The Mechanical Design Process

FIFTH EDITION

David G. Ullman

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David G. Ullman
Professor Emeritus, Oregon State University

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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 it 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 enough ability and experience to generate ideas and enough experience and training to evaluate them are present.
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. Chapters 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. Chapters 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 book 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 FIFTH EDITION

This is a book about best practices. In this edition the fifty best practices in mechanical design form the core of the book. They are clearly identified and developed throughout the chapters.

Nearly thirty templates are available to download that support the best practices. The book includes many of them as examples for student reference.

There are now over fifteen case studies that can be used to show how practicing engineers use the best practices to resolve design issues. Each was written in cooperation with an engineer and each resulted in a quality product.

The material on Design for Sustainability has been improved as has material designing components for Additive Manufacturing.

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

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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.

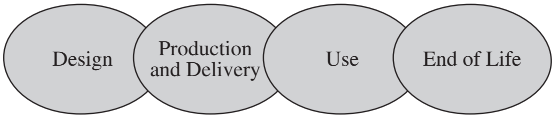

Figure 1.1 The stages of a product's life.

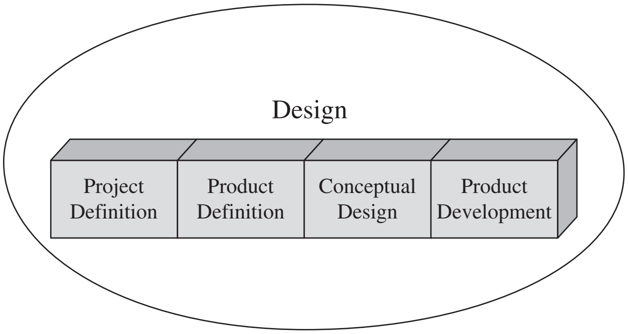

Figure 1.2 The phases of product design.

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

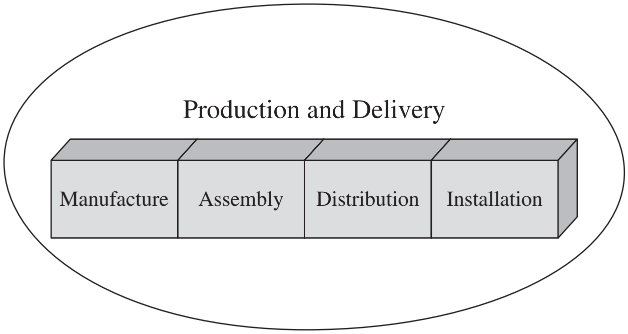

Figure 1.3 The phases of production and delivery.

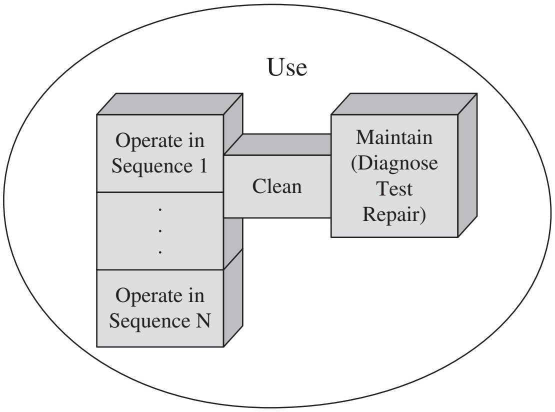

Figure 1.4 The use phases.

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.

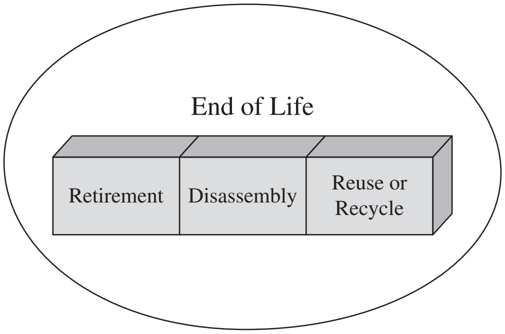

Figure 1.5 The end-of-life phases.

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.

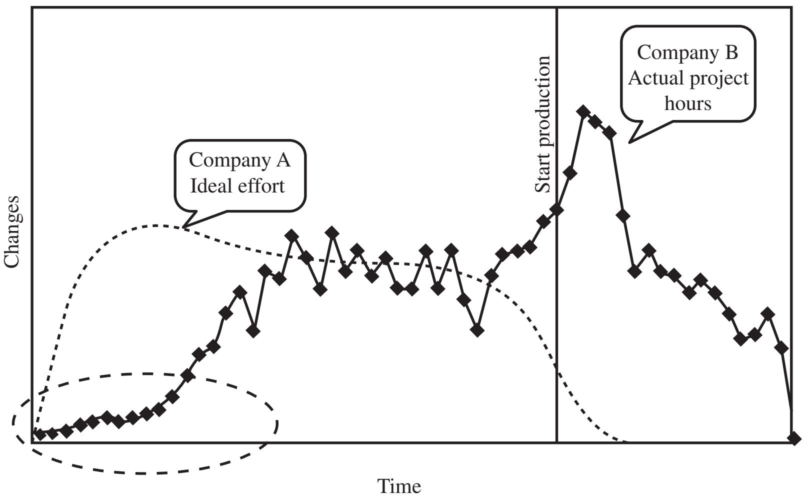

Figure 1.6 Engineering changes during automobile development. (For more details on this figure see Section 2.2.3.)

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.

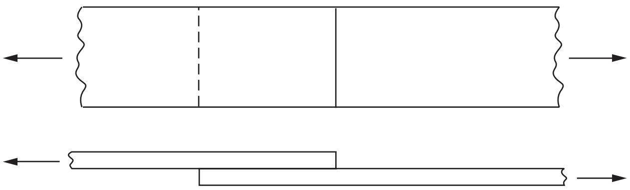

Figure 1.7 A simple lap joint.

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.