THE MECHANICAL DESIGN PROCESS

SECOND EDITION

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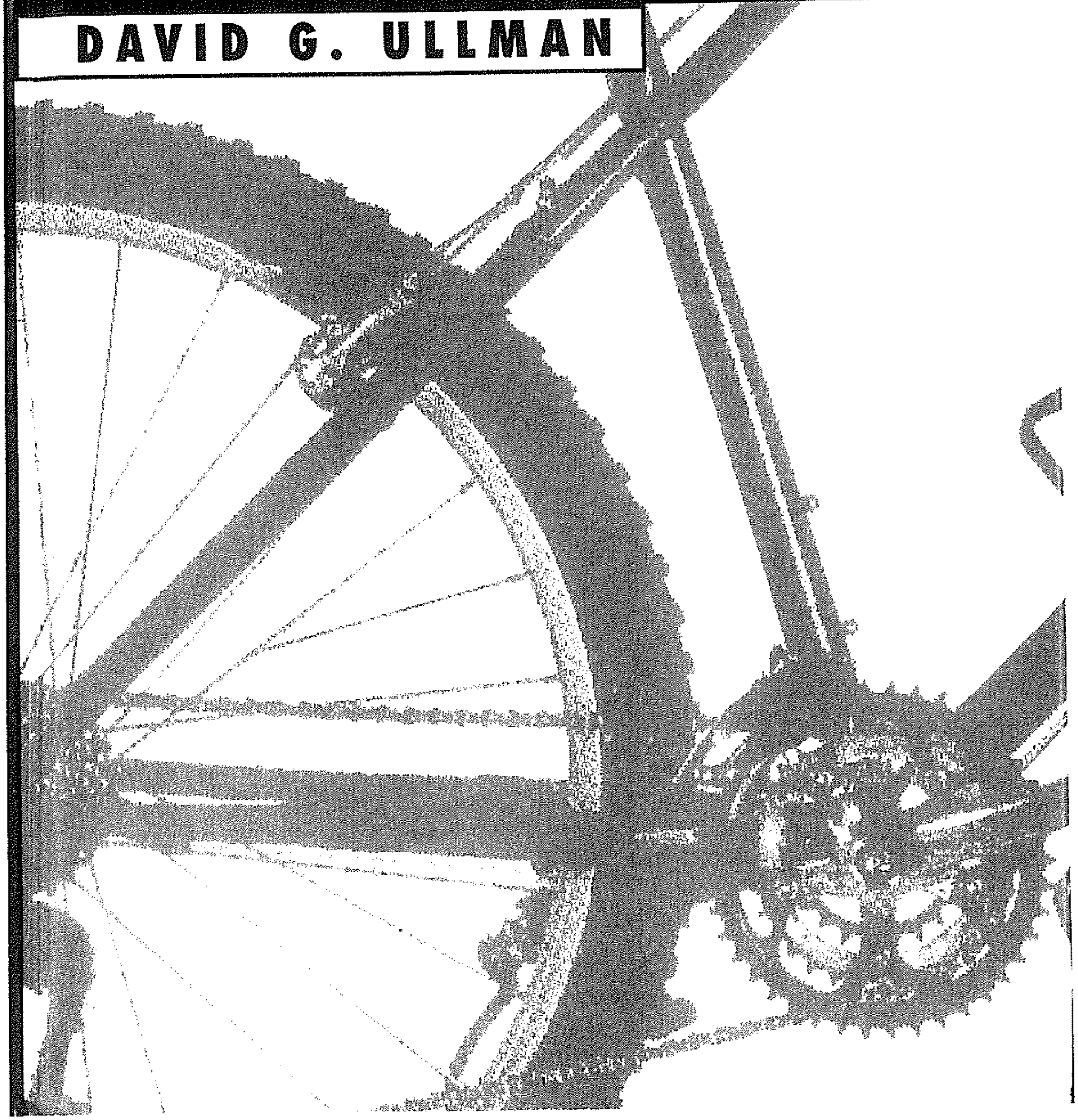

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CHAPTER 1

WHY STUDY THE DESIGN PROCESS?

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 with communication and for structure to ensure that nothing important is overlooked. 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 we will study here that determines the efficiency of new product development. Finally, it has been estimated that 85 percent 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.

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

The three measures of the effectiveness of the design process are cost, quality, and time. Regardless of the product being designed—whether it is an entire system or some small subpart of a larger product—the customer and management always want it cheaper, better, and faster.

The actual cost of design is usually a small part of the manufacturing cost of a product, as can be seen in Fig. 1.1, which is based on data from Ford Motor Company. The data shows that only 5 percent 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.

The effect of the quality of the design on the manufacturing cost is much greater than 5 percent. This is most accurately shown from the results of a detailed study of 18 different automatic coffeemakers. The results of this study are shown in Table 1.1. 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 design quality—the results of the design process. Note that manufacturing efficiency and design quality have the same influence on the cost of manufacturing a product. The results of the design process can change the cost of manufacturing a product by 50 percent (±25 percent for an average manufacturing process) or more. Xerox also attributes 50 percent of the final cost to the results of the design process. In some industries this effect is as high as 75 percent. Thus it can be concluded 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 purchased, the parts, the shape of those parts, the product sold, and, in the end, the scope of management.

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 percent less than American or European firms. Xerox attributed the cost difference to three factors: materials costs were 10 percent less in Japan, tooling and processing costs were 15 percent less, and the remaining 25 percent (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. 1.2, 75 percent of the

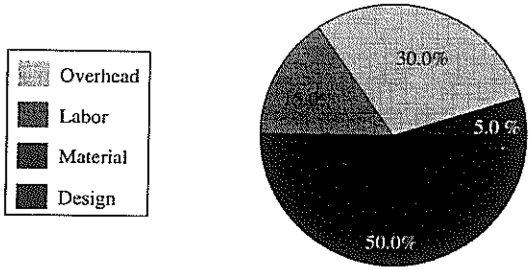

FIGURE 1.1
Design cost as fraction of manufacturing cost.

TABLE 1.1
The effect of design quality on manufacturing cost

	Efficient manufacturing	Average manufacturing	Poor manufacturing
A good design	$.50	$ .75	$ .94
An average design	$.75	$1.00	$1.25
A poor design	$.94	$1.25	$1.50

Data reduced from "Does Product Design Really Determine 80% of Manufacturing Cost?" by K. T. Ulrich and S. A. Pearson, working paper 3601-93, Sloan School of Management, 1993.

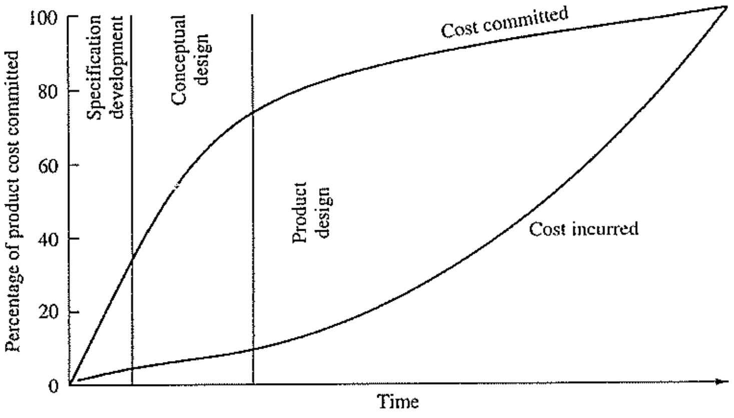

FIGURE 1.2
Manufacturing cost commitment during design.

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 percent 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. 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. It is clear that *quality cannot be built into a product unless it is designed into it.* In a survey taken in 1989, American consumers were asked, "What determines quality?" Their responses, shown in Table 1.2, indicate that "quality" is a composite of factors that are the responsibility of the design engineer. Thus the decisions made during the design process determine the product's quality as perceived by the customers.

Another indicator of quality comes from another Xerox study. This one focused on "line fallout," a measure of the number of components that do not fit together during assembly—the components that literally "fall out" of the assembly line. If it is assumed that a company uses quality-control techniques (for example, measuring a component's geometry and/or other properties during production) to ensure that the components meet the production specifications, and it is further assumed that components that reach the assembly line are within the design specifications, then components that do not fit are poorly designed. These design failures must be either scrapped or reworked; either choice adds costs in the manufacturing process.

The results of Xerox's line fallout study are shown in Fig. 1.3. In the first year it took data, 1981, Xerox had 30 times the line fallout of its Japanese competitors, who had 1 component per 1000. It restructured its design process (in ways similar to those that will be presented in this book), and by 1989 it had reduced its line fallout by a factor of 30. Xerox's ultimate goal, 125 parts per million (0.125 per thousand) was reached in the early 1990s. Xerox now uses a measure that, besides line fallout, includes defective parts identified in the supplier's preshipping inspection, in Xerox's incoming inspection, and in warehouse inspection.

Besides affecting cost and quality, the design process also affects the time it takes to produce a new product. Consider Fig. 1.4, which shows the number of design changes made by two automobile companies with different design philosophies. As shown in this book, 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. The curve for Company B indicates that the company was still making changes after the design had been released for 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.

TABLE 1.2
Results of a consumer survey on product quality: What determines quality?

	Essential	Not essential	Not sure
Works as it should	98	1	1
Lasts a long time	95	3	2
Is easy to maintain	93	6	1
Looks attractive	58	39	3
Incorporates latest technology	57	39	4
Has many features	48	47	5

Based on a survey published in *Time*, Nov. 13, 1989.

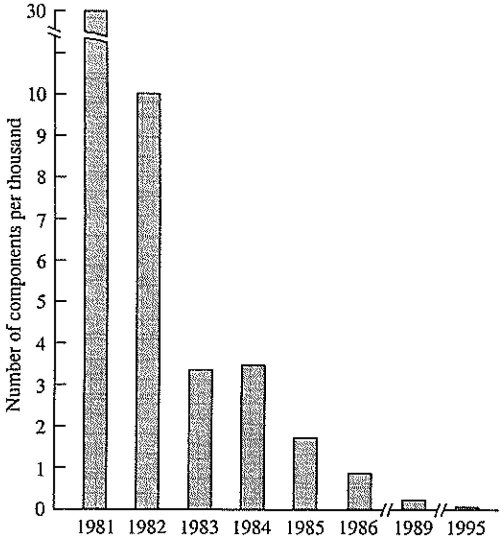

FIGURE 1.3
Line fallout at Xerox.

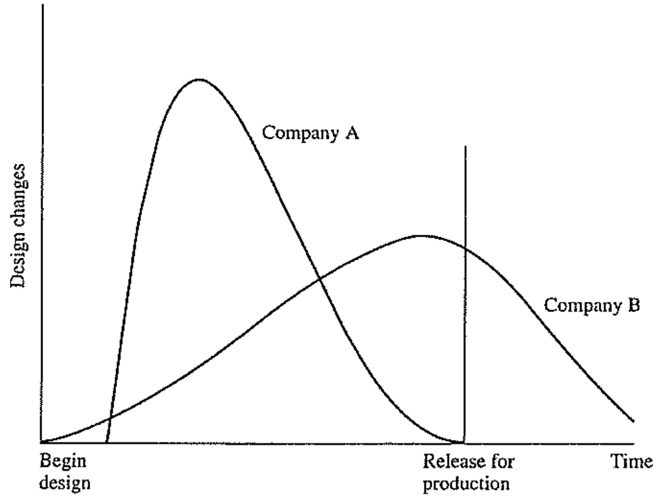

FIGURE 1.4
Engineering changes during automobile development.

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

Figure 1.4 also indicates that Company A made more changes than Company B. This implies that it explored more design alternatives, which at least partially explains why modifications were not still being made at the end of the project. Additionally, Company A took less time to design the automobile than Company B. All these differences are 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 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 curves of Fig. 1.4 are actual representations of the design philosophies of a Japanese company (A) and an American company (B) in the early 1980s. During this period the time to design a car in the United States was a little over five years from the presentation of the initial problem to the production of the final product. For the Japanese the same activities took three and one-half years, and the product was perceived to be so superior to the American that the United States imposed import quotas on Japanese cars in the 1980s. However, American car manufacturers responded to the challenge like Xerox. They instituted better design practices and improved the quality of their products.

Here is one last example from Xerox. In the 1970s it took Xerox about three years to progress from establishing the need for a new product to bringing that item to production. By 1990 Xerox had reduced that process to less than two years, and by 1995, to less than 30 weeks. Xerox's goal is to halve that yet again.

Caterpillar, the manufacturer of heavy equipment, reduced its 50-month 1980 development cycle to 20 months in 1993. Xerox's and Caterpillar's reductions are typical of the performance of most companies in competitive environments.

For many years it was believed that there was a trade-off between high-quality products and low development and manufacturing costs—namely, that it cost more to develop and produce high-quality products. However, recent experience has shown that increasing quality and lowering costs can go hand in hand. Some of the above examples 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. 1.5).

In the structure shown in Fig 1.5, 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." 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

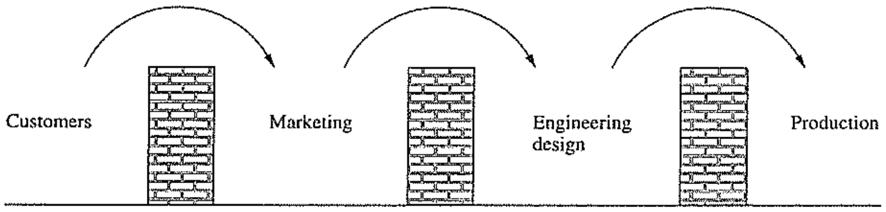

FIGURE 1.5
The over-the-wall design method.

TABLE 1.3
The nine key features of concurrent engineering

Focus on the entire product life (Chap. 1)
Use and support of design teams (Chaps. 3 and 5)
Realization that the processes are as important as the product (Chaps. 4 and 5)
Attention to planning for information-centered tasks (Chap. 5)
Careful product requirements development (Chap. 6)
Encouragement of multiple concept generation and evaluation (Chaps. 7 and 8)
Attention to designing in quality during every phase of the design process (throughout)
Concurrent development of product and manufacturing process (Chaps. 9–13)
Emphasis on communication of the right information to the right people at the right time (throughout)

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* or *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.

Concurrent engineering is built around a concern for the nine key features listed in Table 1.3. These nine are covered in the chapters shown and are integrated into the concurrent engineering method as shown in Fig. 1.6. This figure looks much different from the over-the-wall method in Fig. 1.5. In concurrent engineering the primary focus is on the integration of teams of people having a stake in the product, design tools and techniques, and information about the product and the processes used to develop and manufacture it.

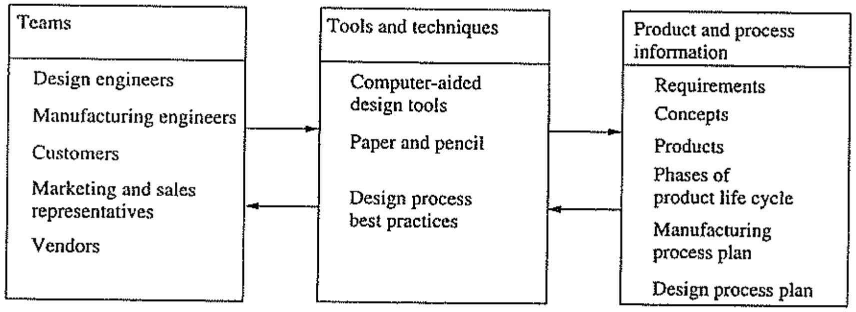

FIGURE 1.6
The concurrent engineering method.

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.

A key point in the concurrent engineering method is a concern for information. Drawings, plans, concept sketches, and meeting notes all provide information that must be shared with the right people at the right time. This concern is not only about the development of this information but also about its distribution. Traditionally, the greatest emphasis during the design process has been on the development of drawings. In concurrent engineering this has been broadened to include concern for information about requirements, concepts, and process plans—items that cannot be represented as formal drawings.

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. In fact, concurrent engineering is 80 percent company culture and only 20 percent computer support. 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.

An important aspect of concurrent engineering is concern for both the development of the product and the associated processes. Two processes listed among the key features are the product development process—the focus of this book—and the manufacturing process. Concurrent engineering forces engineers to put effort into these processes while designing the product.

Finally, during the 1980s and 1990s many design process techniques were introduced and became popular. They are essential to the concurrent engineering philosophy and are introduced throughout the book.

1.4 THE LIFE OF A PRODUCT

Whether the over-the-wall or the concurrent design philosophy is being used, every product has a life history as described in Fig. 1.7. Here, each box represents a phase in the product's life. 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 the designers, who are involved with the first five phases, must fully understand all the subsequent phases if they are to develop a quality product. The product life phases are discussed in the following.

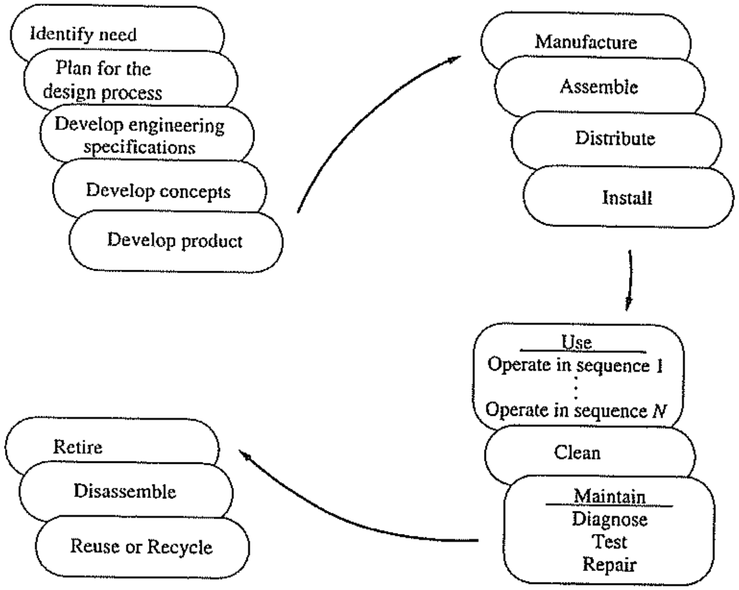

FIGURE 1.7
The life of a product.

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

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. 5.

DEVELOP ENGINEERING REQUIREMENTS. The importance of developing a good set of requirements has become one of the key points in concurrent engineering. It has recently been realized that the time spent evolving complete requirements prior to developing concepts saves time and money and improves quality. A technique to help in developing requirements 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 9–13 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 the product.

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. 12.

ASSEMBLE. Considering how a product is to be assembled is a major consideration during the product design phase. Part of Chap. 12 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."

USE. 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.

Another aspect of a product's use is keeping it clean and maintaining it in usable condition. 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.* 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.

RETIRE, DISASSEMBLE, REUSE, AND RECYCLE. 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 some European countries have 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.

This description of the life of a product 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 OF DESIGN PROBLEMS

Consider the following problem from a textbook on the design of machine components (see Fig. 1.8):

> 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?

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 the following, 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. 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 makers have?

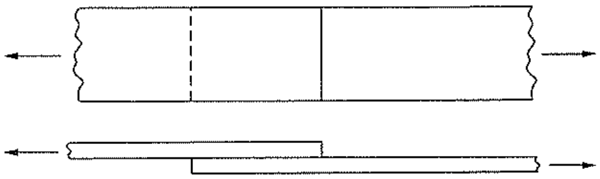

FIGURE 1.8
A simple lap joint.

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. *All design problems are ill-defined.*

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. 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. *Most design problems have a multitude of satisfactory solutions and no clear best solution.* This is shown graphically in Fig. 1.9, 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. 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

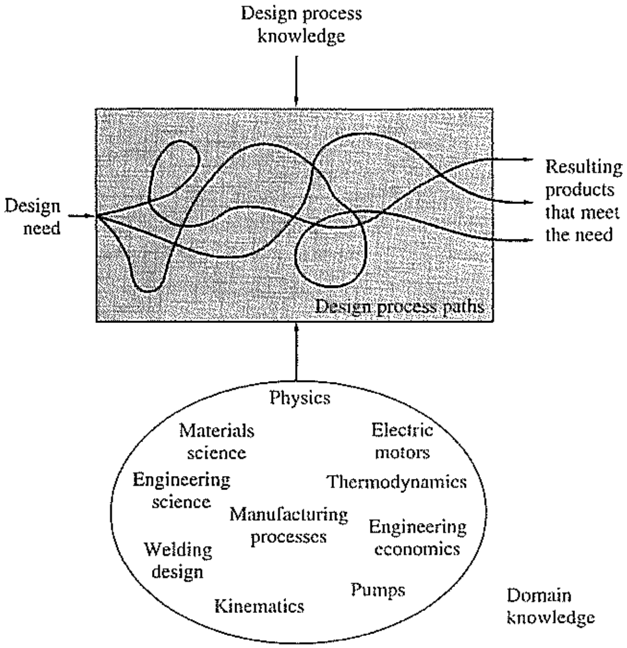

FIGURE 1.9
The many results of the design process.

design problems begin with an ill-defined need and result in a piece of machinery that behaves in a certain way, a way that the designers feel meets this need. This creates a paradox. *A designer must develop a machine 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 taken in 1-2-3 order. In fact they are often intermingled with solution generation and evaluation improving the understanding of the problem, allowing 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 (Figure 1.8). 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 similar to the analysis problem.

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 is 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. 1.10. Therefore, after completing a project, most designers want a chance to start all over in order to do the project properly now that

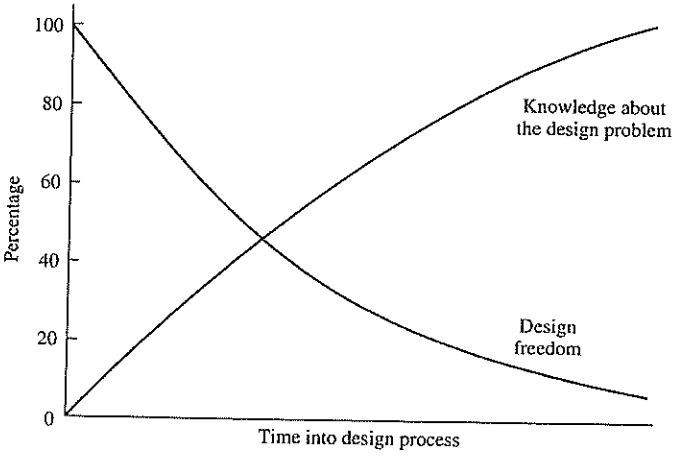

FIGURE 1.10

they fully understand it. Unfortunately, since time and cost—not the designer's sense of good-quality design—drive most design projects, 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 be seen in Fig. 1.10, 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. 1.10 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, 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 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.
- Concurrent engineering 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.
- 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.
- In problem solving there are seven actions to be taken: establish need, plan, understand, generate, evaluate, decide, and communicate.

1.9 SOURCES

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Prasad, B.: *Concurrent Engineering Fundamentals*, Prentice Hall, Englewood Cliffs, N.J., 1996. A good overview of concurrent engineering issues.

Ulrich, K. T., and S. A. Pearson: "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 percent 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 percent on the average (see Table 1.1) but can range as high as 75 percent.

1.10 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, cars, bikes, CD players, and personal computers are examples. For each, list its features, cost, and perceived quality. Compare the ease of maintenance and any obvious thoughts on the retirement of the products.

1.4. To experience the limitations of the over-the-wall design method, try the following. 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. 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 West Point originated this problem.)