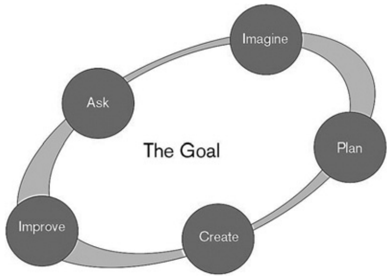
CHAPTER 17

Introduction to Engineering Design



Source: http://www.mos.org/eie/engineering_design.php.

17.1 INTRODUCTION

This chapter describes the **nature of engineering design**, uses the modern design philosophy **Design for Six Sigma**, suggests some benefits of a **hands-on design project**, indicates the qualities of a good designer, and explains the need for a **systematic approach** that consists of an eight-step design process.

17.2 THE NATURE OF ENGINEERING DESIGN

In the course of creating new products, engineering design uses available technology to improve performance, to lower cost, or to reduce risk. For example, if the design of a bridge produces a new structure that is visually stunning with no consideration for its strength, this is design without any engineering. If, on the other hand, the designers of a new concept car use analysis or experiments to evaluate air drag, structural integrity, and manufacturability in addition to style when coming up with a new exterior design, this is engineering design.

Prior to the 1960s, the preceding description of engineering design might have been adequate, but this is no longer the case. The definition has been broadened to include the systematic thought processes and best practices that define the modern engineering design process. This systematic approach, which has become synonymous with engineering design, forms the heart of these design chapters.

Those of you experienced at tinkering with your own inventions in the basement or garage might say that you got along fine without engineering analysis and without training in the systematic approach. Such a view ignores the realities of engineering design. Usually, designers must search for the best possible design under severe conditions of limited time and limited resources (especially cost). For example, in most design situations, there is barely enough time to produce a single prototype. The idea behind an engineering approach, as embodied in engineering analysis and in the systematic approach, is to minimize the number of design iterations required to achieve a successful final design. Fewer design iterations means lower cost and shorter development times.

One of the greatest challenges of engineering design is the breadth of knowledge required of the designer. The diversity of topics covered in earlier chapters provides a hint of what a design might entail; some electromechanical designs could conceivably touch on them all. In addition to those topics, there are issues related to manufacturing, economics, aesthetics, ethics, teaming, government regulations, and documentation of the design, to name but a few. In the spirit of these design chapters, we propose that the best way to introduce the multifaceted nature of engineering design is to experience it for yourself through the following hands-on design exercise.

17.3 DESIGN PROBLEMS VS. HOMEWORK PROBLEMS

A design problem is unlike a traditional college homework problem. Homework problems, like those in Parts 1 and 2 ("Lead-On" and "Minds-On," respectively) in this textbook have specific, unique answers; and the student must find those answers using a logical approach such as the need-know-how-solve method. Design problems, on the other hand, do not have unique answers. Several answers (i.e., designs) may satisfy a design problem statement. There may also be a "best" answer based on critical requirements. For example, a design that minimizes manufacturing costs may not produce a very reliable product. If product reliability is a critical requirement of the customer, then minimizing manufacturing costs may not be the "best" design answer.

The challenge of Part 3 of this textbook, which we call "Hands-On," is to transition you from solving well-formulated, single-answer textbook problems to solving what we call *open-ended* engineering design problems. These problems are often complex and sometimes poorly formulated problems. You will find that excellent design work requires considerable creativity beyond that needed to solve textbook problems. In Part 3 of this text, we allow and encourage you to drop your academic inhibitions and explore the joy of engineering creativity.

The problem-solving process we presented in Part 1 of this text (need-know-how-solve) works well for single-answer textbook problems, but it needs to be expanded to encompass open-ended engineering design problems. In recent years, the process of engineering design has been refined to produce more robust and economical designs. The process that most companies embrace today is a five-step process called Design for Six Sigma.

In Part 3 of this text, we abandon the need-know-how-solve exercise solution method and adopt an eight-step design process based on the Six Sigma design methodology.

17.4 BENEFITS OF A HANDS-ON DESIGN PROJECT

A practicing engineer does not have to be an expert in machining or other basic manufacturing operations. Still, a basic understanding of the challenges involved in manufacturing a product is essential for producing a successful design. The best way to appreciate that fact at an early stage in your career is to manufacture a design yourself.

The lessons to be learned are universal. Don't expect your design to work on the first try. Leave a lot of time for testing. Complicated designs take a lot longer to build and have a lower probability of success. If you have a choice of manufacturing a part yourself or buying it, buy it. Many such lessons are foretold by the design principles and design for manufacture guidelines of later chapters. The consequences of violating those principles are best understood by experiencing the results of having done so.

Other lessons are to be learned from a hands-on design experience. For electromechanical systems with moving parts, that experience might be the only way to accurately evaluate the design. Also, students gain a sense of accountability by learning that it is not enough for a design to look good on paper. To actually be a good design, it has to lead to an end product that works.

In particular, we recommend that the hands-on design project should be done under a competition format, involving interactions between "machines." It is a natural motivator—the challenge of the task is heightened by having to deal with the unpredictability of your human opponent, and the other designs provide a relative scale against which to assess quality of performance.

17.5 QUALITIES OF A GOOD DESIGNER

These are the qualities of a good designer:

- **Curiosity about how things work**. Seeing other design solutions provides you with a toolbox of ideas that you can draw from when faced with a similar design challenge, so when you come across an unfamiliar device, try to figure out how it works. Take things apart; some companies actually do this and refer to it as *reverse engineering*. Visit a toy store; the products there often demonstrate creative ideas and new technology.
- **Unselfishness**. A key ingredient to effective teaming is suppressing ego and sacrificing personal comfort to serve the best interests of the team.
- **Fearlessness**. It takes a leap of faith to step into the unknown and create something new.
- **Persistence**. Setbacks are inevitable in the course of a design project. Remain resilient and determined in the face of adversity.
- **Adaptability**. Conditions during the design process are constantly evolving. For example, new facts may surface or the rules of the design competition may change in some way. Be prepared to take action in response to those new conditions. In other words, if the ship is sinking, don't go down with the ship—redesign it.

17.6 HOW TO MANAGE A DESIGN PROJECT

Project management is a carefully planned and organized effort to accomplish a specific project (for example, designing and constructing a robot vehicle to be entered into a competition on a specific date).

Project management includes developing and implementing a plan that defines the project goals, specifies how and by whom the goals will be achieved, identifying needed resources, and developing budgets and timelines. Project management is usually the responsibility of an individual team leader. When the project team members have been identified, the team (or the course instructor) selects one of its members as the project manager. This person has the responsibility guiding the team design work in a professional, organized, and timely manner. The project manager is also responsible for meeting deadlines and ensuring that the team members are carrying fair workloads. Successful project management involves the following:

- **Understand the project's goals.** You should be able to state the goals of your project in a single sentence.
- **Engage all the team members.** Subdivide the work using functional decomposition to break the project down into individual work assignments, and make sure that everyone knows what he or she is responsible for to meet the project goals (see Ground Rule Number 2, discussed in the next section).
- **Keep the project moving.** Work methodically to meet your benchmarks; don't wait until the last minute and rush to meet a deadline.

17.7 TWO GROUND RULES FOR DESIGN

There are two important ground rules for design, the use of a **design notebook** and **effective teamwork**.

17.7.1 Ground Rule Number 1. Use a Design Notebook

When you are a working on a design project and you want to write something down, the design notebook is the place to do it. There is no need for notepads, reams of paper, or sticky notes. The place to record your thoughts is in a permanently bound volume with numbered pages, a cardboard cover, and a label on the front cover identifying its contents. Every college bookstore has them, though they may be called *laboratory notebooks*.

As a starting engineer, now is the best time to start a career-long habit. Just how important the design notebook is can be explained in the case of Dr. Gordon Gould.[1]

> *On November 9, 1957, a Saturday night just given to Sunday, Gould was unable to sleep. He was 37 years old and a graduate student at Columbia University. For the rest of the . . . weekend, without sleep, Gould wrote down descriptions of his idea, sketched its components, projected its future uses.*
>
> *On Wednesday morning he hustled two blocks to the neighborhood candy store and had the proprietor, a notary, witness and date his notebook. The pages described a way of amplifying light and of using the resulting beam to cut and heat substances and measure distance. . . . Gould dubbed the process light amplification by stimulated emission of radiation, or laser.*

It took the next 30 years to win the patents for his ideas because other scientists had filed for a similar invention, although after Gould. Gould eventually won his patents and received many millions in royalties because he had made a witnessed, clear, and contemporaneous record of his invention.

The lesson is that patents and other matters are frequently settled in court for hundreds of millions of dollars by referring to a notebook that clearly details concepts and results of experiments. You must maintain that notebook in a fashion that will expedite your claim to future inventions and patents.

Another more immediate benefit of using a design notebook is that you will know that everything related to the project is in one place. Finding that key scrap of paper in a pile of books and papers on your desk after working for months on the project can be a rather time-consuming endeavor.

Here are some of the most important guidelines for keeping a design notebook:

- Date and number every page.
- *Never* tear out a page.
- Leave no blank pages between used pages. Draw a slash through any such blank pages.
- Include all your data, descriptions, sketches, calculations, notes, and so forth.
- Put an index on the first page.
- Write everything in real time; that is, do not copy over from scraps of paper in the interest of neatness.
- Write in ink.
- Do not use Wite-Out® or Liquid Paper®; cross out instead.
- Paste in computer output, charts, graphs, and photographs.
- Write as though you know someone else will read it.
- Document team meetings by recording the date, results of discussions, and assigned tasks.

17.7.2 Ground Rule Number 2. Team Effectively

Working in teams on a design project is both a joy and a challenge. While there is a sense of security in knowing that others are venturing into the unknown alongside you, the unpredictability of human interactions can be as perplexing as the design itself. To reduce the risk of ineffective teaming, rules of conduct are presented in this section. These are well-accepted best practices based on observations of effective teams.

Several advantages accrue from attacking a design project in teams. First, design requires a wide range of skills and areas of knowledge. No one person is experienced enough to pursue every unfamiliar design challenge in isolation. Teaming provides an opportunity to expand the talents and life experiences brought to bear on the design problem. Second, if done right, teaming serves to keep personal biases in check. Third, more people

[1] http://inventors.about.com/gi/dynamic/offsite.htm?site=http://www.inc.com/incmagazine/archives/03891051.html.

should mean that more is accomplished in a shorter period of time, although it is puzzling to often see team members standing by politely as one team member does all the work (especially during manufacturing). When best practices are followed, a team is greater than the sum of its parts.

For design projects done during the freshman and sophomore years, three people is the ideal team size. Teams of two may not experience all of the typical dynamics and so may not learn as much about teaming. With teams of four, it may be too easy for one team member to hide. Design teams at this level are usually not assigned a team leader by the instructor. Leadership typically emerges within the team. If a team leader is assigned, the role is *not* to be the boss but rather to organize and facilitate participation by all team members.

Here are some teaming best practices:

- **Assign clear roles and work assignments.** A few things are best done as a team, such as brainstorming and evaluation of concepts. Most of the time, it will pay off if everyone has his or her own assigned responsibilities and tasks to which each is held accountable by the team. These tasks should be assigned or updated at the end of each team meeting.
- **Foster good communication between team members.** An atmosphere of trust and respect should be maintained, in which team members feel free to express their ideas without retribution. That trust extends to allowing for civilized disagreement, delicately done so as not to suppress ideas or discourage participation. Everyone should participate in the discussions. Sometimes, this means reaching out with sensitivity to the shy members of the team. If you succeed, you will have a team operating on all cylinders.
- **Share leadership responsibilities.** If there is a designated team leader, that person should empower the other team members with significant leadership responsibilities. This gives those students a strong sense of ownership in the project. At the same time, team members have to be willing to step forward to assume leadership roles.
- **Make team decisions by consensus.** Teams make decisions in one of three ways: (1) the team leader makes the decision, (2) discussions continue until everyone agrees (as in a trial by jury), or (3) after discussions are exhausted, the team takes a vote. Those who disagree with the outcome of the vote are then asked if they can put their opinions aside and move forward in the best interests of the team. In a college-level design project, the only ways to go are (2) and (3), which are examples of decision making by consensus.

17.8 THE NEED FOR A SYSTEMATIC APPROACH

The two main goals of the systematic approach to engineering design are (1) to eliminate personal bias from the process and (2) to maximize the amount of thinking and information gathering done up front, before committing to the final design. The result is fewer costly design changes late in the product development stages.

The engineering design process also provides a blueprint for design of complex systems. For example, you might be able to get along without a formalized design procedure when designing a new paper clip,[2] but when taking on the daunting task of designing a complex system like the International Space Station, brain gridlock can set in. The design process offers a step-by-step procedure for getting started as well as strategies for breaking down complex problems into smaller manageable parts.

[2]But see just how difficult it originally was to perfect the paper clip: Henry Petroski, *The Evolution of Useful Things: How Everyday Artifacts—from Forks and Pins to Paper Clips and Zippers—Came to Be as They Are* (New York: Alfred A. Knopf, 1992).

17.9 STEPS IN THE ENGINEERING DESIGN PROCESS

A systematic approach to engineering design that uses the elements of the Design for Six Sigma philosophy may be viewed as consisting of eight steps:

1. Define the problem.
2. Generate alternative solutions.
3. Evaluate and select a solution.
4. Detail the design.
5. Defend the design.
6. Manufacture and test.
7. Evaluate the performance.
8. Prepare the final design report.

These steps are shown in Figure 17.1.

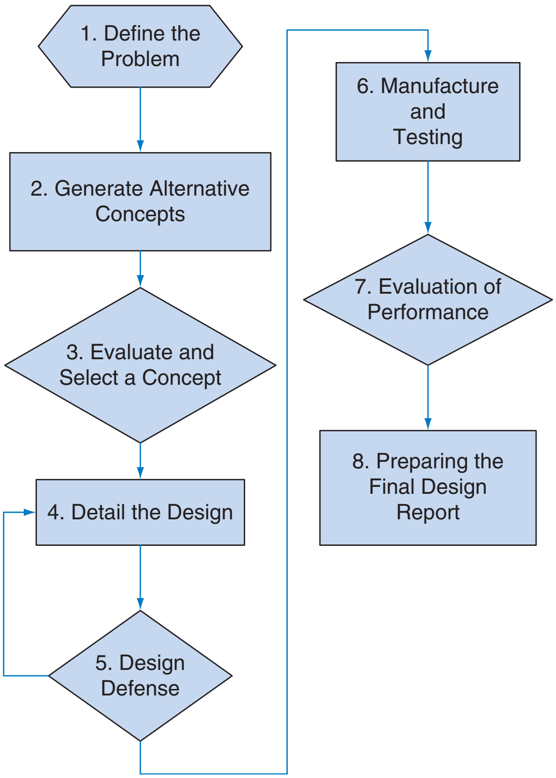


FIGURE 17.1 The Design Process Flowchart

The next chapter presents two ground rules for engineering design. Subsequent chapters treat each of the preceding eight steps in detail. At the end of each chapter is a suggested milestone for successful completion of the step in the design process described in the chapter. Milestones are crucial for measuring progress toward the eventual goal of a successful design. After the eight steps have been described, this portion of the book concludes with a detailed example of an actual design competition.

17.10 HANDS-ON DESIGN EXERCISE: “THE TOWER”

Your first design objective is to build the **tallest tower** out of materials to be supplied. Since there are both individual and team winners here, this is both an individual and a team competition.

17.10.1 Setup

- Divide the class into about eight teams of three or more students per team.
- Each team should be provided with five sheets of 8.5×11 standard copier paper.
- The following material will be distributed **unevenly**:
  - Two teams each receive one roll of Scotch® tape.
  - Two teams each receive a roll of duct tape.
  - Two teams each receive one box of paper clips.
  - Two teams each receive one pair of scissors.

17.10.2 Rules

- Each team has just 10 minutes to build a tower.
- The final tower height measurement must be made by the instructor.
- Teams should indicate to the instructor when they are ready for a measurement.
- If the tower is composed of materials other than the supplied paper, Scotch tape, duct tape, or paper clips, it will be disqualified.
- The tower must be stationary when the measurement is made.
- The tower must be built on a flat surface. The tower cannot lean against or be attached to any other surfaces (wall, table, etc.).
- Any team that intentionally knocks over another team’s tower before it has been measured is disqualified.
- After 3 minutes, **one** individual on each team is offered 8 points to join another team.
- There are no other rules.

17.10.3 Scoring

- One point will be awarded for each inch of tower height. (Heights are to be rounded to the nearest inch.)
- The first team that finishes its tower and is ready to be measured receives a bonus of 10 points.
- The “team” winner is the team with the highest point total,
- The “individual” winner is the student with the highest point total.

17.10.4 After the Exercise

Discuss the importance of the following issues to the outcome of the competition:

- The “quality of teaming” among different teams: Were any of the extra materials (tape, paper clips, scissors) shared between teams?

- The "quality of teaming" within the team: Was everyone within the team given the opportunity to contribute ideas or did one person dominate the decision making?
- Ethics: Was it ethical to jump to another team, not share materials, or copy the design of another team?
- Manufacturability: How important was it to have the right materials?