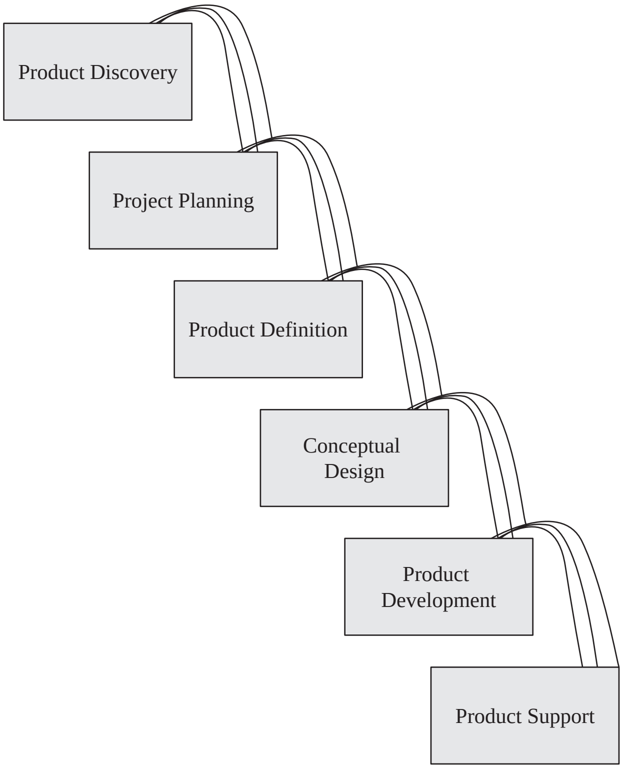

Figure 5.3 The Waterfall model.

prototype development results. These decisions are made by the leadership team including the President, the Vice President of Manufacturing, the Vice President for Research and Development, the Chief Financial Officer, and others. Decisions at this level may seem extreme for something as simple as a clamp, but this is a major product for a company such as Irwin, and thus concern goes all the way to the top of the organization.

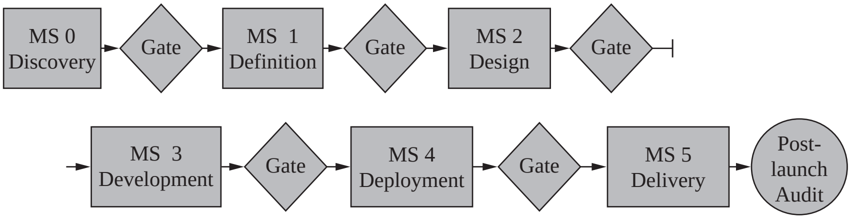

Figure 5.4 Irwin Tools product development process. (Reprinted with permission of Irwin Industrial Tools.)

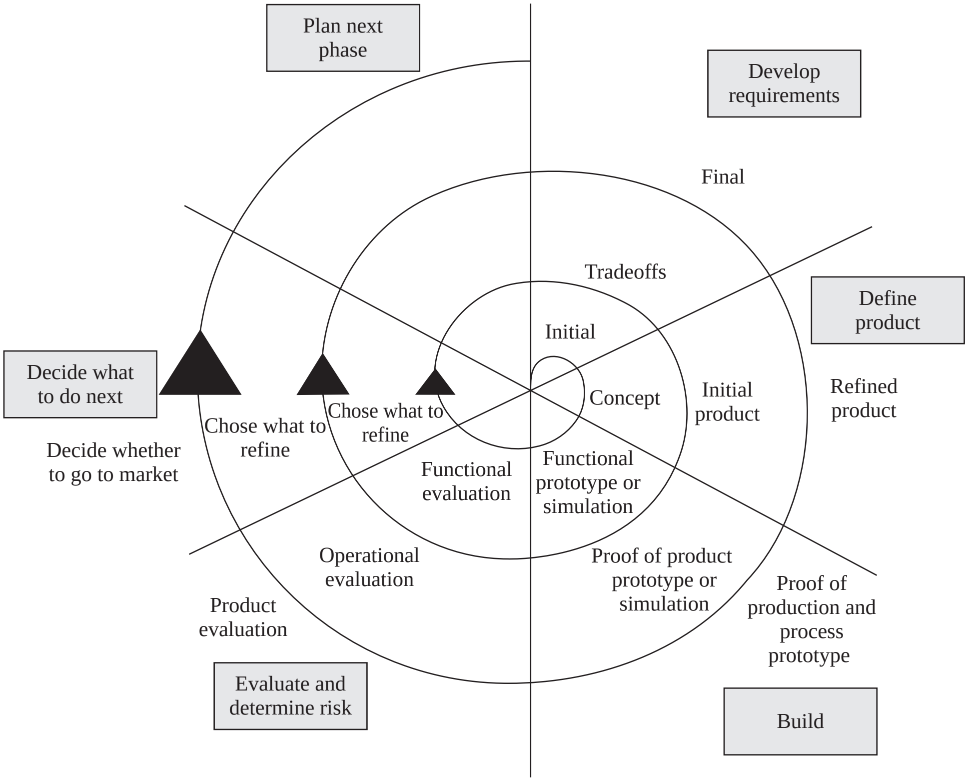

Figure 5.5 Spiral development of mechanical systems.

More recently, a spiral process has become very popular in software design. The spiral (Fig. 5.5) begins at the center with the basic concept and the rapid development of the first prototype; this is then evaluated by customers. The requirements for the product are revisited, and, in the second spiral, a new design prototype is tested. This methodology works in software because code is easier to prototype then most mechanical products. However, the continuing development of rapid prototyping (see Section 5.3) is making this more realistic for hardware development. Primary characteristics of the spiral process are

- The iterative approach enables each task to be revisited during each cycle.
- Requirements can be reassessed.
- Prototypes and simulations can be elaborated and improved.
- The process enables “good enough for the moment” implementations.
- There is a clear decision point in each cycle.
- Each cycle provides objectives, constraints, alternatives, risks, review, and commitment to proceed.
- The level of effort is driven by risk considerations.

The spiral in Fig. 5.5 has been modified to show important activities in the mechanical design process. The spiral begins with initial requirements and progresses through concepts to functional prototypes and simulations, evaluation of these for how well they meet the initial requirements and for the risks incurred with future development, and helps to determine what to do next. Once this is understood, planning for the next cycle can occur. The second level of the spiral shows requirements traded off against each other as an initial product and its evaluation occur. Again, what to do next is determined and plans are made for the next phase, continuing the outward spiral toward the product. There may be more spirals than are shown here. Much of the terminology used in Fig. 5.5 will be defined later in this chapter.

Even more recent than the spiral process in software development is Extreme Programming. Extreme Programming is built around many small releases and integrated testing. One goal is a daily building of new code on the customer’s site for easy testing. This methodology harks back to the early days of mechanical engineering when something would be tried, broken, fixed, and tried again. In the early days of aircraft development, a test pilot would crash, the crew would fix the airplane, and assuming the pilot could still fly, he’d take it up again. As systems became more complex, the ability to make rapid changes in mechanical systems became more difficult. With rapid prototyping, this ability to make rapid changes is beginning to reappear. The down side of Extreme Programming is that there is no set target and you never know when you’re done. This problem is a major topic in Chap. 6.

In this book, we follow the waterfall process for a number of reasons. First spiral or extreme methods are better suited for software, where the development of prototypes usually takes far less time. Second, it is best to know where you’re going before you start or you don’t know when you get there. The flexibility of changing requirements needs to be weighed against not knowing when you’re finished. This is not to say that there is not iteration in the waterfall, just that it is built-in and planned. Third, the spiral process is best for new technologies when there is only a weak market pull and requirements are not clear. Finally, books are by nature serial, one chapter following another. There is no choice but to present the material in this manner. However, any particular project may be a

> Design is an iterative process. The necessary number of iterations is one more than the number you currently have done.
> This is true at any point in time.
> —John R. Page, *Rules of Engineering*

combination of the linear, stage-gate or waterfall, and the more recent spiral and extreme processes.

5.3 PLANNING FOR DELIVERABLES—THE DEVELOPMENT OF INFORMATION

Progress in a design project is measured by deliverables such as drawings, prototypes, bills of materials (e.g., parts lists), results of analysis, test results, and other representations of the information generated in the project. These deliverables are all models of the final product. During product development, many models (i.e., design information representations) are made of the evolving product. Some of these models are analytical models—quick calculations on a bit of paper or complex computer simulations; some will be graphical representations—simple sketches or orthographic mechanical drawings; some will be CAD solid models and some will be physical models—prototypes.

Each of these models or prototypes is a representation of information that describes the product. In fact, *design is the evolution of information punctuated by decisions*. Each model or prototype is not only the embodiment of what is known about the product, but knowledge is gained in building or developing it. So the deliverables serve two purposes—they are the embodiment of the information that describes the product and they are a means to communicate that information to others. Thus, it is important to understand the information developed during the design process.

5.3.1 Physical Models—Prototypes

Physical models of products are often called *prototypes*. The characteristics of prototypes that must be taken into account when planning when to use them and what types to use are their *purpose*, the *phase* in the design process when they are used, and the *media* used to build them.

The four *purposes* for prototypes are proof-of-concept, proof-of-product, proof-of-process, and proof-of-production. These terms are traditionally applied only to physical models; however, solid models in CAD systems can often replace these prototypes with less cost and time.

- A **proof-of-concept or proof-of-function prototype** focuses on developing the function of the product for comparison with the customers' requirements or engineering specifications. This kind of prototype is intended as a learning tool, and exact geometry, materials, and manufacturing process are usually not important. Thus, proof-of-concept prototypes can be built of paper, wood, parts from children's toys, parts from a junkyard, or whatever is handy.

- A **proof-of-product prototype** is developed to help refine the components and assemblies. Geometry, materials, and manufacturing process are as important as function for these prototypes. The recent development of *rapid prototyping* or *desktop prototyping,* using stereo lithography or other methods to form a part rapidly from a CAD representation, has greatly improved the time and cost efficiency of building proof-of-product prototypes.
- A **proof-of-process prototype** is used to verify both the geometry and the manufacturing process. For these prototypes, the exact materials and manufacturing processes are used to manufacture samples of the product for functional testing.
- A **proof-of-production prototype** is used to verify the entire production process. This prototype is the result of a *preproduction run,* the products manufactured just prior to production for sale.

In *Star Trek*, the science fiction series and movies, physical objects were produced in a "replicator." Using just voice commands, this device could produce food, weapons, and just about anything else that could be imagined. Mechanical design is moving toward having replicators. Designers can conceive of a part, represent it in a solid-modeling CAD system, and "print" it out as a solid object using a *rapid prototyping system.* Rapid prototyping or solid printing produces solid parts useful for physical part evaluation, as patterns for molding or casting parts, or as visual models to gain customer feedback. In the 1980s and early in the 1990s, rapid prototype parts were usually made of wax, plastic, or cellulose. By 2000, some methods could make metal parts directly usable for small production runs and as molds for plastic parts capable of making tens of thousands of parts. Some rapid prototyping systems make parts using a laser to cut and glue thin layers of material together. Others use a laser to solidify liquid resins in places where solid material is desired. Still other systems deposit small amounts of materials much like building a part from small bits of clay. In the future, these systems may be able to make parts by building at the atomic level, enabling variations in material properties throughout a single component. These systems will approach science fiction by enabling a component or an entire product to be made in any place, on demand.

5.3.2 Graphical Models and CAD

Some companies rely solely on computer-generated solid models, others still rely on traditional drawings made either with a 2-D CAD package, or output from a solid model. Regardless of how they are produced, the graphical models are not only the preferred form of data communication for the designer, they are also a necessary part of the design process. Specifically, drawings and solid models are used to

1. Archive the geometric form of the design.
2. Communicate ideas between designers and between designers and manufacturing personnel.
3. Support analysis. Missing dimensions and tolerances are determined as the drawing or model is developed.
4. Simulate the operation of the product.
5. Check completeness. As sketches or other drawings are being made, the details left to be designed become apparent to the designer. This, in effect, helps establish an agenda of design tasks left to accomplish.
6. Act as an extension of the designer's short-term memory. Designers unconsciously use drawings as part of their problem-solving process and often consciously use drawings to store information they might otherwise forget.
7. Act as a synthesis tool. Sketches and formal drawings enable the piecing together of unconnected ideas to form new concepts.

During the design process, many types of drawings are generated. Sketches used during conceptualization must evolve to final drawings that give enough detail to support production. This evolution usually begins with a layout drawing of the entire product to help define the geometry of the developing assemblies and components. The details of the components and assemblies are partially specified by the information developed on the layouts. As the product is refined, this information is transferred to detail and assembly drawings.

The development of modern solid-modeling CAD systems has blurred the differentiations between the types of drawings. These systems enable the co-evolution of details and assemblies in a layout environment. Further, they have automated many of the drawing standards. That being said, the traditional types of drawings will be introduced because they have specific characteristics important to even the most modern CAD systems.

The development of the drawings is synergistic with the evolution of the product geometry and further refinement of its function. As drawings are produced, more knowledge about the product is developed. Some of the major characteristics of the different types of drawings produced during product design and their role in the design process are itemized next.

Sketches. Sketching as a form of drawing is an extension of the short-term memory needed for idea generation (see Chap. 3). As the shape of components and assemblies evolve, drawings that are more formal are used to keep the information organized and easily communicated to others. Thus, a well-trained engineer has CAD skills and the ability to represent concepts that are more abstract and best represented as sketches.

Layout Drawings. A layout drawing is a working document that supports the development of the major components and their relationships. A typical layout drawing is shown in Fig. 5.6. Consider the characteristics of a layout drawing:

- A layout drawing is a working drawing and as such is frequently changed during the design process. Because these changes are seldom documented, information can be lost. Good records in the design notebook can compensate for this loss.
- A layout drawing is made to scale.
- Only the important dimensions are shown on a layout drawing. In Chap. 10, we see that starting with the spatial constraints sets the stage for developing the architecture and individual components in the product generation process. These constraints are best shown on a layout drawing.
- Tolerances are usually not shown, unless they are critical.
- Notes on the layout drawing are used to explain a design feature or the function of the product.
- A layout drawing often becomes obsolete. As detail drawings and assembly drawings are developed, the layout drawing becomes less useful. If the

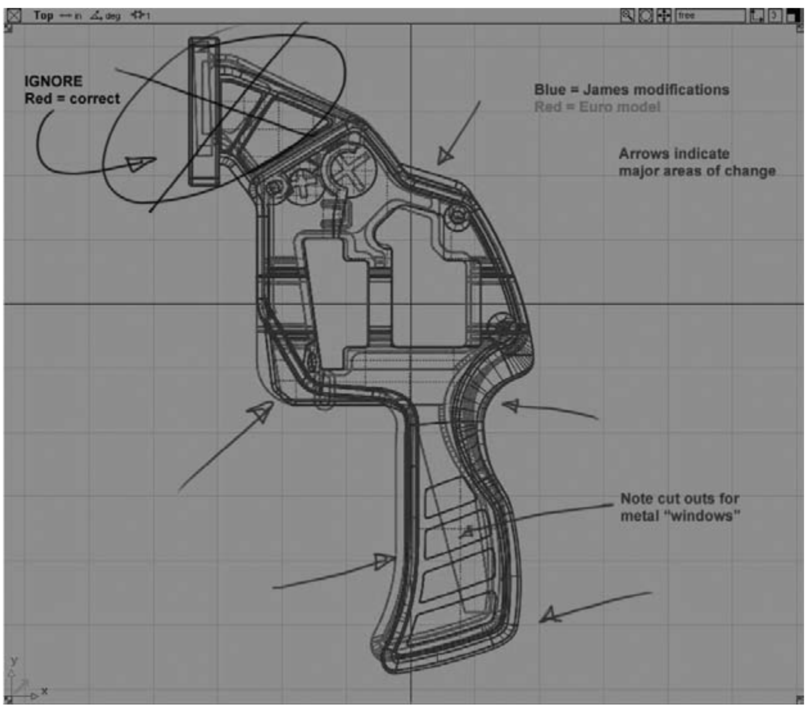

Figure 5.6 Typical layout drawing. (Reprinted with permission of Irwin Industrial Tools.)

product is being developed on a CAD system, however, the layout drawing's data file becomes the basis for the detail and assembly drawings.

The layout drawing shown in Fig. 5.6 was done on a solid-modeling system. This system enables the exploration of changes. The good news is that the solid model enables accurate visualization of the important geometry being studied, and the model provides much of what is needed for detail and assembly drawings. The bad news is that there is much time involved in this model, so changes in the configuration are expensive and discouraged.

Detail Drawings. As the product evolves on the layout drawing, the detail of individual components develops. These are documented on detail drawings. A typical detail drawing is shown in Fig. 5.7. Important characteristics of a detail include the following:

- All dimensions must be toleranced. In Fig. 5.7, many of the dimensions are made with unstated company-standard tolerances. Most companies have standard tolerances for all but the most critical dimensions. The upper and lower limits of the critical dimensions in Fig. 5.7 are given.
- Materials and manufacturing detail must be in clear and specific language. Special processing must be spelled out clearly.

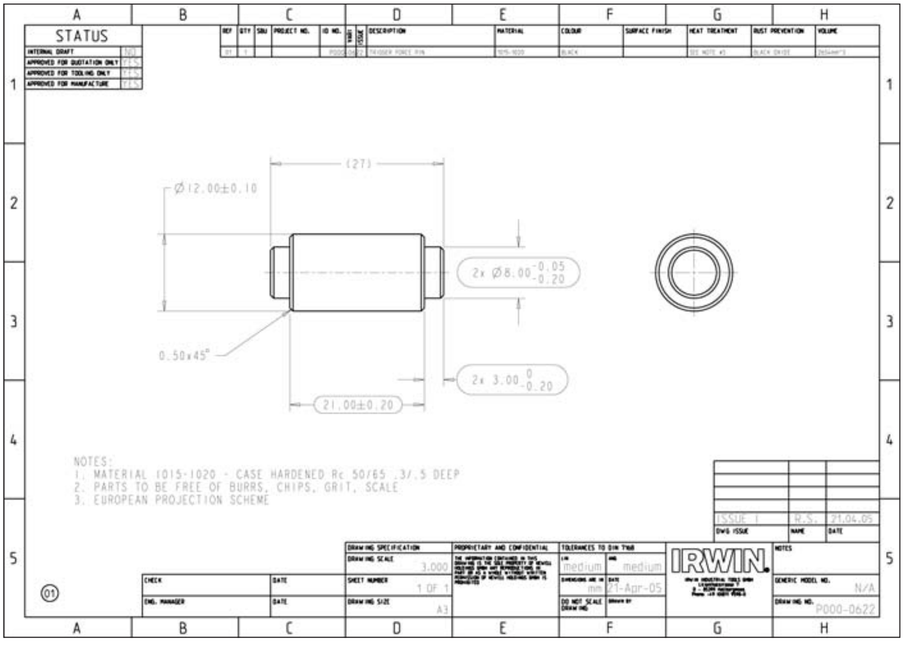

Figure 5.7 Typical detail drawing. (Reprinted with permission of Irwin Industrial Tools.)

- Drawing standards such as those given in ANSI Y14.5M-1994, *Dimensions and Tolerancing,* and in DOD-STD-100, *Engineering Drawing Practices,* or company standards should be followed.
- Since the detail drawings are a final representation of the design effort and will be used to communicate the product to manufacturing, each drawing must be approved by management. A signature block is therefore a standard part of a detail drawing.

Layout and assembly drawing focus on systems or subsystems, detail drawings address single components.

Assembly Drawings. The goal in an assembly drawing is to show how the components fit together. There are many types of drawing styles that can be used to show this. Assembly drawings are similar to layout drawings except that their purpose, and thus the information highlighted on them, is different. An assembly drawing has these specific characteristics:

- Each component is identified with a number or letter keyed to the Bill of Materials (BOM). Some companies put their Bill of Materials on the assembly drawings; others use a separate document. (The contents of the Bill of Materials are discussed in Section 9.2.)
- References can be made to other drawings and specific assembly instructions for additional needed information.

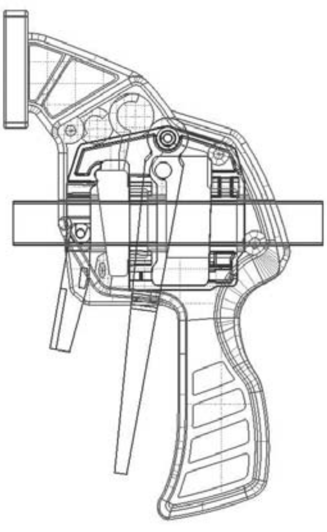

Figure 5.8 Typical assembly drawing. (Reprinted with permission of Irwin Industrial Tools.)

- Necessary detailed views are included to convey information not clear in the major views.
- As with detail drawings, assembly drawings require a signature block.

Graphical Models Produced in Modern CAD Systems. As mentioned in the introduction to this section, in modern solid-modeling CAD systems, layout, detail, and assembly drawings are not distinct. These systems enable the designer to make a solid model of the components and assemblies and, from these, semiautomatically make detail and assembly drawings. In these systems, the layout of components and assemblies and the details of the components and how they fit together into assemblies, all coevolve. This is both a blessing and a curse. On the positive side:

- Solid models enable rapid representation of concepts and the ability to see how they assemble and operate without the need for hardware.
- The use of solid-modeling systems improves the design process because features, dimensions, and tolerances are developed and recorded only once. This reduces the potential for error.
- Interfaces between components are developed so that components share the same features, dimensions, and tolerances, ensuring that mating components fit together.
- Detail and assembly drawings are produced semiautomatically, reducing the need to have expert knowledge of drafting methods and drawing standards.
- Files created are usable for making prototypes using rapid prototyping methods; developing figures for manufacturing and assembly; and providing diagrams for sales, service, and other phases of the product life cycle.

However, these tools also have a negative side:

- There is a tendency to abandon sketching. Sketches are a rapid way to develop a high number of ideas. The time required to develop a solid model is much longer than the time to make a sketch. This means the number of alternatives developed may be lower than it should be.
- Too much time is often spent on details too soon. Solid-modeling systems usually require details in order to even make a “rough drawing.” Thinking through these details in conceptual design may not be a good use of time, and once drawn there is a reluctance to abandon poor designs because of the time invested.
- Often valuable design time is spent just using the tool. Learning a solid-modeling system takes time and using it often requires time-consuming control of the program. This design time is lost.
- Many solid-modeling systems require the components and assemblies to be planned out ahead of time. These systems are more like an automated drafting system than a design aid.

In Table 5.1 (in Section 5.3.4), the different types of models used in mechanical design are itemized. Solid modeling and rapid prototyping are making it so that not only are layout, detailed, and assembly drawings merging, but so is the production of proof-of-concept, proof-of-product, proof-of-process, and proof-of-production prototypes. This merging is making it easier to produce more products in a shorter time.

5.3.3 Analytical Models

Often the level of approximation of an analytical model is referred to as its fidelity. *Fidelity* is a measure of how well a model or simulation analysis represents the state and behavior of a real-world object. For example, up until the late seventeenth century, all military calculations of cannonball trajectories were computed as if the projectile went up in a straight line, then followed a circular arc and another straight line straight down to the target (Fig. 5.9). These were low-fidelity simulations. However, in the late fifteenth century Leonardo da Vinci knew this model was wrong—that the trajectory was actually parabolic—and developed more accurate methods to compute the impact point. Even though he didn't have the mathematics to write the equations to describe his conclusions, his simulations were of better fidelity than preceding ones. It wasn't until Galileo that the parabolic model was developed and higher fidelity estimates could be made. These were later refined by Newton, and even later by the addition of the effects of aerodynamic drag and higher order dynamics.

Back-of-the-envelope calculations are low fidelity, whereas detailed simulations—hopefully—have high fidelity (it depends on the accuracy of the information input into them). Experts often run simulations to predict performance and cost. At the early stages of their projects, these simulations are usually

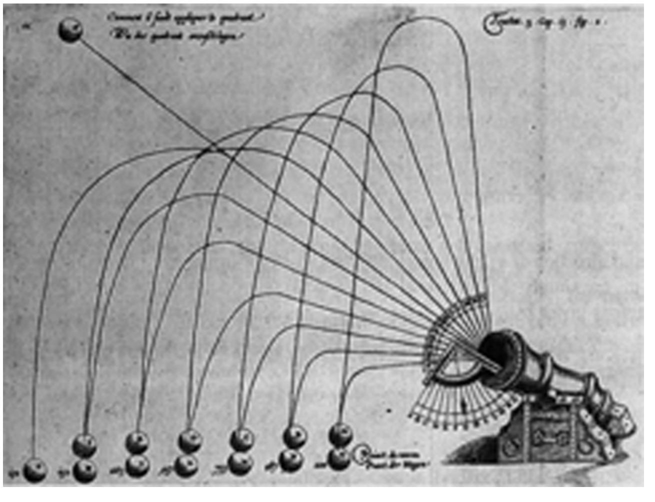

Figure 5.9 Pre–da Vinci trajectory estimations.

at low levels of fidelity, and some may be qualitative. Increasing fidelity requires increased refinement and increased project costs. Increased knowledge generally comes with increased fidelity, but not necessarily; it is possible to use a high-fidelity simulation to model "garbage" and thus do nothing to reduce uncertainty. In Chap. 10, we will talk more about analytical modeling.

5.3.4 Choosing the Best Models and Prototypes

Table 5.1 lists many types of models and prototypes that can be used in developing a product. These are listed by the medium used to build the model and the phase in the design process. There are two columns for drawings as many companies still use traditional layout and detail drawings, whereas others rely totally on CAD solid models.

There are trade-offs to be considered in developing models and prototypes: On one hand, they help verify the product, while on the other, they cost time and money. Further, there is a tension between the specifications for the product (what is supposed to happen) and the prototype (the current reality). In general, small companies are physical model–driven; they develop many prototypes and work from one to the next, refining the product. Large companies, ones that coordinate large volumes of information, tend to try to meet the specification through CAD and analytical modeling, building only a few physical prototypes.

An important decision made during planning is how many models and prototypes to schedule in the design process. There is currently a strong move toward replacing physical prototypes with computer models because simulation is cheaper and faster. This move will become stronger as virtual reality and rapid prototyping are further developed. Toyota has resisted these technologies in favor of developing physical prototypes, especially in the design of components that are primarily visual (e.g., car bodies). In fact, Toyota claims that using many simple prototypes, it can develop cars with fewer people and less time than companies that rely heavily on computers. GE, in its development of X-ray tubes for CT Scanners does much analysis, but moves to physical prototypes for

Table 5.1 Types of models

	Medium			
Phase	**Physical (form and function)**	**Analytical (mainly function)**	**Graphical (Traditional) (mainly form)**	**Graphical (CAD) (form and function)**
Concept	Proof-of-concept prototype	Back-of-the-envelope analysis	Sketches	Hand sketches and solid models
↓	Proof-of-product prototype	Engineering science analysis	Layout drawings	↓
Final product	Proof-of-process and proof-of-production prototypes	Finite element analysis; detailed simultation	Detail and assembly drawings	Solid models

proof-of-concept. The number of models and prototypes to schedule is dependent on the company culture and the ability to produce usable prototypes rapidly.

Finally, when planning for models and prototypes, be sure to set realistic goals for the time required and the information learned. One company had a series of four physical prototypes in its product development plan. But it turned out that the engineers were designing the second prototype (P2) while P1 was still being tested. Further, they developed P3 while P2 was being tested, and they developed P4 while P3 was being tested. Thus, what was learned from P1 influenced P3 and not P2, and what was learned from P2 influenced only P4. This waste of time and money was caused by a tight time schedule developed in the planning stage. The engineers were developing the prototypes on schedule, but since the tasks were not planned around the information to be developed, they were not learning from them as much as they should have. They were meeting the schedule for deliverable prototypes, not for the information that should have been gained.

5.4 BUILDING A PLAN

A project plan is a document that defines the tasks that need to be completed during the design process. For each task, the plan states the objectives; the personnel requirements; the time requirements; the schedule relative to other tasks, projects, and programs; and, sometimes, cost estimates. In essence, a project plan is a document used to keep that project under control. It helps the design team and management to know how the project is actually progressing relative to the progress anticipated when the plan was first established or last updated. There are five steps to establishing a plan. A template such as that in Fig. 5.10 can be used to support these steps. In this example, one task is detailed for a plan to develop a Baja car for an SAE (Society of Automotive Engineers) student contest. The plan is detailed in Fig. 5.16.

5.4.1 Step 1: Identify the Tasks

As the design team gains an understanding of the design problem, the tasks needed to bring the problem from its current state to a final product become clearer. Tasks are often initially thought of in terms of the activities that need to be performed (e.g., "generate concepts" or other terms used in Figs. 4.5–4.10). The tasks should be made as specific as possible, and as detailed in the next step, they should focus on what needs to be achieved rather than the activities. In some industries, the exact tasks to be accomplished are clearly known from the beginning of the project. For example, the tasks needed to design a new car are similar to those that were required to design the last model; the auto industry has the advantage

> A task that only describes an activity, is done when you run out of time.

Project Planning

Design Organization: Oregon State University Baja Team	**Date:** Oct. 2, 2007

Proposed Product Name: Killer Beaver

Task 6

Name of Task: Preliminary Engine Compartment Design

Objective: Develop solid model of the engine compartment
Run initial FEM
Analyze human factors for assembly and maintenance

Deliverables: CAD solid model
FEM results showing weak points based on static and fatigue analysis
Simulation of assembly of engine and components
Simulation of routine maintenance

Decisions needed:

Decision 1: Choose configuration for compartment

Decision 2: Identify work needed to finalize the design

Personnel needed:

Title: student	Hours: 75	Percent full time: 20%
Title:	Hours:	Percent full time:

Time estimate: Total hours: 75 Elapsed time (include units): 3 weeks

Sequence: Predecessors: Task 4, Preliminary roll cage design
Successors: Task 7, Final Engine Compartment Design
Start Date: Oct. 12 Finish Date: Nov. 2

Costs: Capital Equipment Disposables:

Team member: James	Prepared by: James
Team member: Tim	Checked by: Pat
Team member: Pat	Approved by:
Team member:	

The Mechanical Design Process Designed by Professor David G. Ullman
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Figure 5.10 Example plan template.

of beginning with a clear picture of the tasks needed to complete a new design. However, for a totally new product, the tasks may not be so clear.

5.4.2 Step 2: State the Objective for Each Task

Each task must be characterized by a clearly stated objective. This objective takes some existing information about the product—the input—and, through some activity, refines it for output to other tasks. Even though tasks are often initially conceived as activities to be performed, they need to be refined so that the results of the activities are the stated objectives. Although the output information can be only as detailed and refined as the present understanding of the design problem, each task objective must be

- Defined as information to be refined or developed and communicated to others, not as activities to be performed. This information is contained in *deliverables,* such as completed drawings, prototypes built, results of calculations, information gathered, or tests performed. If the deliverables cannot be itemized, the objective is not clear—then you know you are done only when you run out of time.
- Presented in terms of the decisions that need to be made and who will be involved in making them.
- Easily understood by all on the design team.
- Specific in terms of exactly what information is to be developed. If concepts are needed, then tell how many are sufficient.
- Feasible, given the personnel, equipment, and time available. See step 3.

5.4.3 Step 3: Estimate the Personnel, Time, and Other Resources Needed to Meet the Objectives

For each task, it is necessary to identify who on the design team will be responsible for meeting the objectives, what percentage of their time will be required, and over what period they will be needed. In large companies, it may only be necessary to specify the job title of the workers on a project, as there will be a pool of workers, any of whom could perform the given task. In smaller companies or groups within companies, specific individuals might be identified.

Many of the tasks require virtually a full-time commitment; others require only a few hours per week over an extended period. For each person on each task, it is necessary to estimate not only the total time requirement but also the distribution of this time. Finally, the total time to complete the task must be estimated. Some guidance on how much effort and how long a design task might take is given in Table 5.2. (The values given are only for guidance and can vary greatly.)

Similar comments apply to other resources needed to complete the task, especially those used for simulation, testing, and prototype manufacture. These resources and personnel are the means to complete the task.

Notice in Table 5.2 that no entry estimates the required time to be less than a week. *Design takes time.* Often it takes twice as long as the original estimate,

Table 5.2 The time it takes to design

Task	Personnel/time
Design of elemental components and assemblies. All design work is routine or requires only simple modifications of an existing product.	One designer for one week
Design of elemental devices such as mechanical toys, locks, and scales, or complex single components. Most design work is routine or calls for limited original design.	One designer for one month
Design of complete machines and machine tools. Work involved is mainly routine, with some original design.	Two designers for four months
Design of high-performance products that may utilize new (proven) technologies. Work involves some original design and may require extensive analysis and testing.	Five designers for eight months

especially if the design project is not routine or new technologies are used. Some pessimists claim that after making the best estimate of time required, the number should be doubled and the units increased one step. For example, an estimate of one day should really be two weeks.

A more accurate method for estimating the total time required for a project is based on the complexity of the product's function. The theory is that the more complex the function, the more complex the product and the longer the time needed to design the product. Product function development is a key part of concept generation and is covered in detail in Chap. 7. Thus, in order to use this method for time estimation, there has to be some understanding of the functions of the product. During the product development process, often a task in the conceptual design phase is titled "refine plans" to reflect the dependence of the plan on the concept being developed.

The total time required for a project can be estimated by

$$\text{Time (in hours)} = A * \mathrm{PC} * D^{0.85}$$

where

$A =$ a constant based on past projects in the company. This constant is dependent on the size of the company and how well information is communicated among the various functions. Typically, $A = 30$ for a small company with good communication and $A = 150$ for a large company with average communication. Note that communication and thus time is estimated at five times greater in a large organization.

PC $=$ product complexity based on function (discussed shortly).

$D =$ project difficulty: $D = 1$, not too difficult (i.e., using well-known technologies); $D = 2$, difficult (i.e., some new technologies); $D = 3$, extremely difficult (i.e., many new technologies).

> Everything takes twice as long.

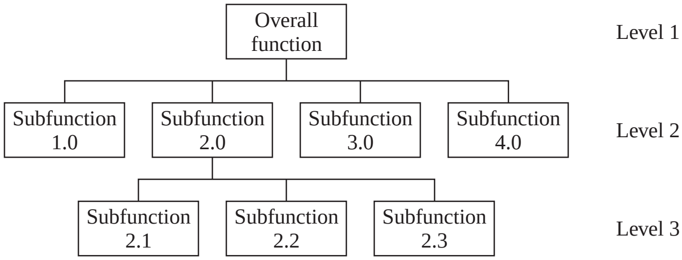

Figure 5.11 Example of a function diagram.

Product complexity is based on the functions of the product. A function diagram will typically look as shown in Fig. 5.11. Details on how to develop such a diagram will be covered in Chap. 7.

The product complexity is estimated by

$$\mathrm{PC} = \sum j * F_j$$

where

j = the level in the function diagram
F_j = the number of functions at that level

For the example in Fig. 5.11, there is 1 function on the top layer (always there), 4 on the second level, and 3 on the third:

$$\mathrm{PC} = 1 * 1 + 2 * 4 + 3 * 3 = 18$$

For example, a small company with good communication ($A = 30$) is designing a difficult product ($D = 2$) that has PC = 18, then an estimate of the total time is 973 hours, or two designers working for 3 months. This method has been shown to be fairly accurate within a single company that has calibrated the value for A, and models function in a consistent manner.

Time estimation is very difficult and subject to error. Thus, it is recommended that task time be based on three estimates: an optimistic estimate o, a most-likely estimate m, and a pessimistic estimate p. From these three, the statistical best estimate of task time is

$$\text{Time estimate} = \frac{o + 4m + p}{6}$$

This formula is used as part of the PERT (Program Evaluation and Review Technique) method. See the sources in Section 5.8 for more details on PERT.

Finally, note that the distribution of time across the phases of the design process is generally in the following ranges:

Project planning: 3 to 5%
Specification definition: 10 to 15%

Conceptual design: 15 to 35%
Product development: 50 to 70%
Product support: 5 to 10%

These percentages are based on studies of actual projects. The exact proportion in each phase greatly depends on the type of product, the amount of original design work, and the structure of the design process within the company.

5.4.4 Step 4: Develop a Sequence for the Tasks

The next step in working out the plan is to develop a task sequence or schedule. Scheduling tasks can be complex. The goal is to have each task accomplished before its result is needed and, at the same time, to make use of all of the personnel, all of the time. Additionally, it is necessary to schedule design reviews or other forms of approval to continue the project. The tasks and their sequence is often referred to as a *work breakdown structure*.

For each task, it is essential to identify its *predecessors*, which are the tasks that must be done before it, and the *successors*, the tasks that can only be done after it. By clearly identifying this information, the sequence of the tasks can be determined. A method called the *CPM (Critical Path Method)* helps determine the most efficient sequence of tasks. The CPM is not covered in this book.

Often tasks are interdependent—two tasks need decisions from each other in order to be completed. Thus, it is important to explore how tasks can be started with incomplete information from predecessors and how they can supply incomplete information to successors.

The best way to develop a schedule is to use a bar chart, shown in Fig. 5.12. (This type of chart is often called a *milestone* or *Gantt chart.*) On the chart, (1) each task is plotted against a time scale (time units are usually weeks, months, or quarters of a year); (2) the total personnel requirement for each time unit is plotted; and (3) the schedule of design reviews is shown. The Gantt chart in Fig. 5.12 was developed on a spread sheet (there are templates available for this). Many Gantt charts are developed using Microsoft Project^{TM}, as shown in Fig. 5.16.

In developing the task sequence pay attention to task dependencies. Step 1 emphasized concern for the information needed by the task and the information generated by the task. If a series of tasks simply build on each other, the information developed by one is the information needed by the next and the tasks are *sequential*. If two or more tasks must be accomplished at the same time to

> A plan is a "work breakdown structure" because without one the Work remaining will grow until you have a Breakdown unless you enforce some Structure on it.
> —Taken from John R. Page, *Rules of Engineering*

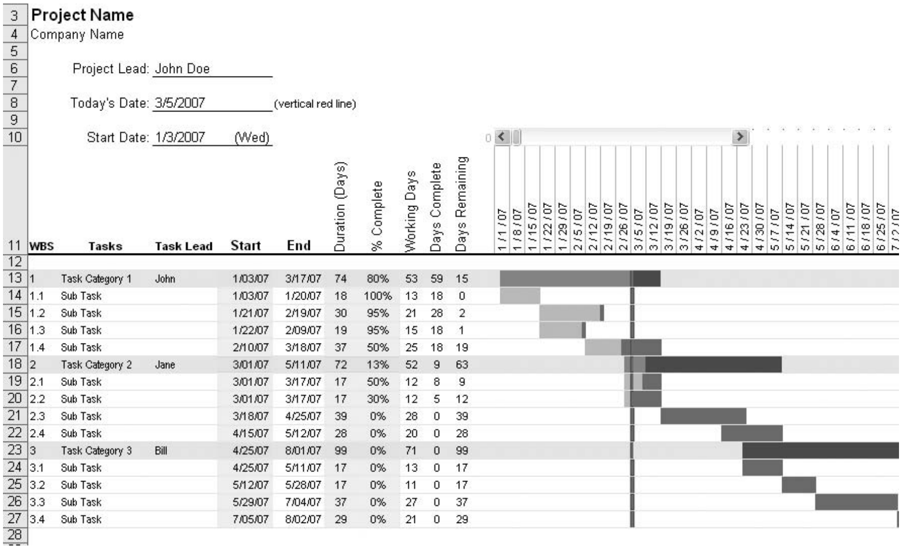

Figure 5.12 Gantt chart built on a spread sheet.

produce information for a future task, then they are *parallel.* There are two types of parallel tasks: *uncoupled* and *coupled.*

For example, in designing the MER, a decision was made early on to use the same type of motor and reduction gears both to power the MER and to steer it. Thus, tasks to develop the steering and drive train were closely coupled. Many other tasks occurred at the same time as the development of the drive train and the steering that were not coupled, for example, the Inertial Measurement Unit (IMU), Warm Electronics Box (WEB), and many other systems (see Fig. 2.7).

The three types of task sequences (serial, parallel coupled, and parallel uncoupled) can be discovered by using a *Design Structure Matrix (DSM).* A DSM is a simple diagram that helps sequence tasks, as shown in Fig. 5.13. Consider in the DSM shown here a subset of the tasks that may be required to develop a new bicycle seat. Each task is assigned a row and given a letter name. These letter names also appear as the names of the columns, in the same order. To develop a DSM, consider the tasks, one at a time. In the task's row put an X for every other task on which it is dependent. In the diagonal put the letter name to make reading easier.

Task A is not dependent on another task and so there are no Xs in the first row. The generation of concepts, Task B, needs the specifications developed in Task A and sequentially follows it. Similarly, Task C follows Task A but is not dependent on Task B. Thus, it can be done in parallel with Task B, but is uncoupled from it. Task D is dependent on Tasks B and C. Tasks E, F, and G are coupled as is evidenced by the Xs in the lower right corner of the matrix. Task E is dependent on Tasks F and G; Task F is dependent on Tasks E and G; and Task G

		A	B	C	D	E	F	G
Generate specifications	**A**	A						
Generate two concepts	**B**	X	B					
Develop test plan	**C**	X		C				
Test the concepts	**D**		X	X	D			
Design production parts	**E**	X	X		X	E	X	X
Design plastic injection mold	**F**	X				X	F	X
Design assembly tooling	**G**					X	X	G

Figure 5.13 Design Structure Matrix.

is dependent on Tasks E and F. Further, Tasks E and F are dependent on other tasks as well.

Reading down a column it is easy to see which tasks are dependent on the information developed. For example, reading down column "B" it is easy to see that Tasks D and E are dependent on the concepts being developed in Task B.

The DSM is very useful when the order of the tasks is not evident. The initial task order can be rearranged so the sequence flows in a manageable fashion.

5.4.5 Step 5: Estimate the Product Development Costs

The planning document generated here can also serve as a basis for estimating the cost of designing the new product. Even though design costs are only about 5% of the manufacturing costs of the product (Fig. 1.2), they are not trivial.

The cost estimate needed here is for the project, not the product. Product cost estimates are covered in Chap. 11. A majority of project costs are in salaries. Some basic guidelines for making a project cost estimate are

- Engineer salaries range from \$50k to \$100k per year, or assuming 2000 work hours year, \$25–\$50/hour. However, the cost to the project is more than just salaries, as all companies add on a "burden" that covers the costs of buildings, utilities, support personnel, and general equipment. Burden rates range from 100% in industry up to 300% in a government lab. Thus, the least expensive engineering in an industrial organization will cost \$50 an hour, and a senior engineer in a government lab will cost \$200 an hour.
- Most mechanical design projects require physical prototypes and test facilities. Each organization has a method to account for these costs. They may be lumped into the burden rate, or may be a separate item paid for by the hour. The same consideration must be given to computer costs to support CAD, simulation, meeting support, PLM, and other needs.
- For many projects, there is the need to travel to meet with other members of the design team, vendors, and suppliers. Travel costs can add up fast and must be included in planning.

5.5 DESIGN PLAN EXAMPLES

5.5.1 A Very Simple Plan

We will now look at two simple problems to see how different problems require different design processes. Recall the problem statements from Chap. 1 (see Fig. 1.9):

> What size SAE grade 5 bolt should be used to fasten together two pieces of 1045 sheet steel, each 4 mm thick and 6 cm wide, which are lapped over each other and loaded with 100 N?

and

> Design a joint to fasten together two pieces of 1045 sheet steel, each 4 mm thick and 6 cm wide, which are lapped over each other and loaded with 100 N.

The solution of the first joint design problem is fairly straightforward (Fig. 5.14). It is fully defined, and understanding the problem is not hard. Since the problem statement actually defines the product, there is no need to generate and evaluate concepts or to generate a product design since it already exists. The only real effort involved in this design problem is to evaluate the product. This is done using standard equations from a text on machine component design or using company or industrial standards. In a component-design text, we find analysis methods for several different failure modes: the bolt can shear, the sheet steel can crush, and so on. After completing the analysis, you will make a decision as to which of the failure modes is most critical and then specify the smallest size of bolt that will not permit failure. This decision, part of the evaluation, is documented as the answer to the problem. In a classroom situation, you will undergo a "design review" when your answer is graded against a "correct" answer.

Very few real design problems have a single correct answer. In fact, reality can cause quite a shift from the design process illustrated in Fig. 5.14. Consider one example: An experienced design engineer began a new job with a company that manufactured machines in an industry new to him. One of his first projects included the subproblem of designing a joint similar to bolt analysis problem. He followed the process in Fig. 5.14 and documented his results on an assembly drawing of the entire product. His analysis told him that a 1/4-in.-diameter bolt would carry the load with a generous factor of safety. However, his manager, an experienced designer in the industry, on reviewing the drawing, crossed off the 1/4-in. bolt and replaced it with a 1/2-in bolt, explaining to the new designer that it was an unwritten company standard based on years of experience never to use bolts of less than 1/2-in. diameter. The standard was dictated by the fact that

Understand the problem → Evaluate the product → Document the result

Figure 5.14 Simple plan for a lap joint.

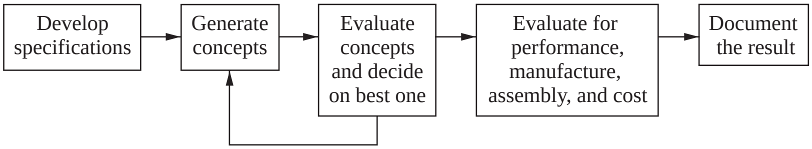

Figure 5.15 Design process for a more complex lap joint.

service personnel could not see anything smaller than a 1/2-in. bolt head in the dirty environment in which the company's equipment operated. On all subsequent products, the designer specified 1/2-in. bolts without performing any analysis.

For the second joint design problem, the process is more complex (Fig. 5.15). There are a number of concepts that might fasten the sheets. Typical options include using a bolt, welding the pieces together, using an adhesive, or folding the metal to make a seam. You might perform an analysis on each of these options, but that would be a waste of time because the results would still provide no clear way of knowing which joint design might be best. What is immediately evident is that the requirements on this joint are not well articulated. In fact, if they were, perhaps none of the earlier concepts would be acceptable.

So the first step in solving this problem should be specification development for the joint. Various questions should be addressed: Does the joint need to be easily disassembled or leak-resistant? Does it need to be less than a certain thickness? Can it be heated? After all the specifications are understood, it will be possible to generate concepts (maybe ones previously thought of, maybe not), evaluate these concepts, and limit the potential designs for the joint to one or two concepts. Thus, before performing analysis on all of the joint designs (evaluating the product), it may be possible to limit the number of potential concepts to one or two. With this logic, the design process would follow the flow of Fig. 5.15, a process similar to that in Fig. 4.1, except there may be no need to generate product. The problem solved here is so mature that the concepts developed are fully embodied products. The concept, a "welded lap joint," is fairly refined. The only missing details are the materials, the weld depth, the length of the weld leg, and other details requiring expertise in welding design. However, if the requirements on the joint were out of the ordinary, then the concepts generated might be more abstract and have many possible product embodiments.

5.5.2 Development of a New Product for a Single or Small Run

Many products are made only once or at most a few times. Planning for manufacture and assembly is different for these products than for those that are mass-produced. Specifically, for a small run there is less latitude for choosing manufacturing methods. Methods such as forging metal, injection-molding plastics, and manufacturing custom control circuits require mass production to amortize the tooling costs required. This restricts the types of components that can

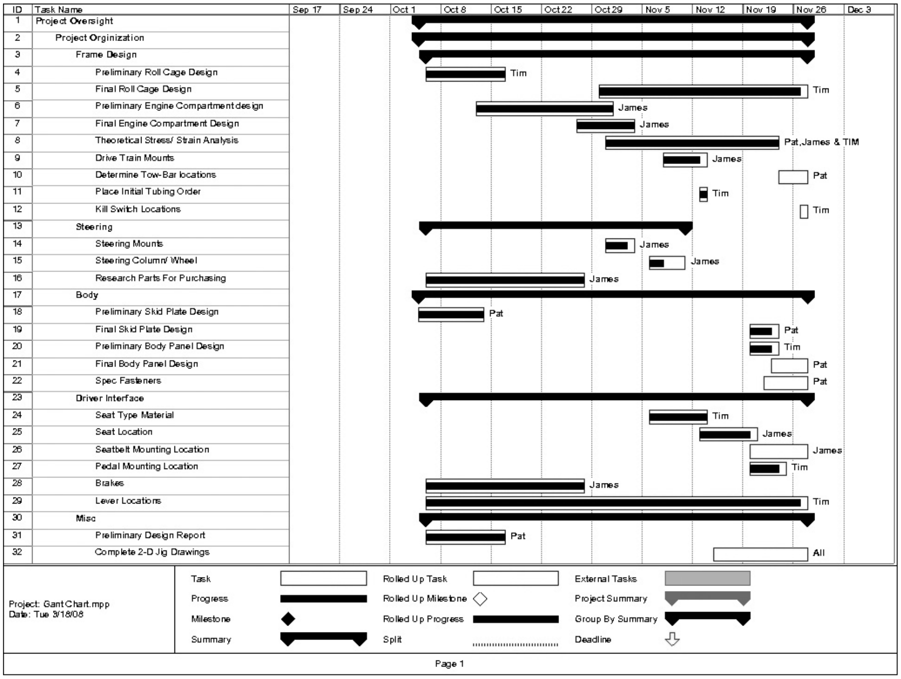

Figure 5.16 Project plan for Baja car.

be designed. Often the first item built is both a prototype and the final product delivered to the customer. There is more of a tendency to buy off-the-shelf components for short-run products. There is also less concern for assembly time than for mass-produced products.

Figure 5.16 is the project plan of Oregon State University's 2007 SAE Baja car. This team consistently places in the top 10 in races they enter. This plan was done on Microsoft Project™ and it shows the major tasks during a six-week period in the fall term. Note that some of the tasks did not take as long as planned, and others were not even done at all. Keep in mind that a plan is just that, a plan for doing work and developing deliverables. Reality seldom fits the plan precisely, even for this team that based their estimates on those developed in prior years.

5.5.3 Development of a New Product for Mass Production

Planning for new products can range from very simple to nearly impossible. Consider these two examples: A toy manufacturer is to develop a new toy that is similar to other toys they currently make (e.g., new action figures and toy

> A plan is only valid until you start working.

cars with cosmetic or minor functional changes). Thus, the product development plan is similar to that for the previously designed toys. At the other end of the planning spectrum is a company that has just developed a new technology and has never made a similar product before. For example, when first producing the iPod, Apple's planning required many tasks that were highly uncertain. The ability to plan for a new product in this situation is much more challenging than it is for the toy company.

Designing products for mass production requires careful planning for manufacture and assembly. These projects give the design engineer more flexibility in selecting materials and manufacturing processes and increase the project's dependence on manufacturing engineers.

5.6 COMMUNICATION DURING THE DESIGN PROCESS

Communication of the right information to the right people at the right time is one of the key features of a successful design project and a key reason for the existence of PLM. All communication begins with informal, face-to-face discussions and notes on scraps of paper. An engineering design paradox arises with these informal forms of communication. First, they are essential and must be informal if information is to be shared and progress to be made. Second, for the most part the information is not in a form that is documented for future use. In other words, the information and arguments used to reach many decisions are not recorded as part of any permanent design record and can be lost or easily misinterpreted. Thus, it is important to make the effort to record important discussions and decisions.

Formal communication generally is in the form of *design notebooks, design records, communications to management*, and *communication of the final design to downstream phases*.

5.6.1 Design Notebooks and Records

Each technique discussed in this book produces documents that will become part of a design file for the product. The company keeps this file as a record of the product's development for future reference, perhaps to prove originality in case of patent application or to demonstrate professional design procedures in case of a lawsuit. However, a complete record of the design must go beyond these formal documents.

In solving any design problem, it is essential to keep track of the ideas developed and the decisions made in a *design notebook*. Some companies require these, with every entry signed and dated for legal purposes. In cases where a patent may be applied for or defended against infringement, it is necessary to have complete documentation of the birth and development of an idea. A design notebook with sequentially numbered, signed, and dated pages is considered good documentation; random bits of information scrawled on bits of paper are not. Additionally, a lawsuit against a designer or a company for injury caused by a product can be won or lost on the basis of records that show that state-of-the-art design practices were used in the development of the product. Design notebooks also serve as reference to the history of the designer's own work. Even in the case of a simple design, it is common for designers to be unable to recall later why they made a specific decision. Also, it is not uncommon for an engineer to come up with a great idea only to discover it in earlier notes.

The design notebook is a diary of the design. It does not have to be neat, but it should contain all sketches, notes, and calculations that concern the design. Before starting a design problem, be sure you have a bound notebook—one with lined paper on one page and graph paper on the other is preferable. The first entry in this notebook should be your name, the company's name, and the title of the problem. Follow this with the problem statement, as well as it is known. Number, date, and sign each page. If test records, computer readouts, and other information are too bulky to be cut and pasted into the design notebook, enter a note stating what the document is and where it is filed.

There have been efforts to keep design notebooks on computers. It is still difficult for computer-based systems to manage the sketches and notes, and they lack the permanence to hold up in court.

More formal design records are created with each step of the design process. In this book, there are over 20 templates used that give an outline for the needed records. The information contained in these is what is managed and integrated in a PLM system.

5.6.2 Documents Communicating with Management

During the design process, periodic presentations to managers, customers, and other team members will be made. These presentations are usually called *design reviews* and are shown as an "approve plan" decision point in Fig. 5.1. Although there is no set form for design reviews, they usually require both written and oral communication. Whatever the form, these guidelines are useful in preparing material for a design review.

Make it understandable to the recipient. Clear communication is the responsibility of the sender of the information. It is essential in explaining a concept to others that you have a clear grasp of what they already know and do not know about the concept and the technologies being used.

Carefully consider the order of presentation. How should a bicycle be described to someone who has never seen one? Would you describe the wheels first, then the frame, the handlebars, the gears, and finally the whole assembly? Probably not, as the audience would understand very little about how all these bits fit together. A three-step approach is best: (1) Present the whole concept or assembly and explain its overall function, (2) describe the major parts and how they relate to the whole and its function, and (3) tie the parts together into the whole. This same approach works in trying to describe the progress in a project: *Give the whole picture; detail the important tasks accomplished; then give the whole picture again.* There is a corollary to this guideline: *New ideas must be phased in gradually.* Always start with what the audience knows and work toward the unknown. Above all, do not use jargon or terms with which the audience is not familiar. If in doubt about a concept or TLA (Three Letter Acronym), define it.

Be prepared with quality material. The best way to make a point, and to have any meeting end well, is to be prepared. This implies (1) having good visual aids and written documentation, (2) following an agenda, and (3) being ready for questions beyond the material presented.

Good visual aids include diagrams and sketches specifically prepared to communicate a well-defined point. In cases in which the audience in the design review is familiar with the design, mechanical drawings might do, but if the audience is composed of nonengineers who are unfamiliar with the product, such drawings communicate very little. It is always best to have a written agenda for a meeting. Without an agenda, a meeting tends to lose focus. If there are specific points to be made or questions to be answered, an agenda ensures that these items are addressed.

5.6.3 Documents Communicating the Final Design

The most obvious form of documentation to result from a design effort is the material that describes the final design. Such materials include computer solid models, drawings (or computer data files) of individual components (detail drawings) and of assemblies to convey the product to manufacturing. They also include written documentation to guide manufacture, assembly, inspection, installation, maintenance, retirement, and quality control. These topics will be covered in Chaps. 9 and 12.

Often it is necessary to produce a design report. The following format is a good outline to follow.

1. **Title page:** The title of the design project is to be in the center of the page. Below it, list the following items:
   a. Date:
   b. Course/Section:
   c. Instructor:
   d. Team Members:
2. **Executive summary:**
   a. The purpose of the Executive Summary is to provide key information up front, such that while reading the report, a reader has expectations that are fulfilled on a continuous basis. Key to a good summary is the *first* sentence, which *must* contain the most essential information that you wish to convey.

   b. The summary is to be written as if the reader is totally uninformed about your project and is not necessarily going to read the report itself.
   c. It must include a short description of the project, the process and the results.
   d. The Executive Summary is to be one page or less with one figure maximum.
3. **Table of contents:** Include section titles and page numbers.
4. **Design problem and objectives:** Give a clear and concise definition of the problem and the intended objectives. Outline the design constraints and cost implications.
   a. Include appropriate background on the project for the reader to be able to put the information provided in context.
   b. The final project objectives *must* also be presented in the form of a set of engineering specifications.
5. **Detailed design documentation:** Show all elements of your design including an explanation of
   a. Assumptions made, making sure to justify your design decisions.
   b. Function of the system.
   c. Ability to meet engineering specifications.
   d. Prototypes developed, their testing and results relative to engineering specifications.
   e. Cost analysis.
   f. Manufacturing processes used.
   g. DFX results.
   h. Human factors considered.
   i. All diagrams, figures, and tables should be accurately and clearly labeled with meaningful names and/or titles. When there are numerous pages of computer-generated data, it is preferable to put this information in an appendix with an explanation in the report narrative. For each figure in the report, ensure that every feature of it is explained in the text.
6. **Laboratory test plans and results** for all portions of the system that you built and tested. Write a narrative description of test plan(s). Use tables, graphs, and whatever possible to show your results. Also, include a description of how you plan to test the final system, and any features you will include in the design to facilitate this testing. This section forms the written record of the performance of your design against specifications.
7. **Bills of materials:** Parts costs include only those items included in the final design. A detailed bill of materials includes (if possible) manufacturer, part number, part description, supplier, quantity, and cost.
8. **Gantt chart:** Show a complete listing of the major tasks to be performed, a time schedule for completing them, and which team member has the primary responsibility (and who will be held accountable) for each task.

9. **Ethical consideration:** Provide information on any ethical considerations that govern the product specifications you have developed or that need to be taken into account in potentially marketing the product.
10. **Safety:** Provide a statement of the safety consideration in your proposed design to the extent that is relevant.
11. **Conclusions:** Provide a reasoned listing of only the most significant results.
12. **Acknowledgments:** List individuals and/or companies that provided support in the way of equipment, advice, money, samples, and the like.
13. **References:** Including books, technical journals, and patents.
14. **Appendices:** As needed for the following types of information:
    - **a.** Detailed computations and computer-generated data.
    - **b.** Manufacturers' specifications.
    - **c.** Original laboratory data.

5.7 SUMMARY

- Planning is an important engineering activity.
- The use of prototypes and models is important to consider during planning.
- Every product is developed through five phases: discovery, specification development, conceptual design, product development, and product support. Planning is needed to get through these phases in a timely, cost-effective manner.
- There are five planning steps: identify the tasks, state their objectives, estimate the resources needed, develop a sequence, and estimate the cost.
- There are many types of project plans. A goal is to design a plan to meet the needs of the project.
- Communication through reports and drawings are key to the success of any project.

5.8 SOURCES

Bashir, H., and V. Thompson: "Estimating Design Complexity," *Journal of Engineering Design,* Vol. 16, No. 3, 1999, pp. 247–256. Estimates on project time are based on this paper.

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Cooper, Robert G.: *Winning at New Products: Accelerating the Process from Idea to Launch,* Third Edition, Perseus Books Group, 2001. The basic book on Stage-Gate methods.

Meredith, D. D., K. W. Wong, R. W. Woodhead, and R. H. Wortman: *Design Planning of Engineering Systems,* Prentice-Hall, Englewood Cliffs, N.J., 1985. Good basic coverage of mathematical modeling, optimization, and project planning, including CPM and PERT.

MicroSoft Project™. Software that supports the planning activity. There are many share-ware versions available.

For details on the Design Structure Matrix see *The DSM Website* at MIT, http://www.dsmweb.org/. A tutorial there is instructive.

The Design Report format is used, with permission, from the Electrical Engineering Program at The Milwaukee School of Engineering.

5.9 EXERCISES

5.1 Develop a plan for the original or redesign problem identified in Exercise 4.1 or 4.2.

- **a.** Identify the participants on the design team.
- **b.** Identify and state the objective for each needed task.
- **c.** Identify the deliverables.
- **d.** Justify the use of prototypes.
- **e.** Estimate the resources needed for each task.
- **f.** Develop a schedule and a cost estimate for the design project.

5.2 For the features of the redesign problem (Exercise 4.2) develop a plan as in Exercise 5.1.

5.3 Develop a plan for making a breakfast consisting of toast, coffee, a fried egg, and juice. Be sure to state the objective of each task in terms of the results of the activities performed, not in terms of the activities themselves.

5.4 Develop a plan to design an orange ripeness tester. In a market, people test the freshness of oranges by squeezing them, and based on their experience, how much they compress when squeezed gives an indication of ripeness. There are some sophisticated methods used in industry, but the goal here is to develop something simple, that could be built for low cost.

5.10 ON THE WEB

Templates for the following documents are available on the book's website: www.mhhe.com/Ullman4e

- Project Plan
- Design Report

CHAPTER 6

Understanding the Problem and the Development of Engineering Specifications

KEY QUESTIONS

- Why emphasize developing engineering specifications?
- How can you identify the "customers" for a product?
- Why is it so important to understand the voice of the customer and work to translate this into engineering specifications?
- How can you best benchmark the competition to understand design and business opportunities?
- How can you justify taking time at the beginning of a project to do specification development instead of developing concepts immediately?

6.1 INTRODUCTION

Understanding the design problem is an essential foundation for designing a quality product. "Understanding the design problem" means to *translate customers' requirements into a technical description of what needs to be designed.* Or, as the Japanese say, "Listen to the voice of the customer." This importance is made graphically clear in the cartoon shown in Fig. 6.1. Everyone has a different view of what is needed by the customer and it takes work to find out what this really is.

Surveys show that poor product definition is a factor in 80% of all time-to-market delays. Further, getting a product to market late is more costly to a company than being over cost or having less than optimal performance. Finding the "right" problem to be solved may seem a simple task; unfortunately, often it is not.

Besides finding the right problem to solve, an even more difficult and expensive problem for most companies is what is often called "creeping specifications."

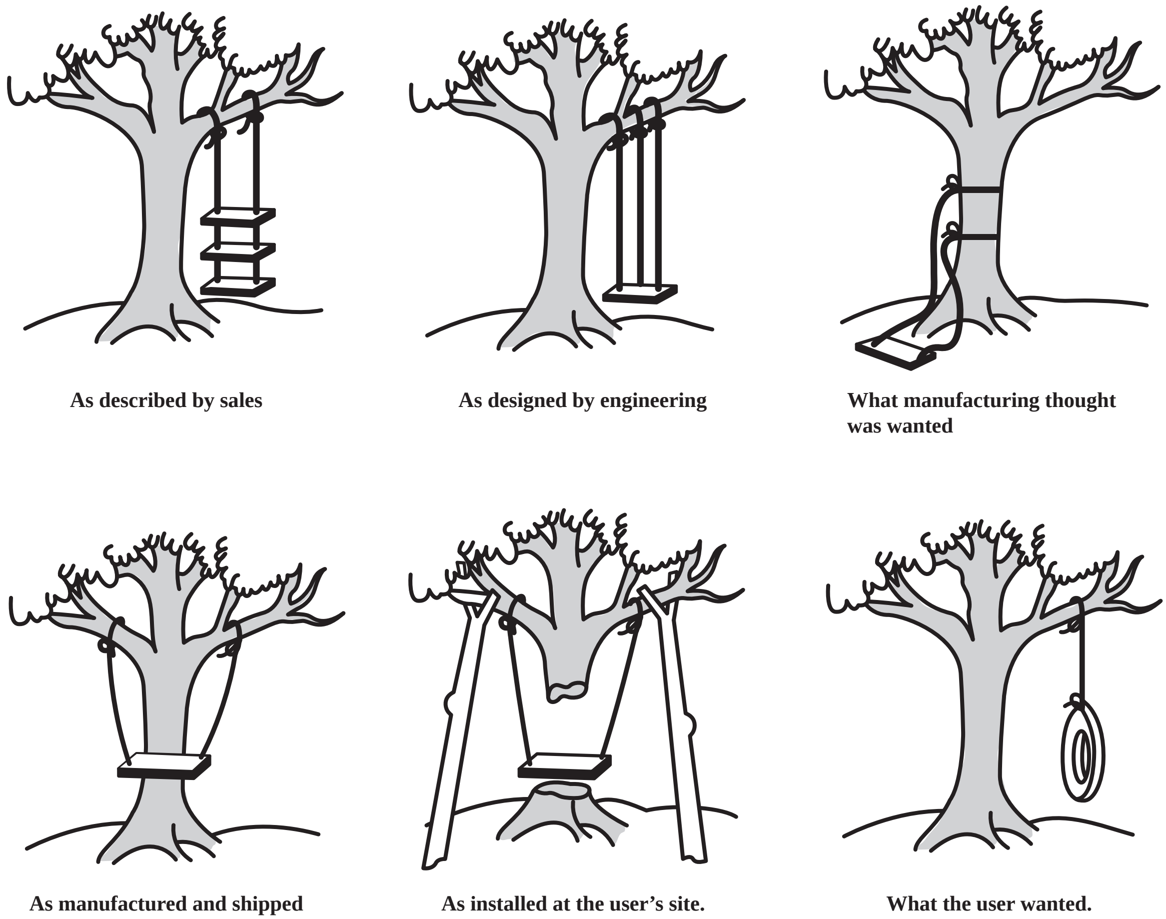


Figure 6.1 Understanding the product need.

Creeping specifications change during the design process. It is estimated that fully 35% of all product development delays are directly caused by such changes. There are three factors that cause creeping specifications. First, as the design process progresses, more is learned about the product and so more features can be added. Second, since design takes time, new technologies and competitive products become available during the design process. It is a difficult decision whether to ignore these, incorporate them (i.e., change the specifications), or start all over (i.e., decide that the new developments have eliminated the market for what you are designing). Third, since design requires decision making, any specification change causes a readdressing of all the decisions dependent on that specification. Even a seemingly simple specification change can cause redesign of virtually the whole product. The point is that when specification changes become necessary, they should be done in a controlled and informed manner.

> All design problems are poorly defined.

The importance of the early phases of the design process has been repeatedly emphasized. As pointed out in Chap. 1, careful requirements development is a key feature of an effective design process. In this chapter, the focus is on understanding the problem that is to be solved. The ability to write a good set of engineering specifications is proof that the design team understands the problem.

There are many techniques used to generate engineering specifications. One of the best and currently most popular is called *Quality Function Deployment (QFD).* What is good about the QFD method is that it is organized to develop the major pieces of information necessary to understanding the problem:

1. Hearing the voice of the customers
2. Developing the specifications or goals for the product
3. Finding out how the specifications measure the customers' desires
4. Determining how well the competition meets the goals
5. Developing numerical targets to work toward

The QFD method was developed in Japan in the mid-1970s and introduced in the United States in the late 1980s. Using this method, Toyota was able to reduce the costs of bringing a new car model to market by over 60% and to decrease the time required for its development by one-third. It achieved these results while improving the quality of the product. A recent survey of 150 U.S. companies shows that 69% use the QFD method and that 71% of these have begun using the method since 1990. A majority of companies use the method with cross-functional teams of ten or fewer members. Of the companies surveyed, 83% felt that the method had increased customer satisfaction and 76% indicated that it facilitated rational decisions.

Before itemizing the steps that comprise this technique for understanding a design problem, consider some important points:

1. No matter how well the design team thinks it understands a problem, it should employ the QFD method for all original design or redesign projects. In the process, the team will learn what it does not know about the problem.
2. The customers' requirements must be translated into *measurable design targets for identified critical parameters.* You cannot design a car door that is "easy to open" when you do not know the meaning of "easy." Is easiness measured by force, time, or what? If force is a critical parameter, then is "easy" 20 N or 40 N? The answer must be known before much time and resources are invested in the design effort.
3. The QFD method can be applied to the entire problem and any subproblem. (Note that the design of a door mechanism in the previous point is a subproblem in automobile design.)

4. It is important to first worry about *what* needs to be designed and, only after that is understood, to worry about *how* the design will look and work. Our cognitive capabilities generally lead us to try to assimilate the customers' functional requirements (what is to be designed) in terms of form (how it will look); these images then become our favored designs and we get locked onto them. The QFD procedure helps overcome this cognitive limitation.
5. This method takes time to complete. In some design projects, about one-third of the total project time is spent on this activity. Ford spends 3–12 months developing the QFD for a new feature. Experimental evidence has shown that designers who spend time here end up with better products and do not use any more total time when compared to others who do a superficial job here. Time spent here saves time later. Not only does the technique help in understanding the problem, it also helps set the foundation for concept generation.

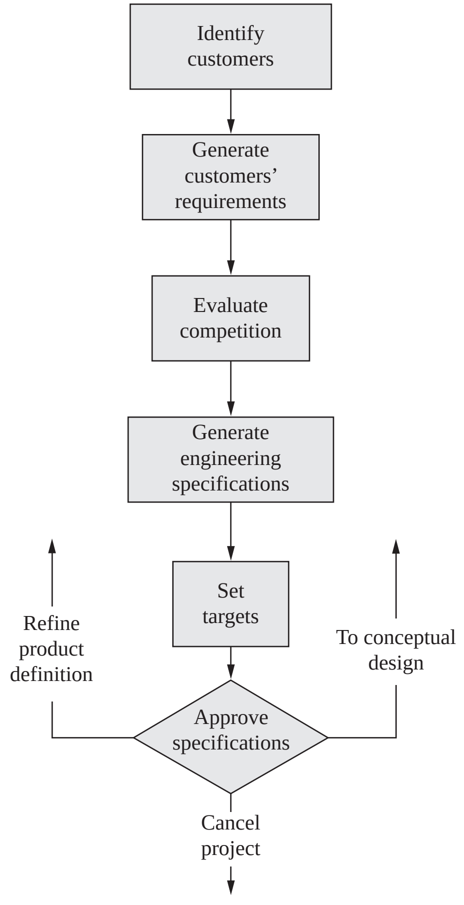


Figure 6.2 The Product Definition phase of the mechanical design process.

The QFD method helps generate the information needed in the engineering Product Definition phase of the design process (Fig. 4.1). That phase is reproduced in Fig. 6.2. Each block in the diagram is a major section in this chapter and a step in the QFD method.

Applying the QFD steps builds the *house of quality* shown in Fig. 6.3. This house-shaped diagram is built of many rooms, each containing valuable information. Before we describe each step for filling in Fig. 6.3, a brief description of the figure is helpful. The numbers in the figure refer to the steps that are detailed in the sections below. Developing information begins with identifying *who* (step 1) the customers are and *what* (step 2) it is they want the product to do. In developing this information, we also determine to whom the "what" is important—*who versus what* (step 3). Then it is important to identify how the problem is solved *now* (step 4), in other words, what the competition is for the product being designed. This information is compared to what the customers desire—*now versus what* (step 4 continued)—to find out where there are opportunities for an improved product. Next comes one of the more difficult steps in developing the house, determining *how* (step 5) you are going to measure the product's

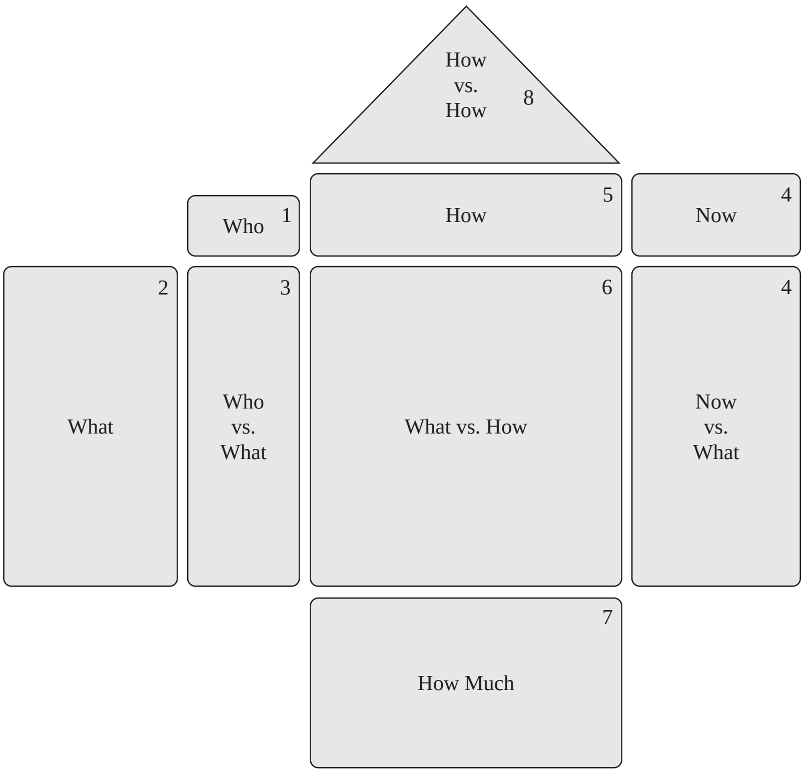


Figure 6.3 The house of quality, also known as the QFD diagram.

ability to satisfy the customers' requirements. The hows consists of the engineering specifications, and their correlation to the customers' requirements is given by *whats versus hows* (step 6). Target information—*how much* (step 7)—is developed in the basement of the house. Finally, the interrelationship between the engineering specifications are noted in the attic of the house—*how versus how* (step 8). Details of all these steps and why they are important are developed in Sections 6.2 through 6.9. Postage stamp-size versions of Fig. 6.3 tie the steps together.

The QFD method is best for collecting and refining functional requirements, hence the "F" in its name. However, in the material presented here, it will be used to help ensure that all requirements are collected and refined. In each step, the design of an "aisle chair" will be used as an example. This example is taken from a project to design a wheelchair to rapidly help passengers board and deplane from a Boeing 787 Dreamliner. This type of wheelchair is brought into the waiting area, the passenger transfers from their regular wheelchair to the aisle chair, which is then wheeled to the plane and down the aisle to the assigned seat where the passenger transfers out of the aisle chair into their seat. The process is reversed at the end of the flight. Aisle chairs are narrower than regular chairs so they can fit between the rows on an aircraft. A typical aisle chair is shown in Fig. 6.4.

The design effort for the Dreamliner chair resulted in the QFD shown in Fig. 6.5. This House of Quality developed during this project contained over 60 customer requirements and over 50 engineering specifications. This effort, although time consuming, resulted in the increased project understanding that was essential to develop a product that was superior to those already on the market.

The entire House is too large to read or make for a good example, so a reduced version of it will be used (Fig. 6.6). This example contains all the important points used in the larger, complete QFD. The contents of this house are developed in the following sections.

Figure 6.4 A typical aisle chair. (Reprinted with permission of Columbia Medical.)

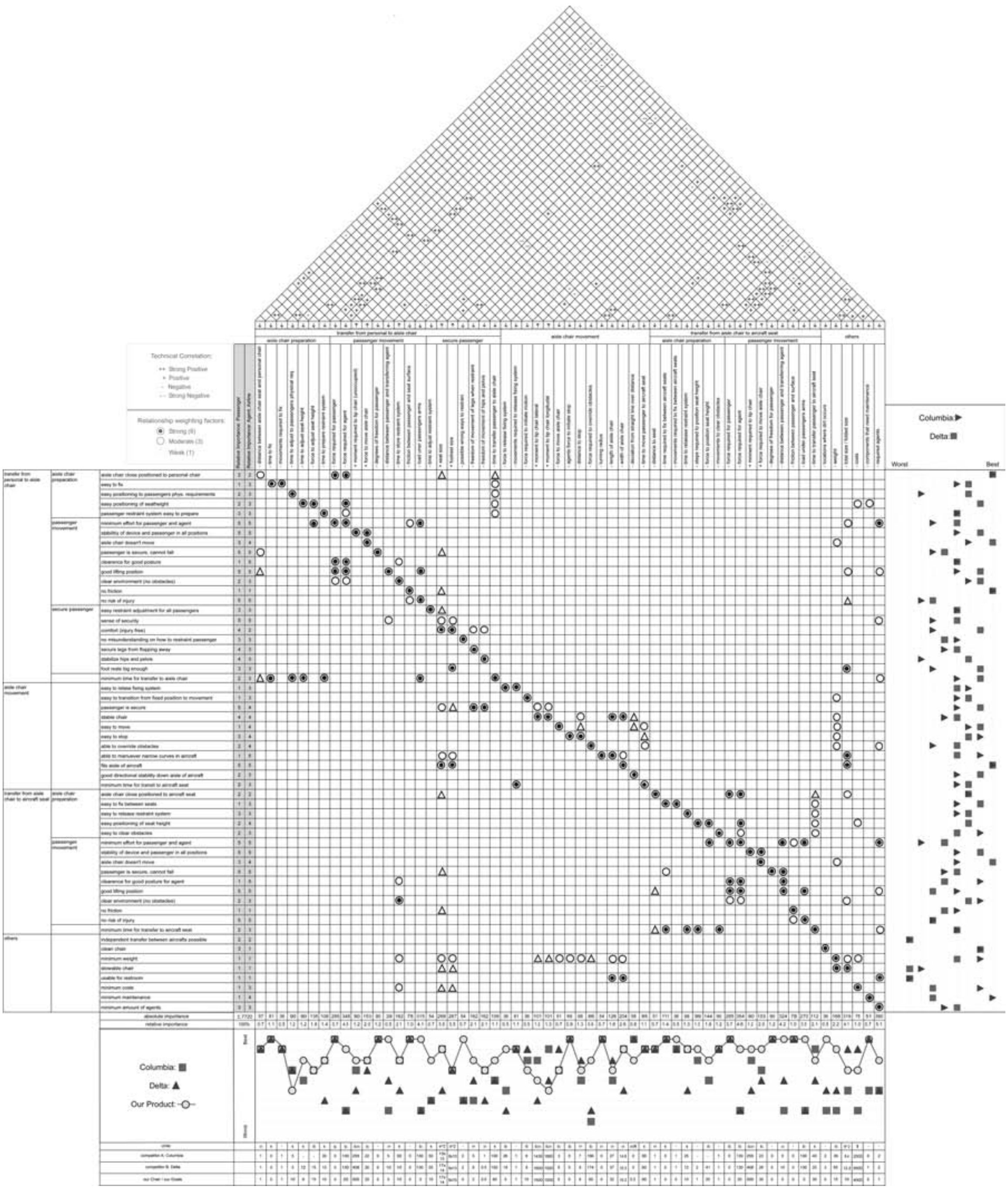
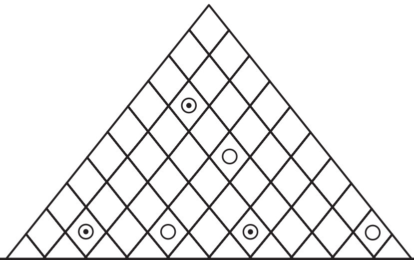


Figure 6.5 Aisle chair QFD (original available on book web site).



⊙ = 9
○ = 3
Δ = 1

1 = very bad
5 = very good

▸ Colub
■ Deltor

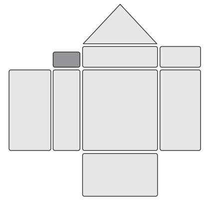
What			Who: Passenger	Who: Agent	How: Seat width relative to frame width	Steps to adjust seat height	Force to adjust seat height	Force to slide 95% male passenger	Lifting force required for agent	Push force over 2 cm bump	Force to push aisle chair	Time to transfer between seats	Fore/aft tipping force at handles	Side tipping force at handles	Now: 1	2	3	4	5
					↑	↑	↓	↓	↓	↓	↓	↓	↑	↑					
					%	steps	N	N	N	N	N	sec	N	N					
Transfer from personal to aisle chair	Aisle chair preparation	Easy positioning of seat height	4	4		⊙	⊙									▸	■		
		Easy to position chairs	6	10	⊙												▸ ■		
	Passenger movement	Minimum effort for all	15	10				⊙	⊙							■	▸		
		Good lifting position	10	12	○													▸	■
		Minimum time for transfer	3	14		Δ						⊙				▸ ■			
Aisle chair movement		Easy to move	7	8						⊙	⊙		○	○		■			▸
		Fits in aircraft aisle	-	-													▸	■	
		Good stability	24	10									⊙	⊙	▸	■			
Transfer from aisle chair to seat	Aisle chair preparation	Aisle chair close to aircraft seat	6	2	⊙											▸	■		
		Easy positioning of seat height	5	8		⊙	⊙										▸ ■		
	Passenger movement	Minimum effort for all	15	12		○	○				⊙					▸	■		
		Minimum transfer time	5	10		Δ						⊙				▸	■		
Importance (Passenger)					10	9	8	9	9	4	14	5	16	16					
(Agent)					11	13	11	7	7	5	14	16	8	8					
Colub					85	2	3	20	15	11	7	15	20	15					
Deltor					87	3	5	27	25	22	15	18	15	10					
Target (Delighted)					90	1	2	20	10	8	7	15	15	10					
Threshold (Disgusted)					85	2	4	25	15	12	10	18	20	12					

Figure 6.6 Example aisle chair QFD.

Your decisions, good or bad, affect everyone downstream.

The House of Quality can be easily built on a spreadsheet with the exception of the roof portion at the top. A simple method to construct this also on a spreadsheet is given in step 8.

6.2 STEP 1: IDENTIFY THE CUSTOMERS: WHO ARE THEY?



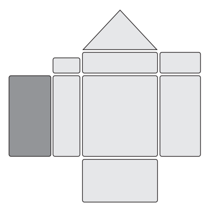
For most design situations, there is more than one customer; for many products, the most important customers are the consumers, the people who will buy the product and who will tell other consumers about its quality (or lack thereof). Sometimes the purchaser of the product is not the same as its user (e.g., gym equipment, school desks, and office desks). Some products—a space shuttle or an oil drill head—are not consumer products but still have a broad customer base.

For all products it is important to consider customers both outside the organizations that design, manufacture, and distribute the product—external customers—and those inside of them—internal customers. For example, beyond the consumer, the designer's management, manufacturing personnel, sales staff, and service personnel must also be considered as customers. Additionally, standards organizations should be viewed as customers, as they too may set requirements for the product. For many products, there are five or more classes of customers whose voices need to be heard.

One method to make sure you have identified all the customers is to consider the entire life of the product (see Fig. 1.7). Pretend you are the product; visualize all the people that encounter you as you go through the internal and external phases itemized in life cycle diagram.

For the aisle chair, the main customers are the passengers being transported and the airline agents who assist in transporting the passengers on and off the airplane. Note that neither of these two customers purchases the aisle chair. Nor do they maintain it, clean it, or disassemble it. In Fig. 6.6 the only customers shown are the passenger and agent as "who" examples. The area below the "passenger" and "agent" will be filled in during Step 3.

6.3 STEP 2: DETERMINE THE CUSTOMERS' REQUIREMENTS: *WHAT* DO THE CUSTOMERS WANT?



Once the customers have been identified, the next goal of the QFD method is to determine *what* is to be designed. That is, what is it that the customers want?

- Typically, as shown by the customer survey in Table 1.1, the *consumers* want a product that works as it should, lasts a long time, is easy to maintain, looks attractive, incorporates the latest technology, and has many features.

> You only think you know what your customers want.

- Typically, the *production customer* wants a product that is easy to produce (both manufacture and assemble), uses available resources (human skills, equipment, and raw materials), uses standard parts and methods, uses existing facilities, and produces a minimum of scraps and rejected parts.
- Typically, the *marketing/sales customer* wants a product that meets consumers' requirements; is easy to package, store, and transport; is attractive; and is suitable for display.

The key to this QFD step is collecting information from customers. There are essentially three methods commonly used: observations, surveys, and focus groups.

Fortunately, most new products are refinements of existing products, so many requirements can be found by *observing* customers using the existing product. For example, automobile manufacturers send engineers into shopping center parking lots to observe customers putting purchases into cars to better understand one aspect of car door requirements.

Surveys are generally used to gather specific information or ask people's opinions about a well-defined subject. Surveys use questionnaires that are carefully crafted and applied either through the mail, over the telephone, or in face-to-face interviews. Surveys are well suited for collecting requirements on products to be redesigned or on new, well-understood product domains. For original products or to gather the customers' ideas for product improvement, focus groups are best.

The *focus-group* technique was developed in the 1980s to help capture customers' requirements from a carefully chosen group of potential customers. The method begins by identifying seven to ten potential customers and asking if they will attend a meeting to discuss a new product. One member of the design team acts as moderator and another as note taker. It is also best to electronically record the session. The goal in the meeting is to find out what is wanted in a product that does not yet exist, and so it relies on the customers' imaginations. Initial questions about the participants' use of similar products are followed with questions designed to find performance and excitement requirements. The goal of the moderator is to use questions to guide the discussion, not control it. The group should need little intervention from the moderator, because the participants build on each other's comments. One technique that helps elicit useful requirements during interviews is for the moderator to repeatedly ask "Why?" until the customers respond with information in terms of time, cost, or quality. Eliciting good information takes experience, training, and multiple sessions with different participants. Usually the first focus group leads to questions needed for the second group. It often takes as many as six sessions to obtain stable information.

Later in the design process, surveys can be used to gather opinions about the relative merit of different alternatives. Observation and focus groups can be used both to generate ideas that may become alternatives and to evaluate alternatives. All these types of information gathering rely on questions formulated ahead of time. With a survey, the questions and the answers must be formalized. Both surveys and observations usually use closed questions (i.e., questions with predetermined answers); focus groups use open-ended questions.

Regardless of the method used, these steps will help the design team develop useful data:

Step 2.1: Specify the Information Needed Reduce the problem to a single statement describing the information needed. If no single statement represents what is needed, more than one data-collecting effort may be warranted.

Step 2.2: Determine the Type of Data-Collection Method to Be Used Base the use of focus groups, observations, or surveys on the type of information being collected.

Step 2.3: Determine the Content of Individual Questions A clear goal for the results expected from *each question* should be written. Each question should have a single goal. For a focus group or observation, this may not be possible for all questions, but it should be for the initial questions and other key questions.

Step 2.4: Design the Questions Each question should seek information in an unbiased, unambiguous, clear, and brief manner. Key guidelines are

Do not assume the customers have more than common knowledge.
Do not use jargon.
Do not lead the customer toward the answer you want.
Do not tangle two questions together.
Do use complete sentences.

Questions can be in one of four forms:

- Yes–no–don't know. (Poor for focus groups.)
- Ordered choices (1, 2, 3, 4, 5; strongly agree, mildly agree, neither agree nor disagree, mildly disagree, strongly disagree; or A = absolutely important, E = extremely important, I = important, O = ordinary, or U = unimportant [AEIOU]). Be sure that any ordered list is complete (i.e., that it covers the full range possible and that the choices are unambiguously worded). Scales with five gradations, as in the examples here, have proven best.
- Unordered choices (a, b, and/or c).
- Ranking (a is better than b is better than c).

The best questions ask about attributes, not influences. Attributes express what, where, how, or when. *Why* questions should lead to what, where, how, or when as they describe time, quality, and cost.

Step 2.5: Order the Questions Order the questions to give context. This will help participants in focus groups or surveys follow the logic.

Step 2.6: Take Data It usually takes repeated application to generate usable information. The first application of any set of questions should be considered a test or verification experiment.

Step 2.7: Reduce the Data A list of customers' requirements should be made in the customers' own words, such as "easy," "fast," "natural," and other abstract terms. A later step of the design process will be to translate these terms into engineering parameters. The list should be in positive terms—what the customers want, not what they don't want. We are not trying to patch a poor design; we are trying to develop a good one.

To gather information for the aisle chairs, focus groups of passengers were used. These began with a free discussion of people's experiences traveling by air. There is no way that an able-bodied person can understand the challenges of traveling when a wheelchair is involved, and once a group of wheelchair-bound travelers start trading stories, much is learned about what will be needed to make their experience tolerable. It is better that travel should be a "Wow" experience, as discussed in Kano's model (Section 4.4.2) than a "tolerated" experience. A similar focus group was held with agents. Finally, a researcher went to the airport and observed over 20 people boarding and off-loading using wheelchairs.

A sampling of the results of the focus groups and observations are (in no particular order)

- Easy positioning of seat height of the aisle chair so that it matches the wheelchair and the plane's seat so that the passenger can easily slide from on to the other.
- Once in the aisle chair it should be easy to move and stable.
- The aisle chair should fit in all aircraft aisles
- When transferring between chairs, the passenger with possibly some help from the agent must lift their weight enough to slide from chair to chair, so there needs to be a good lifting position for both of them so they can exert minimal effort.
- All want the transfer from seat to seat to be as fast as possible.
- It should be easy to position chairs next to each other and have them not slide apart.

To make sense of these results it is best to organize them into a hierarchical structure. In reviewing the observations it is evident that there are three main phases to the use of the aisle chair: (1) transfer the passenger from their personal wheelchair to the aisle chair, (2) move the aisle chair from the waiting area to the assigned seat, and (3) transfer the passenger from the aisle chair to the assigned seat. The same basic functions have to occur when deplaning. This is a simple form of functional modeling, which will be covered in detail in Chap. 7. Further, the action of transferring to the aisle chair requires two steps, prepare the chair and move the passenger. This decomposition of the function leads to a structure for organizing the results of voice of the customer. This can be organized like an outline (below) and also entered into the QFD as shown in Fig. 6.6.

Transfer from personal to aisle chair

1. Aisle chair preparation

  a. Easy positioning of seat height
  b. Easy to position chairs

2. Passenger movement

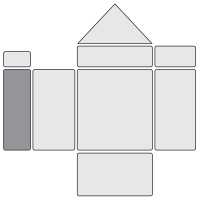
  a. Minimum effort for all
  b. Good lifting position
  c. Minimum time for transfer

Building a hierarchy like this can help you look for completeness. If the structure has discontinuities, these may be indicators of needed information. The aisle chair has only one major function and thus the hierarchy is fairly simple. Products that have multiple uses may have multiple hierarchies.

Suggestions to get the best possible customers' requirements

- #1—Do not assume you know what the customer wants.
- If customer requirements are too vague (e.g., product must be durable), then go back to the customer and flesh these out a little more in the customer's words. What is "durability"? Does that mean you can jump up and down on it? Does it mean that it lasts more than a minute?
- Frequently, customers will try to express their needs in terms of *how* the need can be satisfied and not in terms of *what* the need is. This limits consideration of development alternatives. You should ask *why* until you truly understand what the root need is. Do keep in mind that the only way they may have of expressing what they want is in terms of analogies and comparisons to other products.
- Use Kano's model to help you steer away from basic requirements to performance and excitement requirements.
- Break down general requirements into more specific requirements by probing what is needed.
- Challenge, question, and clarify requirements until they make sense and you can put them in an outline format—a hierarchy. This helps understand function and look for completeness.
- Document situations and circumstances to illustrate a customer need.

6.4 STEP 3: DETERMINE RELATIVE IMPORTANCE OF THE REQUIREMENTS: *WHO VERSUS WHAT*



The next step in the QFD technique is evaluating the importance of each of the customers' requirements. This is accomplished by generating a weighting factor for each requirement and entering it in Fig. 6.6. The weighting will give an idea of how much effort, time, and money to invest in achieving each requirement. Two questions are addressed here: (1) to whom is the requirement important? and (2) how is a measure of importance developed for this diverse group of requirements?

Since a design is "good" only if the customers think it is good, the obvious answer to the first question is, the customer. However, we know that there may be more than one customer. In the case of a piece of production machinery, the desires of the workers who will use the machine and those of management may not be the same. This discrepancy must be resolved at the beginning of the design process or the requirements may change partway through the job. Sometimes a designer's hardest job is determining whom to please.

The region of the house of quality labeled "who vs. what" in Fig. 6.3 is for the input of the importance of each requirement. It is essential to understand which requirements each type of customer thinks is important. Note that, in most cases, less than half of the requirements have most of the importance. The best way to represent importance is with a number showing its *weight* relative to the other requirements.

Traditionally, weighting has been done by instructing the customers to rate the requirements on a scale of 1 to 10 with 10 being important and 1 being unimportant. Unfortunately, often these methods result in everything being scored 8, 9, or 10—everything is important.

A better method, the fixed sum method, is to tell each customer that they have 100 points to distribute among the requirements. Using the fixed sum of 100 forces the customer to rate some of the requirements low if they want others to be high. This method works much better than just telling them to rate requirements on a scale of 1 to 10.

To aid in weighting, write each requirement on a piece of self-stick note paper, put the notes on a wall, and ask each customer to arrange them in order of importance. If two or more requirements seem to be equally important, be sure that they don't measure the same thing, that they are independent. Once the notes are in order, allocating the 100 points should be easier.

If there are more than 30 requirements, allocating weights can be very difficult. It is suggested that the large group of requirements be broken into smaller groups using the hierarchy, weighting each, and then renormalizing across all the requirements.

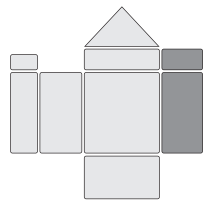
If you collect weightings from more than one representative of a customer group and they are in fairly good agreement with each other, then just average them. If weightings are significantly different from each other, then this is a signal that you have two different types of customers and you need to revisit the step 1.

The results of weighting the requirements for the aisle chair are shown in Fig. 6.6 for the passenger and the agent. The fixed sum method was used to set the weights. Note that the requirement "Fits in aircraft aisle" was not weighted. It was realized that this was a basic requirement (in Kano's terminology) as an

> One man's treasure is another's trash.
> Both will judge your work.

aisle chair that does not fit in the aisle is not a viable product. Requirements that measure basic needs are not helpful. Before you eliminate them, however, go back and ask if the requirement can be reworded so that it addresses performance or excitement. Also note that the passenger is more concerned about ease of use and the agent more focused on time. This is as expected.

6.5 STEP 4: IDENTIFY AND EVALUATE THE COMPETITION: HOW SATISFIED ARE THE CUSTOMERS *NOW*?



The goal here is to determine how the customer perceives the competition's ability to meet each of the requirements. Even though you may be working with a totally new design, there is competition, or at least products that come close to filling the same need that your product does. The purpose for studying existing products is twofold: first, it creates an awareness of what already exists (the "now"), and second, it reveals opportunities to improve on what already exists. In some companies, this process is called *competition benchmarking* and is a major aspect of understanding a design problem. In benchmarking, each competing product must be compared with customers' requirements (now versus what). Here we are concerned only with a subjective comparison that is based on customer opinion. Later, in step 8, we will do a more objective comparison. For each customer's requirement, we rate the existing design on a scale of 1 to 5:

1. The product does not meet the requirement at all.
2. The product meets the requirement slightly.
3. The product meets the requirement somewhat.
4. The product meets the requirement mostly.
5. The product fulfills the requirement completely.

Though these are not very refined ratings, they do give an indication of how the competition is perceived by the customer.

This step is very important as it shows opportunities for product improvement. If all the competition rank low on one requirement, this is clearly an opportunity. This is especially so if the customers ranked that specific requirement highly important in step 3. If one of the competitors meets the requirement completely, this product should be studied and good ideas used from it (note patent implications as discussed in Section 7.5).

If your organization already makes a product and you are redesigning this product, then the current product is one benchmark. If it ranks high on an important requirement, don't change the features that helped it meet that requirement. In

> To steal from one person is plagiarism, to be influenced by many is good design.

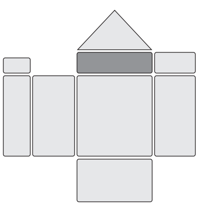
other words—Don't fix what aint broken! This step in the QFD method can help avoid needless work and product weakening.

The results of this step for the aisle chair are shown in Fig. 6.6. Here two competitor's chairs were evaluated (note that names have been changed). To determine how well the competitors met the requirements, the design team used questionnaires to evaluate them. The average results from passengers are shown in the "now vs. what" section of Fig. 6.6.

Important points to note are that

1. Both competitors have good lifting position when transferring the passenger from the personal chair to the aisle chair—study what makes this work well.
2. Both products have poor stability. Clearly, this is a market opportunity.
3. The Colub is easy to move and Delton is not, need to determine why and do what Colub does or better.
4. For most of adjustment requirements, neither of the competitors score above 3, leaving room for the development of a superior product in these areas.

There used to be a commercial on television for a family van in which the manufacturer bragged that its product was so good that one of its competitors bought and studied it. The commercial showed the competitor's technicians in white coats disassembling the van. What the commercial did not say was that the advertiser also bought and studied its competitor's product and that this is just good design practice.



6.6 STEP 5: GENERATE ENGINEERING SPECIFICATIONS: *HOW* WILL THE CUSTOMERS' REQUIREMENTS BE MET?

The goal here is to develop a set of *engineering specifications* from the customers' requirements. These specifications are the restatement of the design problem in terms of parameters that can be measured and have target values. Without such information the engineers cannot know if the system being developed will satisfy the customers. Engineering specifications consist of parameters of interest and targets for parameters. The parameters are developed in this step, and the target values for them are developed in step 8. In reality this step and the following one happen concurrently as will be made clear.

These specifications are a translation of the voice of the customer into the voice of the engineer. They serve as a vision of the ideal product and are used as criteria for design decisions. Conversely, this part of the QFD also builds a picture

> Find the target before you empty your quiver.

of how design decisions affect the customer's perception of the quality of their product. We will make use of this in Chap. 10, where the effect of trading off the ability to meet one specification for the inability to meet another is addressed.

In this step, we develop parameters that tell *how* we know if customers' requirements have been met. We begin by finding as many engineering parameters as possible that indicate a level of achievement for customers' requirements. For example, a requirement for "easy to attach" can be measured by (1) the number of steps needed to attach it, (2) the time to attach it, (3) the number of parts, and (4) the number of standard tools used. Note that a set of units is associated with each of these measures—step count, time, part count, and tool count. *If units for an engineering parameter cannot be found, the parameter is not measurable and must be readdressed.* Each engineering parameter must be measurable and thus must have units of measure. However, "time to attach" may not be a reliable measure as it will be dependent on the skill and training of the customer. Either the customer's skill level needs to be defined or this parameter eliminated.

An important point here is that every effort must be made to find as many ways as possible to measure customers' requirements. If there are no measurable engineering parameters for customers' requirements, then the customer's requirement is not well understood. Possible solutions are to break the requirement into finer independent parts or to redo step 2 with specific attention to that specific requirement.

When developing the engineering specifications, carefully check each entry to see what nouns or noun phrases have been used. Each noun refers to an object that is part of the product or its environment and should be considered to see if new objects are being assumed. For example, if one specification in the aisle chair problem was for "easy to adjust seat height" then an adjustable seat height (a noun phrase) has been assumed as part of the solution. If the design team has made a decision that there is to be an adjustable seat height, this is acceptable. However, if no such assumption has been made, the product solution has been unknowingly limited. Paying attention to the objects that are part of the product is a major topic in concept generation.

Also shown on Fig. 6.6 are the units for each specification and the direction of improvement—the "sense" where either more is better (↑) or less is better (↓). These arrows tell whether more of the feature or parameter measured good, or bad. For example less "force required for agent" is good (↓). More "side tipping force" is desired (↑). A third option, not shown in the example is whether a specific target is best. Targets will be further discussed in step 7.

To help find specifications a checklist of the major types is given in Table 6.1. Comparing this list with the list of specifications developed for a product can reveal missing information. The major types of specifications in this list are detailed next.

Table 6.1 Types of engineering specifications

Functional performance	Life-cycle concerns (continued)
Flow of energy	Diagnosability
Flow of information	Testability
Flow of materials	Reparability
Operational steps	Cleanability
Operation sequence	Installability
Human factors	Retirement
Appearance	Resource concerns
Force and motion control	Time
Ease of controlling and sensing state	Cost
Physical requirements	Capital
Physical properties	Unit
Available spatial envelope	Equipment
Reliability	Standards
Mean time between failures	Environment
Safety (hazard assessment)	Manufacturing/assembly requirements
Life-cycle concerns	Materials
Distribution (shipping)	Quantity
Maintainability	Company capabilities

Functional performance requirements are those elements of the performance that describe the product's desired behavior. Although the customers may not use technical terms, function is usually described as the flow of energy, information, and materials or as information about the operational steps and their sequence. In Chap. 7 we develop concepts by building a functional model, based on the flow of energy, information, and materials. We will see that *developing functional requirements with the QFD and building a functional model of the product are often iterative.* The more the function is understood, the more complete are the requirements that can be developed.

Any product that is seen, touched, heard, tasted, smelled, or controlled by a human will have *human factors requirements* (see App. D for details on human factors). This includes nearly every product. One frequent customers' requirement is that the product "looks good" or looks as if it has a certain function. These are areas in which a team member with knowledge about industrial design is essential. Other requirements focus on the flow of energy and information between the product and the human. Energy flow is usually in terms of force and motion, but can take other forms as well. Information flow requirements apply to the ease of controlling and sensing the state of the product. Thus, human factors requirements are often functional performance requirements.

Physical requirements include needed physical properties and spatial restrictions. Some physical properties often used as requirements are weight; density; and conductivity of light, heat, or electricity (i.e., flow of energy). Spatial constraints relate how the product fits with other, existing objects. Almost all new design efforts are greatly affected by the physical interface with other objects that cannot be changed.

In the *Time* magazine survey on quality quoted in Chap. 1, the second most important consumer concern was “Lasts a long time,” or the product’s *reliability.* It is important to understand what acceptable reliability means to the customer. The product may only have to work once with near-absolute certainty (e.g., a rocket), or it may be a disposable product that does not need much reliability. As discussed in Chap. 11, one measure of reliability is the *mean time between failures.*

A part of reliability involves the questions, what happens when the product does fail? and, what are the *safety* implications? Product safety and hazard assessment are very important to the understanding of the product, and they are covered in Chap. 8.

An often overlooked class of requirements is the class of those relating the product life cycle other than product use. All specification types listed in Table 6.1 were taken from life cycle phases in Fig. 1.7. In designing the first BikeE, one of the design requirements set by sales/marketing was that the bicycle had to be shipped by a commercial parcel service. Such services have weight and size limits, which greatly affected the design of the product. If the advantages of distributing the product by commercial parcel service had not been realized early, extensive redesign might have been necessary. The same applies to the other life-cycle phases listed in Table 6.1 and Fig. 1.7.

A limited resource on every design project is time. *Time requirements* may come from the consumer; more often they originate in the market or in manufacturing needs. In some markets there are built-in time constraints. For example, toys must be ready for the summer buyer shows so that Christmas orders can be taken; new automobile models traditionally appear in the fall. Contracts with other companies might also determine time constraints. Even for a company without an annual or contractual commitment, time requirements are important. As discussed earlier, in the 1960s and 1970s Xerox dominated the copier market, but by 1980 its position had been eroded by domestic and Japanese competition. Xerox discovered that one of the problems was that it took it twice as long as some of its competitors to get a product to market, and Xerox put new time requirements on its engineers. Fortunately, Xerox helped its engineers work smarter, not just faster, by introducing techniques similar to those we talk about here.

Cost requirements concern both the capital costs and the costs per unit of production. Included in capital costs are expenditures for the design of the product. For a Ford automobile, design costs make up 5% of the manufacturing cost (Fig. 1.2). Many product ideas never get very far in development because the initial requirements for capital are more than the funds available. (Cost estimating will be covered in detail in Section 11.2.)

Standards spell out current engineering practice in common design situations. The term *code* is often used interchangeably with *standard.* Some standards serve as good sources of information. Other standards are legally binding and must be adhered to—for example, the ASME pressure vessel codes. Although the actual information contained in standards does not enter into the design process in this early phase, knowledge of which standards apply to the current situation are important to requirements and must be noted from the beginning of the project.

Standards that are important to design projects generally fall into three categories: performance, test methods, and codes of practice. There are *performance standards* for many products, such as seat-belt strength, crash-helmet durability, and tape-recorder speeds. The *Product Standards Index* lists U.S. standards that apply to various products; most of those referenced are also covered by ANSI (American National Standards Institute), which does not write standards but is a clearinghouse for standards written by other organizations.

Test method standards for measuring properties such as hardness, strength, and impact toughness are common in mechanical engineering. Many of these are developed and maintained by the American Society for Testing and Materials (ASTM), an organization that publishes over 4000 individual standards covering the properties of materials, specifying equipment to test the properties, and outlining the procedures for testing. Another set of testing standards that are important to product design are those developed by the Underwriters Laboratories (UL). This organization's standards are intended to prevent loss of life and property from fire, crime, and casualty. There are over 350 UL standards. Products that have been tested by UL and have met their standards can display the words "Listed UL" and the standard number. The company developing the product must pay for this testing. Consumer products are usually not marketed without UL listing because the liability risk is too high without this proof of safe design.

Codes of practice give parameterized design methods for standard mechanical components, such as pressure vessels, welds, elevators, piping, and heat exchangers.

It is important for the design team to ensure that requirements imposed by *environmental concerns* have been identified. Since the design process must consider the entire life cycle of the product, it is the design engineer's responsibility to establish the impact of the product on the environment during production, operation, and retirement. Thus, requirements for the disposal of wastes produced during manufacture (whether hazardous or not), as well as for the final disposition of the product, are the concern of the design engineer. This topic is further discussed in Chap. 11.

Some of the *manufacturing/assembly requirements* are dictated by the quantity of the design to be produced and the characteristics of the company producing it. The quantity to be produced often affects the kind of manufacturing processes to be used. If only one unit is to be produced, then custom tooling cannot be amortized across a number of items and off-the-shelf components should be selected when possible (see Chap. 9). Additionally, every company has internal manufacturing resources whose use is preferable to contracting work outside the company. Such factors must be considered from the very beginning.

Guidelines for good specifications are

1. Each specification should measure at least one customers' requirement at the strong relationship level (see step 7). Ideally, each specification should

measure multiple requirements. If you have a diagonal of scores in step 7, you need to revisit the specifications.

2. Each specification should be measurable. Every specification should be written as if you were going to give instructions to someone to go down to the lab and measure something. It should be clear what they are going to measure. For example, the specification "Fore/aft tipping force" is a good title for a specification, but to be measurable it needs many more words. Thus, it is suggested that for each specification list, a full description of how to measure it also be developed. For example:

> Fore aft tipping force = The force needed at the push handles to tip over the aisle chair when moving forward at 1 km/hr with 78.5-kg passenger (a 50% male, see App. D).

If a good statement like this cannot be developed, then the specification is not clear and needs to be reworked.

3. If the units are not clear, the specification is not clear.

4. If the sense (↑ or ↓) is not obvious, then the specification is not clear.

5. If you need to measure something like "looks good" try transforming it into a testable measure such as "High score on 5-point attractiveness scale by >65% of passengers." This means that you set up a 5-point attractiveness scale (units = "points") such as 1 = ugly, 2 = tolerable, 3 = acceptable, 4 = attractive, 5 = captivating. Obviously the sense is (↑). And the target (to be set in Step 7 will be ≥ 4).

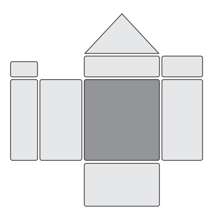
Specifications for the aisle chair are shown in Fig. 6.6. Some comments about them in light of the guidelines are

1. The first specification "seat width relative to frame width" is not clear. What is to be measured here?

2. Two points about specifications that are in terms of "number of steps": (1) steps are better than time as time varies from individual to individual, and (2) you need to clearly define what a step is. A good guide for determining steps is in Section 11.5.

3. "Seat size" is not clear. What exactly needs to be measured?

6.7 STEP 6: RELATE CUSTOMERS' REQUIREMENTS TO ENGINEERING SPECIFICATIONS: *HOW* TO MEASURE *WHAT?*



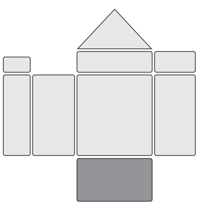
To complete this step, we fill in the center portion of the house of quality. This relationship matrix is completed in parallel to Step 5, and it yields additional knowledge. Each cell of the form represents how an engineering specification relates to a customer's requirement. Many specifications will measure more than one customer's requirement. The strength of this relationship can vary, with some engineering specifications, providing strong measures for a customer's requirement and others providing no measure at all. The relation is conveyed through specific symbols or numbers:

◉ = 9 = strong relationship
◯ = 3 = medium relationship
△ = 1 = weak relationship
Blank = 0 = no relationship at all

The 0-1-3-9 values are used to reflect the dominance of strong relationships. The symbols are used in the example (Fig. 6.6) and the number is used in the math that follows for the aisle chair.

Some guidelines for this step are as follows:

- Each customer's requirement should have at least one specification with a strong relationship.
- There is the temptation to make this a diagonal matrix of ◉s or 9s—one engineering specification for each customer requirement. This is a weak use of the method. Ideally, each specification should measure more than one customer requirement.
- If a customer's requirement has only weak or medium relationships (see "Fits in aircraft aisle" or "good lifting position"), then it is not well understood or the specification has not been well thought through. It is evident what is meant by "fits in aircraft aisle." The specification needs work. It is not so evident what "good lifting position" means and thus the customer's requirement needs more effort.



6.8 STEP 7: SET ENGINEERING SPECIFICATION TARGETS AND IMPORTANCE: *HOW MUCH IS GOOD ENOUGH?*

In this step we fill in the basement of the house of quality. Here we set the targets and establish how important it is to meet each of them. There are three parts to this effort, as shown in Fig. 6.6, calculate the specification importance, measure how well the competition meets the specification, and develop targets for your effort.

6.8.1 Specification Importance

The first goal in this step is determining the importance for each specification. If a target is important, then effort needs to be expended to meet the target. If it is not important, then meeting the goal can be more easily relaxed. In the development of products, it is seldom that all targets can be met in the time available and so this effort helps guide what to work on. The method to find importance is as follows:

Step 2.1: For each customer multiply the importance weighting from step 3 with the 0-1-3-9 relationship values from step 6 to get the weighted values.

Step 2.2: Sum the weighted values for each specification. For specification "steps to adjust seat height" in Fig. 6.6, the passenger score is:

$4*9+6*0+15*0+10*0+3*1+7*0+24*0+6*0+5*9+15*3+5*1 = 134.$

Step 2.3: Normalize these sums across all specifications. The sum across all the specifications is 1475 so this specification has importance of 134/1475 = 9%.

Figure 6.6 shows the importance from both the passengers' and agents' viewpoints. Note that for the passenger specifications revolving around moving from their chair to the aisle chair are most important. From the agents' viewpoint both these specifications and time measures are important.

6.8.2 Measuring How Well the Competition Meets the Specifications

In step 4, the competitions' products were compared to customers' requirements. In this step, they will be measured relative to engineering specifications. This ensures that both knowledge and equipment exist for evaluation of any new products developed in the project. Also, the values obtained by measuring the competition give a basis for establishing the targets. This usually means obtaining actual samples of the competition's product and making measurements on them in the same way that measurements will be made on the product being designed. Sometimes this is not possible and literature or simulations are used to find values needed here.

The competition values are shown in Fig. 6.6.

6.8.3 Setting Specification Targets

Setting targets early in the design process is important; targets set near the end of the process are easy to meet but have no meaning as they always match what has been designed. However, setting targets too tightly may eliminate new ideas. Some companies refine their targets throughout concept development and then make them firm. The initial targets, set here, may have ±30% tolerance on them.

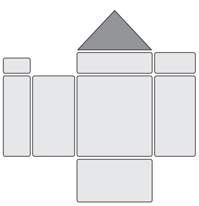
Most texts on QFD suggest that a single value be set as a target. However, once the design process is underway, often it is not possible to meet these exact values. In fact, a major part of engineering design is making decisions about how to manage targets and the tradeoff meeting them. There are two points to be made here. To make them, we will use a simple example.

Say you want to buy a new camera. You want to spend less than $300 and want at least 7.2 megapixels (your only two specifications). You look online and find a camera with the resolution you want, but it costs $305. Will you buy it? Probably. What if it costs $315?—maybe. What about $400?—probably not. The point here is that most targets are flexible and they may not be met during design. This is not true of all targets. You definitely need to achieve a velocity of 7 m/sec to escape the Earth's gravitational pull. You cannot say 6.5 is good enough. For those targets that have flexibility, a more robust method for setting targets is to establish the levels at which the customers will be delighted and those where they will be disgusted. The delighted value is the actual target and the disgusted is the threshold beyond which the product is unacceptable. For the camera example, the target cost (delighted) is at $300 and the threshold (disgusted) between $315 and $400, say $350. For the resolution, delighted may be 7.2 megapixels and disgusted 6.3 megapixels. Note that for cost, less is better and for resolution, more is better.

A second point is that, as a design engineer you often have to trade off one specification against another. Continuing with the camera example, say there are two cameras available, one has 6.3 megapixels and costs $305 and the other 7.2 megapixels and costs $330. The question is, how much am I willing to trade off cost for resolution? If the targets were single valued, $300 and 7.2 megapixels, then neither camera meets the targets. But, by setting the two targets, delighted and disgusted, you can better judge which camera is best.

A final comment on target setting is that if a target is much different than the values achieved by the competition, it should be questioned. Specifically, what do you know that the competition does not know? Do you have a new technology, do you know of new concepts, or are you just smarter than your competition? What is possible should fall in the range of the delighted and disgusted targets.

Figure 6.6 shows values for the aisle chair delighted and disgusted targets.



6.9 STEP 8: IDENTIFY RELATIONSHIPS BETWEEN ENGINEERING SPECIFICATIONS: HOW ARE THE *HOWS* DEPENDENT ON EACH OTHER?

Engineering specifications may be dependent on each other. It is best to realize these dependencies early in the design process. Thus, the roof is added to show that as you work to meet one specification, you may be having a positive or negative affect on others.

In Fig. 6.6, the roof for the aisle chair QFD shows diagonal lines connecting the engineering specifications. If two specifications are dependent, a symbol is noted in the intersection. There are many different styles of symbols used. One is to use the same symbols as in Step 6. The simplest method is to use a "+" to denote that improvement in meeting one of the specifications will improve the other (they are synergistic), and to use a "–" to show that improvement in meeting one may harm the other (a compromise may be forced). Some people use ++ and −− to show a strong dependency.

In building a house of quality on a spreadsheet, a good way to simulate the roof is as shown in Fig. 6.7. Here the specifications are listed in both the

Seat width relative to frame width	Steps to adjust seat height	Force to adjust seat height	Force to slide 95% male passenger	Lifting force required by agent	Push force over 2cm bump	Force to push aisle chair	Time to transfer between seats	Fore/aft tipping force at handles	Side tipping force at handles	
									■	Side tipping force at handles
								■	+	Fore/aft tipping force at handles
							■			Time to transfer between seats
						■				Force to push aisle chair
					■	+				Push force over 2cm bump
				■						Lifting force required by agent
			■	??			–			Force to slide 95% male passenger
		■								Force to adjust seat height
	■	–					–			Steps to adjust seat height
■										Seat width relative to frame width
cm	#	kg	kg	kg	cm	kg	sec	kg	kg	
↓	↑	↓	↓	↓	↑	↓	↓	↓	↓	

Figure 6.7 Alternative QFD roof for a spreadsheet.

columns and rows and a diagonal matrix used to show the relationships also shown in Fig. 6.6.

Some guidelines for building the roof are

- In the ideal world, all the specifications are independent. However, the reality is that sometimes when you improve one thing, you either improve or hurt something else. These relationships give guidance about trade-offs.
- If the roof has many of the cells full, then the specifications are too dependent and should be revisited.
- If the relationship is not clear, then at least one of the specifications is not clear. This is the case with the relationship between "force required

for the passenger to slide" and "force required by the agent." The lack of clarity is caused by a poor understanding of exactly what force the agent is applying.

6.10 FURTHER COMMENTS ON QFD

The QFD technique ensures that the problem is well understood. It is useful with all types of design problems and results in a clear set of customers' requirements and associated engineering measures. It may appear to slow the design process, but in actuality it does not, as time spent developing information now is returned in time saved later in the process.

Even though this technique is presented as a method for understanding the design requirements, it forces such in-depth thinking about the problem that many good design solutions develop from it. No matter how hard we try to stay focused on the requirements for the product, product concepts are invariably generated. This is one situation when a design notebook is important. Ideas recorded as brief notes or sketches during the problem understanding phase may be useful later; however, it is important not to lose sight of the goals of the technique and drift off to one favorite design idea.

The QFD technique automatically documents this phase of the design process. Diagrams like those in Figs. 6.5 and 6.6 serve as a design record and also make an excellent communication tool. Specifically, the structure of the house of quality makes explaining this phase to others very easy. In one project, a member of the sponsoring organization was blind. A verbal description of the structure helped him understand the project and recommend the QFD method to other sighted colleagues.

Often, when working to understand and develop a clear set of requirements for the problem, the design team will realize that the problem can be decomposed into a set of loosely related subproblems, each of which may be treated as an individual design problem. Thus, a number of independent houses may be developed.

The QFD technique can also be applied during later phases of the design process. Instead of developing customers' requirements, we may use it to develop a better measure for functions, assemblies, or components in terms of cost, failure modes, or other characteristics. To accomplish this, review the steps, replacing customers' requirements with what is to be measured and engineering requirements with any other measuring criteria.

Although QFD seems to imply a waterfall-type development plan, much learning occurs during the design process. The QFD is considered a working document that is reviewed and updated as needed. Thus, it also is important for spirally developed products. The formality and complexity of the technique forces any change to be carefully considered and thus keeps the project moving toward completion. Without a system like QFD, changes in specifications can occur at the whim of a manager or without the design team even realizing it. These changes will lead to a failure to meet the schedule and a potentially poor product.

6.11 SUMMARY

- Understanding the design problem is best accomplished through a technique called Quality Function Deployment (QFD). This method transforms customers' requirements into targets for measurable engineering requirements.
- Important information to be developed at the beginning of the problem includes customers' requirements, competition benchmarks, and engineering specifications complete with measurable benchmarks.
- Time spent completing the QFD is more than recovered later in the design process.
- There are many customers for most design problems.
- Studying the competition during problem understanding gives valuable insight into market opportunities and reasonable targets.

6.12 SOURCES

ANSI standards are available at www.ansi.org

ASTM standards are available at www.astm.org

Cristiano, J. J., J. K. Liker, and C. C. White: "An Investigation into Quality Function Deployment (QFD) Usage in the U.S.," in *Transactions for the 7th Symposium on Quality Function Deployment,* June 1995, American Supplier Institute, Detroit. Statistics on QFD usage were taken from the study in this paper.

Hauser, J. R., and D. Clausing: "The House of Quality," *Harvard Business Review,* May–June 1988, pp. 63–73. A basic paper on the QFD technique.

Index of Federal Specifications and Standards, U.S. Government Printing Office, Washington, D.C. A sourcebook for federal standards.

Krueger, R. A.: *Focus Groups: A Practical Guide for Applied Research,* Sage Publishing, Newbury Park, Calif. 1988. A small book with direct help for getting good information from focus groups.

Roberts, V. L.: *Products Standards Index,* Pergamon, New York, 1986. A sourcebook for standards.

Salant, P., and D. Dillman: *How to Conduct Your Own Survey,* John Wiley & Sons, New York, 1994. A very complete book on how to do surveys to collect opinions.

Software packages

QFD/CAPTURE, http://www.qfdcapture.com/default.asp

QFD Designer, IDEACore, http://www.ideacore.com/v1/Products/QFDDesigner/

Templates for Excel are at http://www.qfdonline.com/templates/

6.13 EXERCISES

6.1 For a design problem (Exercise 4.1), develop a house of quality and supporting information for it. This must include the results of each step developed in this chapter. Make sure you have at least three types of customers and three benchmarks. Also, make a list of the ideas for your product that were generated during this exercise.

6.2 For the features of the redesign problem (Exercise 4.2) to be changed, develop a QFD matrix to assist in developing the engineering specifications. Use the current design as a benchmark. Are there other benchmarks? Be careful to identify the features needing change before spending too much time on this. The methods in Chap. 7 can be used iteratively to help refine the problem.

6.3 Develop a house of quality for these objects.

- **a.** The controls on an electric mixer.
- **b.** A seat for an all-terrain bicycle.
- **c.** An attachment for electric drills to cut equilateral-triangle holes in wood. The wood can be up to 50 mm thick, and the holes must be adjustable from 20 mm to 60 mm per side.
- **d.** A tamper-proof fastener as used in public toilet facilities.

6.14 ON THE WEB

A template for the following document is available on the book's website: www.mhhe.com/Ullman4e

- Voice of the Customer