CHAPTER 1

Introduction to the Mechanical Design Process

KEY QUESTIONS

- What are the stages of a product's life cycle?
- What are the important phases of the design stage?
- How are design problems different from analysis problems?
- Why is it that during design, the more you know, the less design freedom you have?
- Why are design problems characterized by information that is uncertain, incomplete, and conflicting?
- What are the four basic actions of decision making?
- What are best practices and why are they important?

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 5000 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, certain techniques 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 5000 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 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.

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.* Throughout the remainder of the book, the term *product* will be used to describe any physical device that is being designed, whether it is a one-off fixture used in an experiment, a device that is mass produced and sold to thousands, a shelf to hold your books, or a Mars Rover suspension.

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. This division of labor forced the formalization of design process and the evolution of methods that help each step along the way. These methods are referred to as *best practices*. A best practice is a professional method that is accepted or prescribed as being most effective. This book is really a compendium of best practices that can help you design quality products.

The three main goals of this book are to:

1. Give you the knowledge about best practices used in industry to develop and refine products.
2. Give you the tools to string these best practices together to develop an efficient design process regardless of the product being developed.
3. Make you aware of new challenges and opportunities in the mechanical design process.

1.2 WHAT IS THE DESIGN PROCESS?

Every product has a life history that evolves through four distinct stages, shown in Fig. 1.1.

The first stage concerns the development of the product, the focus of this book. The second stage is the production and delivery of the product to the customer. The third is the product's use by the customer. And the final stage focuses on what happens to the product after it is no longer useful. Clearly, the first stage is the domain of the designer. But, how the product fares in all the other stages is a direct consequence of decisions made by the designer in this first stage.

Each stage can be broken down into more detailed phases. Design has four phases as shown in Fig. 1.2.

The four design phases are:

1. ***Project definition.*** Efficient product development hinges on choosing the right projects to work on and planning for the most efficient use of people's time and of other resources.
2. ***Product definition.*** The importance of building a good definition of the product to be developed has become one of the key points in product development. Time spent defining what the product is to be, prior to developing concepts, saves time and money and improves quality.
3. ***Conceptual design.*** An important part of a successful product is in generating and evaluating new concepts. Decisions made here affect all the downstream phases.
4. ***Product development.*** Turning a concept into a manufacturable product that performs as it should is a major engineering challenge. This phase ends with manufacturing specifications and release to production.

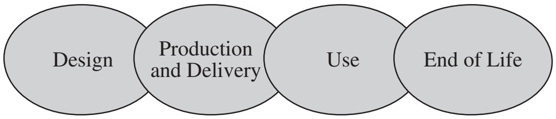

Figure 1.1 The stages of a product's life.

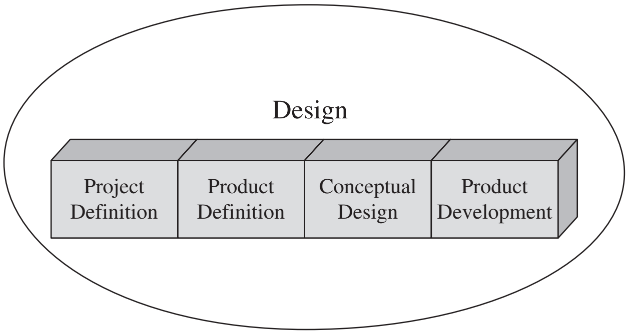

Figure 1.2 The phases of product design.

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

When the design work is completed, the product is released for production, and except for engineering changes, the designers have no further direct involvement with it. However, these first four phases all have a great effect on what will happen to the product and its success for the remainder of its lifetime.

The four production and delivery phases, shown in Fig 1.3, are:

1. ***Manufacture.*** Most products need unique components formed from raw materials and thus require some manufacturing. Design decisions directly determine the materials used and their impact on the environment during manufacture; the manufacturing processes that can be used and the resulting cost to make the parts; and their subsequent reuse or recycling.
2. ***Assembly.*** The ease of product assembly is a major consideration during product design.
3. ***Distribution.*** 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. Additionally, design requirements may include the need for the product to be shipped in a container designed by marketing or in some standard box.
4. ***Installation.*** 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 three "use" phases, shown in Fig. 1.4, are:

1. ***Operate.*** Products may have many different operating sequences that describe their use. Consider as an example a common hammer that can be used to put

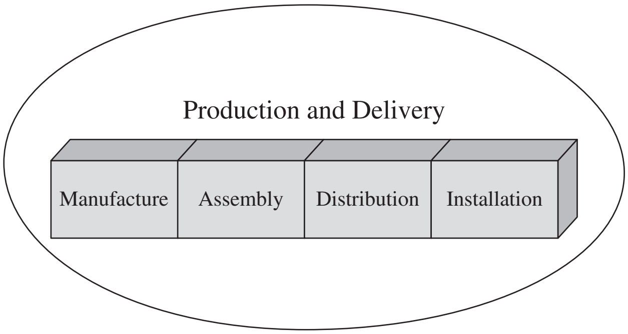

Figure 1.3 The phases of production and delivery.

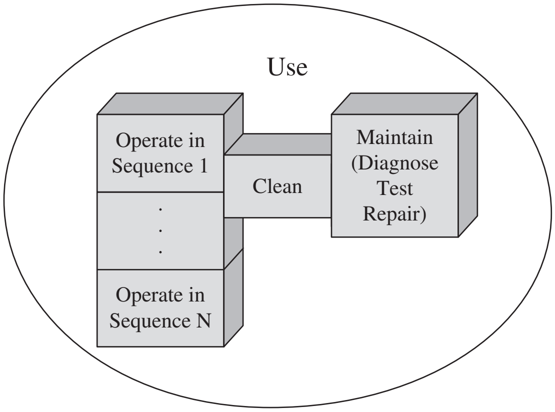

Figure 1.4 The use phases.

in nails or take them out. Each use involves a different sequence of operations, and all must be considered during the design of a hammer.

2. ***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 easily clean a product. This inability is seldom designed into the product on purpose; rather, it is usually simply the result of not considering cleanablity during the design process.
3. ***Maintain.*** Many of today's products are throwaways. When it fails, you throw it away and buy a new one. Concern for sustainability may force this to change, to go back to being able to *diagnose,* where the diagnosis may require *tests,* and then to *repair* the product. Whether a product is a throwaway or is repairable is a function of the design of the product.

Finally, every product has a finite life and thus, end-of-life concerns, as shown in Fig 1.5. The end-of-life phases used to not be of much concern to designers.

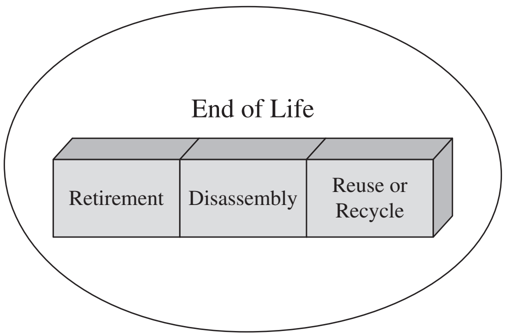

Figure 1.5 The end-of-life phases.

But with the increased emphasis on sustainability, the impact of design on the environment has become increasingly clear.

The three end-of-life phases are:

1. ***Retirement.*** 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.
2. ***Disassembly.*** 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.
3. ***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).

The phases introduced here give some idea about how important the product design is throughout the life of a product. A majority of this book will be spent on addressing best practices to accomplish design with an eye on all the other concerns introduced here.

1.3 DESIGN BEST PRACTICES

This book is a compendium of product design best practices. These are activities undertaken every day in industry that have been successful and adopted by others. Table 1.1 itemizes techniques generally considered as best practice and discussed in this book. They appear by chapter and 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 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 best practices described in this book make up 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. 1.6.

This figure 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

Table 1.1 Rest practices presented in this text

Chapter 1—Introduction to the Mechanical Design Process

1. Develop mechanical, electronic, and other systems concurrently.

Chapter 2—Understanding Mechanical Design

2. Benchmark existing products to understand how they are made, assembled, and function.

Chapter 3—Designers and Design Teams

3. Assemble product design teams with diverse, specific expertise.
4. Make positive use of team members' problem-solving behaviors.

Chapter 4—The Design Process

5. Recognize that the design process is a series of decisions.
6. Document all concepts and decisions for reuse, patent application and defense, and regulatory requirements.
7. Build product and project history with a PDM/PLM system.

Chapter 5—Project Definition

8. Ensure you have good reasons for beginning a project.
9. Make rational product portfolio decisions.
10. Have a clear design process reflected in the project plan.
11. Use models and prototypes as learning opportunities.
12. Plan tasks around deliverables.

Chapter 6—Product Definition

13. Identify product customers.
14. Capture customers' requirements.
15. Determine what is important to customers.
16. Generate clear and measurable engineering specifications.
17. Determine how the engineering specifications relate to the customers' requirements.
18. Establish targets, thresholds, and inter-dependence of engineering specifications.

Chapter 7—Concept Generation

19. Generate multiple concepts.
20. Reverse engineer to understand function.
21. Build functional models as a basis for form generation.
22. Generate concepts using brain storming.
23. Generate concepts using analogies with nature and devices in other fields.
24. Generate concepts using prior patents.
25. Generate concepts using contradictions.
26. Generate concepts using TRIZ.
27. Generate concepts using morphologies.
28. Develop product architectures using design structure matrices.
29. Complete provisional patent applications.

Chapter 8—Concept Evaluation and Selection

30. Use a design-test-build sequence when possible.
31. Know each system's technology readiness.
32. Use decision matrices to evaluate concepts and support decision making.
33. Understand the product, project, and decision risks.
34. Make robust decisions—decisions insensitive to noise.

Chapter 9—Product Generation

35. Use bills of materials to manage the evolution of products.
36. Develop products from constraints to configuration to connections to components.

Chapter 10—Product Evaluation for Performance and the Effects of Variation

37. Use P-diagrams to manage product performance evaluation.
38. Use factor of safety as a design variable.
39. Develop tolerances consistent with needed function, fit, and manufacturing methods.
40. Support trade-offs with sensitivity analysis.
41. Test products using design of experiments/robust design methods.

Chapter 11—Product Evaluation: Design for Cost, Manufacture, Assembly, and Other Matters

42. Design for cost.
43. Design for manufacture.
44. Design for assembly.
45. Design for reliability.
46. Access and manage risks.
47. Design for test and maintenance.
48. Design for sustainability.

Chapter 12—Wrapping up the Design Process and Supporting the Product

49. Manage post-release engineering changes.
50. Apply for design and utility patents as good design and business practice.

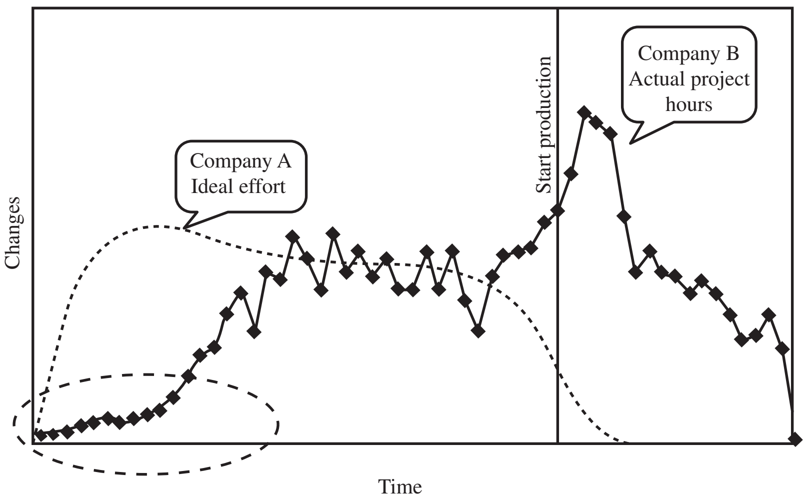

Figure 1.6 Engineering changes during automobile development. (For more details on this figure see Section 2.2.3.)

are subjected to a low-quality product. It is important to realize that a "change" requires a decision(s) and thus the ordinate of the figure could be labeled "decisions."

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 and decisions early in the process. The best practices listed in Table 1.1 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 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.

1.4 WHAT MAKES DESIGN HARD?

Besides the need to focus on the entire life cycle when designing products, there are other characteristics of design problems that make the process hard.

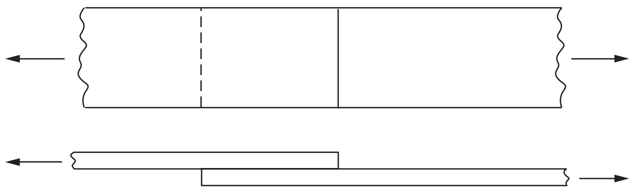

Figure 1.7 A simple lap joint.

1.4.1 Design Problems Have Multiple Possible Answers

Consider a problem from a textbook on the design of machine components, described in Fig. 1.7.

> *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 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 is 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 to understand it fully.

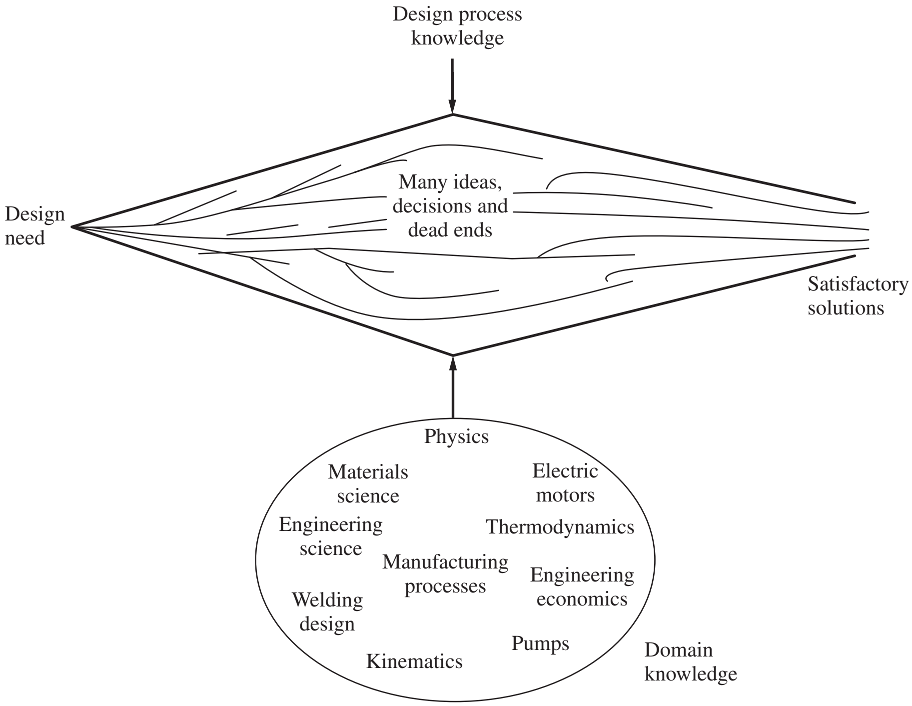

Figure 1.8 The many results of the design process.

A big 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 in Fig. 1.8, where the factors that affect the solution 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

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

creates a paradox. *A designer must develop a device that, by definition, has the capabilities to meet some need that is not fully defined.*

1.4.2 As Knowledge Is Gained Design Freedom Is Lost

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. 1.9. 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. 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.

Conversely, since design is a series of decisions and each decision eliminates alternative possibilities, design freedom is lost as the process proceeds. Poor decisions made early may be difficult and expensive (or impossible) to rectify later in the project. 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.*

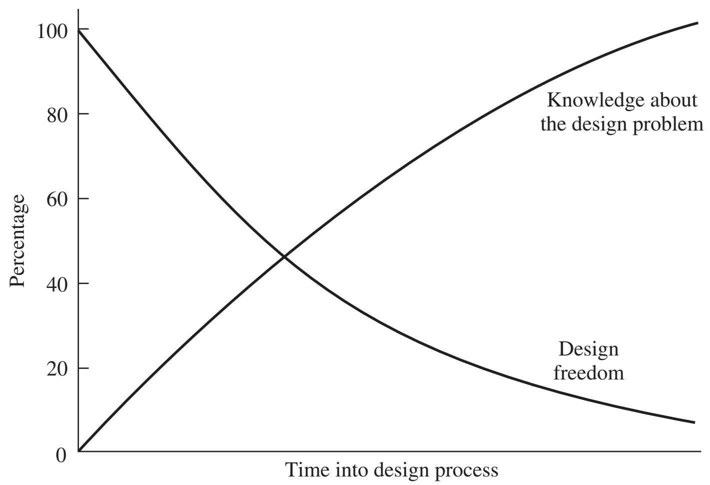

Figure 1.9 The design process paradox.

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

1.4.3 Decisions Are Made Throughout the Design Process

Regardless of the design problem or phase in the design process, designers need to make many decisions. A decision is needed whenever there is a choice among multiple alternatives. Typically decisions will be made about what design goals to choose, which concepts to consider, how to break the product into systems and subsystems, what shapes to use, which manufacturing process to use, and so on. What makes these decisions hard is described here.

The information is uncertain. In the previous section we discussed how you gain knowledge as you design. The less knowledge, the higher the uncertainty and, the more the uncertainty, the higher the risk that the design will fail. Thus, it is important to understand what is known and what is unknown, and to use methods that manage uncertainty.

The information is incomplete, you simply may not have all the information you need to make a decision. You may be forced to make decisions because time is running out, other people need your commitment, or a superior demands an answer: regardless of completeness. The alternative is to use resources (i.e., time and money) to fill in the missing information if possible.

Information is conflicting in that one party (i.e., a member of the design team or a customer) thinks one thing and another party disagrees. It may be possible to resolve the conflict through more analysis of the situation (using resources) or maybe not. The hard part here is that design is not only a technical effort but a social problem, and the conflict may be based on the conflicting parties' values and not easily changed.

These are the realities of design. They make it messy. There is never enough time and money to get rid of all the uncertainty and incompleteness, and there will always be conflicting information. One goal here is to develop methods that help manage these realities as best we can. These methods, best practices, are all designed to help make design decisions and control the messiness as best as is possible.

Every decision requires five basic actions as shown connected with solid lines in Fig 1.10: understand, develop, generate, evaluate, and decide what to do next.

Beginning on the left side of Fig. 1.10, you must **understand the issue**. Decisions are needed to resolve issues and the resolution is only as good as the understanding. Here the term *issue* is used to note the problem or question at hand. Product definition, one of the design process phases, is almost totally focused on understanding the design problem. Making sure the right issue is being attacked is a key part of all the other methods in this book as well. In the previous section the issue was to design a lap joint to fasten together two pieces of metal.

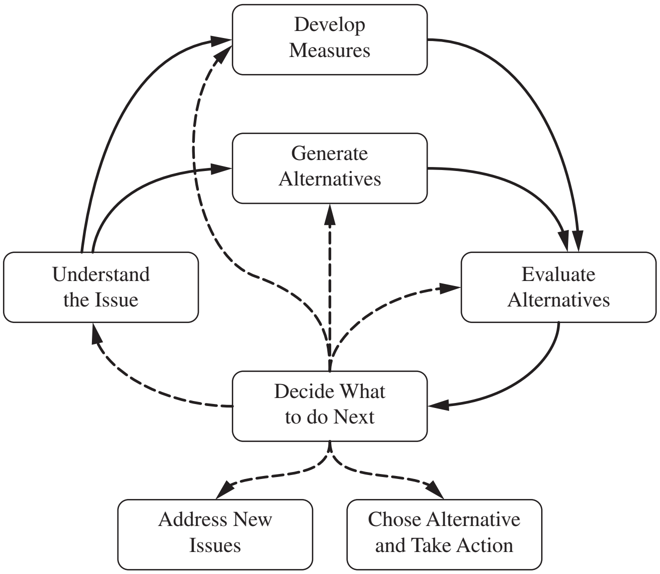

Figure 1.10 Decision-making actions.

This is a well-defined issue, but many are less so, such as "design a propulsion system for lunar rover."

The second action is to **develop measures**. How will you know if you have a solution for the issue? You can only tell if you have a good lap joint if you know "measures" like joint strength, thickness, corrosion resistance, etc. You only know which propulsion system is best for the lunar rover if you know how fast it should propel the rover and for how long. Developing measures is a big part of understanding a design problem, as will be discussed in Chapter 6.

The third action is to **generate alternatives** that can possibly resolve the issue or answer the question. If you only have one alternative, you don't have a decision to make. For some problems the alternatives are evident, and there are only two or three realistic options. But, for most design problems, the search for alternatives is a major part of the effort. For the lap joint, the alternatives are bolts, welds, glue, etc. For the lunar rover, the options are wheels of many different configurations, treads, rocket packs, and many others, depending on problem boundaries realized during issue understanding.

The fourth action is to **evaluate the alternatives** relative to what is learned during understanding. For the lap joint, there are analysis methods learned in mechanical components courses, or through vendor handbooks, that can be compared to goals discovered during issue understanding to provide information for decision making. But not all evaluation relies on analysis, as some information is hard to quantify, especially during conceptual design. Finally, all evaluations are uncertain, most are incomplete, and some are conflicting. Part of any best practice is to reduce the effect of these on the decision, or at a minimum make their effect evident.

While “decision making” is usually seen as choosing an alternative, it is really more to **decide what to do next**, as shown in Fig. 1.10. There are six different paths that could be taken, shown as dashed lines. The next action could be to refine the issue understanding, generate refined or more alternatives, or do more evaluation of the alternatives. Ideally, an alternative can be chosen and documented. Often, the effort to understand, generate, and evaluate raises new issues that then start other understand, generate, evaluate, and decide sequences.

Not shown in Fig 1.10, but very important, is the meta decision of planning how to best understand, generate, evaluate, and decide. Best practices are basically templates for how to manage these actions for specific types of issues. A good designer knows which to use and when to use them.

1.4.4 It Is Easy to “Silo” Mechanical Design

In the structure shown in Fig. 1.11, 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 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.

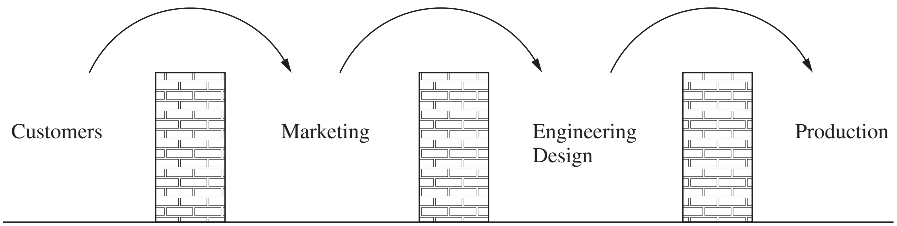

Figure 1.11 The over-the-wall design method.

> Human beings don't have a pollution problem; they have a design problem. *The Upcycle*, W. McDonough and M. Braungart, 2013.

The best practices in this book try to ensure that the walls are broken down by improving communication, ensuring the right people are involved in the decision-making process and that the best possible information is used each step of the way. This requires a systems view of product development. This view is that many functions in a product can be fulfilled mechanically, electronically, or in software; and that many products have all three interacting to make the best product. To develop these systems requires concurrent development of the hardware, electronics, and software, leading to our first best practice.

Best Practice: Develop mechanical, electronic, and other systems concurrently.

In many ways this book is a systems design book. Although titled *The Mechanical Design Process* the methods and best practices apply across the entire product develop process.

1.5 TWENTY-FIRST-CENTURY DESIGN PROCESS CHALLENGES AND OPPORTUNITIES

Three evolving influences will affect the design process: design for sustainability, design for additive manufacturing, and the effect of the Internet and social media on the design process. While it is impossible to tell how these will change the practice of design, they will. Most probably they will provide the opportunity to make better products or to make bigger blunders, faster. It is certain that new best practices will evolve from the effect of these on the design process.

1.5.1 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 Design for Sustainability (DFS). 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.

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

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 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. 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. We will specifically detail DFS in Section 11.7.

An additional concern here is that some materials now commonly available for products will become more expensive or even impossible to obtain. This will have an effect on the design of future products, which may be, to some degree, offset by additive manufacturing, the subject of the next section.

1.5.2 Additive Manufacturing

Additive manufacturing, also known as 3D printing, rapid prototyping, or desktop manufacturing, is the process of making three-dimensional solid objects from computer models. It is called "additive" because layers or dots of material are built up to make the part. While this manufacturing method has been evolving since the 1980s, its use has exploded since 2000 as the cost and machine size have come down and the range of materials has increased. The machine cost and size have come down to the point that it is possible to have a manufacturing machine on your desktop, hence one of its names, "desktop manufacturing." While its initial use was a rapid prototyping tool (hence another of its names), in recent last years it has begun to be used as a manufacturing method for lowvolume products.

What makes this technology revolutionary and important to mention up front in this book is that it may, as it continues to mature, have a profound effect on the design process. There are five ways this could change the design process:

1. **The ability for anybody to easily and rapidly make components.** This has two major implications. Anybody who can make a solid model of a component can print it at home. This means that anyone can design components and realize them almost instantly. While this opens the way for a total change in how products are realized, there is little stopping poor, even dangerous products.
2. **The ability to make parts not previously possible.** In the past, one of the signs of a poor designer was creating components that were hard or even impossible to manufacture. With additive manufacturing, this is no longer true—if you can draw it, you can make it.
3. **The ability to change materials in a single component.** In the past a component had to be made of a single material. The best you could do to change material properties in a part was a surface treatment (e.g., heat-treating metals) or using a multistep process (co-extrude plastics with the inner extrusion of one material and the outer layer another material). With additive manufacturing, the material properties can be altered throughout the component. For example, a toothbrush could be printed as a single item with a rigid handle, flexible yet stiff bristles, and a soft gum massager.
4. **The ability to combine functions in ways not previously possible.** The previous two capabilities allow product functions to be combined in ways never before possible. As will be developed in the next chapter, mechanical design is very much a function-driven exercise. The effect of additive manufacturing on the design of function is still evolving.
5. **The ability to make custom products.** Each item printed can be slightly different from the other, leading to mass customization. For example, glasses frames could be printed for each individual based on a scan of head shape and color desires. The glasses could be made in the store where the frames were purchased, at a mobile site, or even on the kitchen table.

This technology may alter who does design, how much of the process is automated, and what will appear in later editions of this book.

1.5.3 Design in the Connected World

Designers started using the Internet in the late 1980s. Until quite recently, it has been primarily for communication and sharing files. Since 2010 the evolving use of the Cloud and social media has begun to affect the design process in new ways. The long-term consequence of these technologies on the design process can only be imagined. Consider these four features of a connected world:

1. **Online communication.** Prior to 2000 communication was limited to email communication, file sharing for images, and limited quality video conferencing. Since that time communication via the Web has improved though much richer information sharing and the ability to design with distributed teams. The support capabilities are still evolving at a rapid pace.
2. **Social media.** While social media tools have had a profound effect on communication amongst friends and the ability to support sales, they have had little effect on the design process. But this is changing. In a 2011 survey, early adopters of using social media to support design reported more (and better) product alternatives and measures (46%), faster time to market (18%), faster product adoption (15%), lower product costs (15%), and lower product development costs (15%). It is hard to foresee how these systems will evolve and affect how designers collaborate and share information.
3. **Crowd sourcing.** The ability to have multiple people co-developing a product, each adding their ideas and knowledge to it, is what the design process is all about. Extending the involvement in the design process to others who are not in your group or company may greatly change the design process. Wikipedia, the ultimate example of crowd sourcing, was only launched in 2001. It remained a weak reference source until about 2010, when the mainstream began to realize that the quality of the entries in it was really quite good. Experiments in crowd sourcing physical products is in its infancy.
4. **Information glut.** Soon the number of electronic devices and sensors on the Web will surpass one trillion in number. The information content being communicated amongst these devices will contain important product design nuggets. For example, how each person is using a specific product will soon be captured by an on-board processor that will communicate this information for your use in developing improvements. How this information will be managed and used is unknown, but it will certainly affect the design process.

The influences introduced here will evolve while this book is in print. They will change what is said here. Read the 6th edition to see what has developed.

1.6 DESIGN PROCESS CASE STUDIES AND TEMPLATES IN THIS BOOK

Two online capabilities tied to best practices support this book: Case studies and templates. The case studies are an ever-growing series of five- to ten-page descriptions of how some of the best practices in this book were used by a company to improve or develop new products. Each case study was written by a working design engineer describing best practices used. These case studies can be downloaded from the McGraw-Hill or the author's website as noted at the end of each relevant chapter.

Also supporting the best practices are templates. These Word or Excel files enable many best practices in a fill-in-the-blanks format. They too can be downloaded from the McGraw-Hill or the author's website as noted at the end of each relevant chapter.

1.7 SUMMARY

- The design process is the organization and management of people and the information they develop in the evolution of a product—any physical device.
- The process described in this book integrates all the stakeholders from the beginning of the design process through production and delivery, use, and end of life.
- The design process includes project definition, product definition, conceptual design, and product development.
- Design is made hard because:
  - Design problems have multiple possible answers.
  - As knowledge is gained design freedom is lost.
  - Decisions must be made throughout the design process based on uncertain, incomplete, and conflicting information.
  - It is easy to "silo" mechanical design.
- The information flow in making a decision is: understand, generate, evaluate, and decide what to do next.
- Three influences will change the design process.
  - Design for sustainability, which is well described in the Hanover Principles.
  - Additive manufacturing.
  - Design in the connected world.

1.8 SOURCES

Two sources for the Hanover Principles:

Hanover Principles: Design for sustainability, www.mcdonough.com/wp-content/uploads/2013/03/Hannover-Principles-1992.pdf

McDonough, W., and M. Braungart: *Cradle to Cradle*, North Point Press is N.Y. N.Y.

Kenly A., and B. Poston: Social media and product innovation, Kalypso white paper, 2011. http://kalypso.com/downloads/insights/Kalypso_Social_Media_and_Product_Innovation_1.pdf

1.9 EXERCISES

1.1 From the Key Questions at the beginning of the chapter:

a. What are the stages of a product's life cycle?

b. What are the important phases of the design stage?

c. How are design problems different from analysis problems?

d. Why is it that during design, the more you know, the less design freedom you have?

e. Why are design problems characterized by information that is uncertain, incomplete, and conflicting?

f. What are the four basic actions in decision making?

g. What are best practices and why are they important?

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

1.3. How well do the following products meet the Hannover Principles?

a. Your cell phone

b. The packaging your cell phone came in

c. Your car

d. A newspaper

1.4. 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, the first person describes 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 re-describes 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. Try this by word of mouth only and also taking notes. (Professor Mark Costello of Georgia Institute of Technology originated this problem.)