CHAPTER 7

Design Process

INTRODUCTION

One definition of engineering is “design under constraint.” For private enterprise to be successful, a product line must be competitive in many ways. Products must be attractive, functional, efficient, durable, reliable, affordable and most importantly, they must satisfy the needs of the customer. Also, products must reach the marketplace quickly. A structured design process helps the design engineer achieve these goals.

One view of the design process is shown in Figure 7.1. Most products begin “in the clouds,” as an expression of a specific need, but with no clear vision of how to fill that need. Eventually, a shiny new product will emerge. In between, however, the design engineer will generate many alternative concepts and will decide among those concepts. Sometimes, one concept will conflict with the project constraints, shown in Figure 7.1 as the hard boundaries that cannot be crossed. Constraints can range from the laws of physics to economic or even political constraints. Another feature of the design process is that it is *iterative*—it may be necessary to back up and start over. Also, successful products usually evolve over time. Today’s automobile, for example, is the result of many years' evolution, with improvements being added continuously.

DESIGN PROCESS TOOLS

There are many tools and concepts that are useful in the design process. A few of the more useful tools are design journals and the design concepts of K.I.S.S., conservation of ambiguity, E.T.C. and rapid prototyping.

Design Journals

Good documentation is essential. Keeping a design journal is a good idea practiced by most successful designers. In addition to serving as a useful reference, a written design journal can provide critical evidence of when an idea was conceived, which may be important in getting a patent.

Some suggestions for keeping a journal include:

- Use a bound notebook, as opposed to loose leaf.
- Do not be timid—write in ink!
- Carry the journal everywhere (good ideas pop up at all times).
- Paste in business cards, computer printouts, short articles, etc.
- Date all journal entries.
- Have two witnesses sign and date the page of a critical new idea.
- Write in the journal daily.

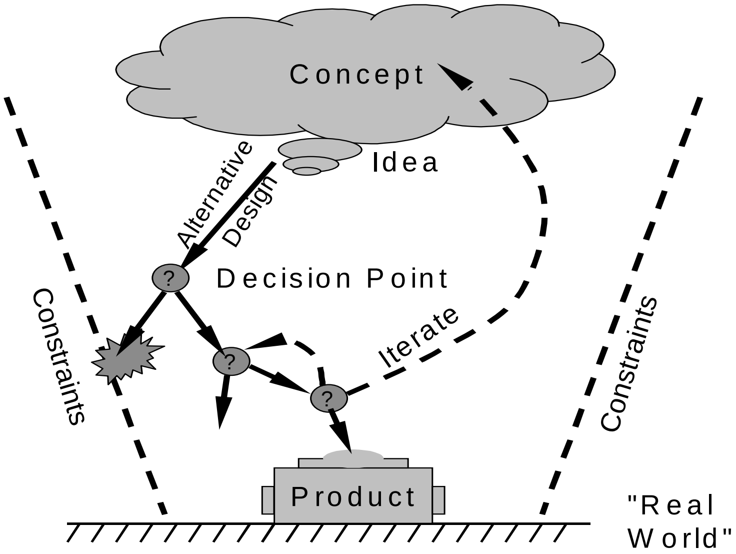

Figure 7.1. Schematic of the design process.

Some Design Concepts

The following are basic concepts that can apply to any design project.

K.I.S.S.

This stands for “keep it simple, stupid!” In general, the simplest design is usually the best; it tends to be the easiest to make, requires the fewest parts and is the most reliable. Even in a complex system, the simpler the individual components are, the better.

Conservation of Ambiguity

Coined by Stanford University’s Design Division in Mechanical Engineering, “conservation of ambiguity” means that in the early stages of design, the designer should keep as many options open as possible. At this stage, it is important to focus on “what,” as opposed to “how.” Do not become too committed to the first idea that comes up, but instead keep searching for better (i.e., cheaper, faster, easier, etc.) ways to solve the same problem.

E.T.C.

Another Stanford concept, E.T.C. stands for “experiment-test-cycle.” As shown in Figure 7.2, E.T.C. suggests the iterative nature of design. Once a designer has a concept that s/he thinks will work, an experiment is designed to test the concept, and this process keeps cycling until it works well.

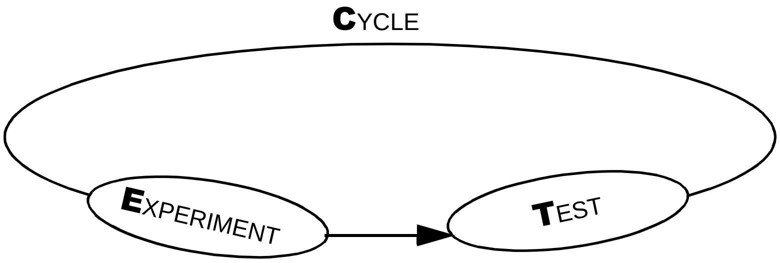

Figure 7.2. E.T.C. — The iterative nature of design.

Rapid Prototyping

It always works on paper! Only when new ideas are physically tried out does the designer get a real feel for the advantages—and disadvantages—of a new idea. Details on the use of modeling in the design process will be discussed in a later section.

STEPS IN THE DESIGN PROCESS

One framework for the design process is described below [1]:

1. Recognize the need.
2. Define the problem.
3. Plan and manage the project.
4. Gather information.
5. Generate alternative concepts to satisfy the design requirements.
6. Evaluate the alternatives.
7. Select the most promising concept.
8. Communicate the design.
9. Implement the design.

Although this listing is sequential, many of these phases should be done concurrently. “Concurrent engineering,” a process that conducts these phases in parallel—not in series, is widely practiced in industry today. This chapter provides more detailed information on the various steps in the design process, which may be useful on many open-ended design projects.

Step 1: Recognize the Need — The Customer

Designers develop a product to sell at a profit, which implies that someone will like it enough to purchase it. Therefore, it is essential to determine in advance what the customer wants. One approach is to interview customers directly about their needs. For example, Storage Technology Corporation (STC) in Louisville, CO, produces high-capacity data storage systems. At the earliest stages of designing a new product line, STC flew in (at their expense) customer representatives from around the country and listened to their needs. An even better approach, though, would be to have a company go directly to the customer and listen to their needs, rather than have the customer come to them. Another method is to observe and video tape a customer actually using an existing product to explore potential improvements to that product.

But *who* is the customer? Clearly, the person buying a product is a customer. The outside client who sponsors a university design project is a customer. But usually, there are others who are customers as well: the factory worker who builds the product; the person who repairs the product if it fails; and perhaps even the store manager, who decides which products to purchase and stock. Ultimately, a successful product should satisfy the needs of as many customers as possible.

Step 2: Define the Problem

There are two distinct phases to problem definition: articulating a *problem statement* and determining *design requirements*.

Problem Statement

Expressing the design challenge in a succinct, carefully thought-out statement can help focus the issues. Suggestions for creating effective problem statements include:

- Generalize the statement to stimulate creative solutions (conservation of ambiguity).
- Do not include a preconceived solution to the problem.
- Express the problem in *functional* terms (i.e., a verb and a noun).

The intent is to focus on solving the correct problem. One of the most common mistakes that designers make is to create an elegant solution to the wrong problem. Following are some examples of problem statements:

Acceptable	→	**Better**
Make a better can opener.		Extract the contents from a can.
Build a better mousetrap.		Keep mice outside.
Design a better lawnmower.		Shorten grass, or keep grass short.

Design Requirements

It is important to articulate the exact specifications for the product. If possible, have the customer review the specifications. Wherever possible, design requirements should be expressed in quantitative terms.

Following are some examples of design requirements:

Acceptable	→	**Better**
Light weight		Weigh less than 10 lbs
Inexpensive		Manufacturing cost less than $50
Fast		Accelerate from 0 to 60 mph in 6 secs
Compact		Fit inside a 2-ft cube

Not all design requirements can be expressed quantitatively, but it is important to list them anyway. For example, *all* products should be safe to use. When designing a product for safety, try to envision all the possible ways it could be misused and then design a way to prevent that misuse. Do not assume that the user of your product will read the instruction manual or warning labels!

Step 3: Plan and Manage the Project

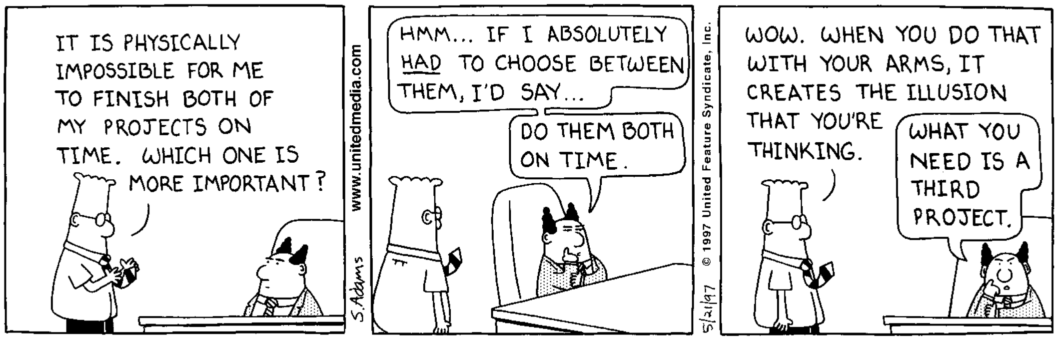

Figure 7.3. Keeping engineers busy with multiple projects. (DILBERT reprinted by permission of United Feature Syndicate, Inc.)

Most people perform better once they understand what they are doing. This means that you must *observe* and *manage* your actions. Even during the early stages of design, a little bit of planning and process management can work wonders. Continuous assessment of the design process allows the opportunity to improve the process both in terms of effectiveness and efficiency.

Although management of real-world engineering design can be a complex task, the application of a simple management approach can improve the design process immensely. The most basic sequence of project management activities is the *Plan - Assess - Adjust* sequence.

Plan

Design work planning involves thinking about the tasks to be accomplished, the resources that are available and the deadlines for products—or parts thereof—to be ready. Next, distribute the resources over the tasks and over time. The result is a "schedule," which shows *who* will work on *what* issues *when* and *which* materials will be applied to *what* task.

The combined scheduling of tasks and people can be handled in various ways. When tasks are driven by predetermined deadlines, a backward approach is especially useful. For instance, if the preliminary design review is on April 8th, plan on finalizing the design presentation a few days before that.

Note that a workplan generally evolves from a raw sketch with rather abstract tasks into a detailed plan in which each of the major tasks is subdivided into smaller tasks, requiring more detailed scheduling. Good plans take into consideration the dependencies between tasks. For instance, the drywalling of a house comes after the framing but before the painting. It would be ineffective to schedule the drywalling before the completion of the framing, but it would also be inefficient for the drywall to arrive before it is ready to be hung. It could sit outside becoming ruined by the weather (and the distributor would be paid earlier than necessary), or the additional cost of temporary storage might be realized. The latter is one of the reasons that in manufacturing the “just-in-time” concept is so popular.

Uncertainty also plays an important role. For example, if the completion date of a certain task is uncertain, then the start date of the next task becomes uncertain as well. To reduce the risk of wasting valuable resources, plan for alternative tasks (contingency plans) that other people can pursue in case the first task takes longer than expected.

Use Scheduling Tools

A useful tool for specifying and tracking task scheduling is a Gantt[1] chart (Figure 7.4), a table in which each task is allocated in time. The chart indicates the progression of work over time and provides an easy way of seeing which activities are planned at any given time.

Task	January	February	March	April
Requirement Meetings with Customers	■■■■	■■■		
Initial Conceptual Design		■■■■		
Initial Development Plan		■■■	■■■	
Final Conceptual Design			■■■	
Initial Materials Design			■■	■
Customer’s Approval of Conceptual Design				■■■■■

Figure 7.4. Gantt chart.

Like a Gantt chart, a PERT[2] chart (Figure 7.5) indicates the timing of activities, but it also contains their dependency relationships. In Figure 7.5, for instance, the “Testing Task” depends on completion of both the first and second programming task.

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[1] H.L. Gantt was an industrial engineer who pioneered this technique during World War I.

[2] PERT stands for Program Evaluation and Review Technique.

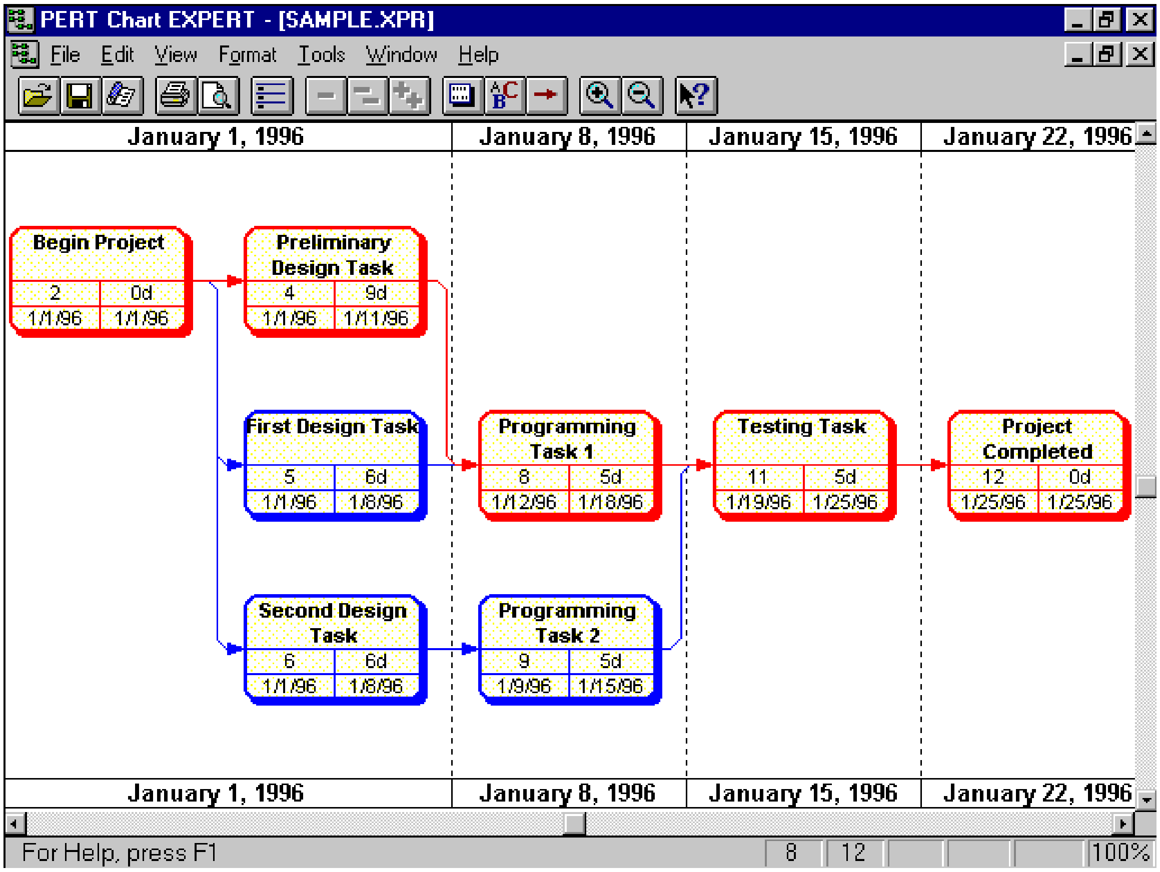

Figure 7.5. PERT chart.

Although these tools are often handy and easy to use, they are only as good as the estimates of how long a task will actually take. Experience reduces the uncertainty of the estimates, but even the most experienced task estimators often increase their estimates to allow for future unknowns.

When scheduling tasks, it is wise to document different types of information associated with each task:

- A short description of the task.
- The task's staffing.
- The task's planned start and completion dates.
- An overview of task dependencies.
- The task's estimated cost.
- An estimate of the consequences of missing a planned date.

A plan must be communicated to all members of the design team. This can be done through a team leader who presents and monitors the plan. Another method is to post the plan in an accessible location where team members can periodically verify their perception of the plan, annotate the plan or even indicate that certain tasks are finished.

Assess

Plans are only plans, and schedules and deadlines seem to be made to be violated. Therefore, it is wise to periodically assess how the project is actually matching with the plan: scheduled start and completion dates are compared with actual start and completion dates, and estimated costs are compared with actual costs. When plan and process are no longer in sync with each other, the uncertainties for the rest of the process increase. To bring this uncertainty back within manageable limits, the plan must be modified.

Periodic assessment of how well the process is following the plan is critical to any type of engineering process. Not only does it provide an opportunity to review current practice and improve the process, but it is also the means to curtail any future damage and cost. Although no team leader likes to hear that a task is behind schedule, effective team leaders prefer learning such news a month—rather than a day—before the deadline. The key, naturally, is that the earlier the problem is noticed, the greater the likelihood it can be fixed or mitigated.

Periodic progress reports keep a team, and its customers, informed about the state of the project. At regular intervals, report on the state of the tasks and the overall state of the plan maintained in the Gantt or PERT charts. Attach to each task some new information:

- Actual vs. planned start and end dates for a task.
- A brief explanation for the difference between planned and actual dates.
- A brief summary of the incurred cost or gains as a consequence of missing or beating the planned dates.
- A set of brief statements about *who* needs *what* from *whom*. If a customer does not provide the required feedback on a design plan, clearly state so in the progress report.

Adjust the Plan

Although assessment is useful in itself, its primary utility lies in the changes it brings about. Small deviations from the planned vs. actual start and end dates of a task, for instance, may not require a modification to the plan. However, when the discrepancy between plan and process becomes too large, the plan must be adjusted.

At this point, it should be clear that periodic assessment is vital for project management. Indeed, it is from the information collected during assessment that we learn not only *that* we have to modify the plan, but also *how* to modify the plan for the future. For instance, the average difference between previously estimated task durations and their actual duration contains information about our general capability to estimate a task’s time requirements. Also, data about how resources are being used tell us whether we over- or under-utilize certain people in our group. This, in turn, should provide information as to how to staff future tasks in a more balanced way.

Manage as a Team

“Leadership” and “management” are not the same thing. Good management implies good leadership, but it also needs structured and predictable processes, careful measurement and critical analysis. Charging ahead with great enthusiasm can easily degrade into frustration and non-productivity when the current course of action is not periodically subjected to critical analysis. The late Karl Popper, famous theorist of science, maintained that the mistakes we make are our *only* source of learning [2] [3]. From this perspective, it is crucial that an engineering team remains open to critique and recognizes that in good management, there are roles and tasks for most styles and approaches to managing a process.

Step 4: Gather Information

The more information, the better. Complete and thorough information can prevent a product from being designed that already exists in the marketplace or that violates federal standards. One source of information is to purchase and test competing products. Referred to as *benchmarking*, this industry practice establishes market norms for the product. A new product must improve on those norms if it is to be successful.

A *patent search* is another source of useful information that can help prevent designing a product that infringes on someone else's legal protection. A full patent search can be expensive and time-consuming, but information is available on the Internet:

IBM Patent Information	http://www.patents.ibm.com
US Patent and Trademark Office	http://www.uspto.gov
Do It Yourself Patenting/Inventors FAQ	http://doityourself.com/finance/invent.htm
Interviews with Inventors	http://www.thetech.org/revolutionaries
Inventor's Digest Magazine	http://www.inventorsdigest.com/

Extensive codes and standards established by federal, state or local governments, or even by industry itself, bind many products. Standards are useful because they allow for easy interchangeability of parts. For example, a ¼"-20 nut purchased at any hardware store in the country will fit a ¼"-20 bolt purchased elsewhere, thanks to precise industry standards for threaded fasteners.

Step 5: Generating Alternative Design Concepts — Invention

Invention can be the most creative and stimulating phase of the design process. It can also be the most frustrating! The challenge is to come up with as many alternative design concepts as possible from which to choose. For example, in designing a power sander, there must be a method of fastening the sandpaper to a sanding pad. Possible solutions to this problem include a clamp, glue, vacuum, magnets, snaps, a zipper or Velcro®. Some of these seven design concepts are well known, but others may be novel. Hopefully, the use of one of these concepts will be both new and feasible. The goal of this section is to present some useful techniques to stimulate the generation of creative ideas. Most of them are especially useful in a team situation and can be applied to overall design concepts or to focused components or subsystems.

Brainstorming

Although a commonly used term today, *brainstorming* was originally coined by Osborn in 1948 [4]. Brainstorming is an effective group problem-solving process, especially if a few simple rules are followed:

1. All ideas are written down.
2. Criticism is forbidden during the brainstorming session (critique comes later).
3. Combinations and improvements to ideas are sought.
4. The more ideas, the better.
5. Wild and crazy ideas are especially encouraged; they stimulate new, feasible solutions that may not have been considered otherwise.

As an example of the last point, a group of engineers at General Electric, including Osborn, were trying to come up with an easy way to connect a wire to a circuit in order to measure voltage. Existing methods at the time included screwing a wire to a post or soldering, both of which were time-consuming and too permanent. Someone suggested having a mouse bite two wires. This obviously “crazy” idea led to a very practical device in widespread use today, the alligator clip (Figure 7.6).

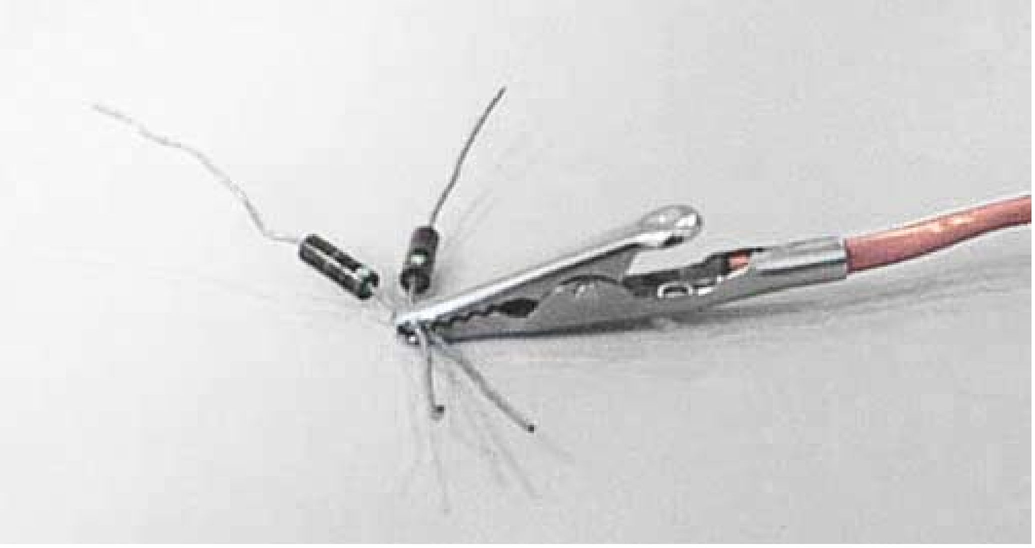

Figure 7.6. The alligator clip was the result of a "crazy" idea in a brainstorming session.

Choose a facilitator to moderate the brainstorming session. Pose the problem to the team (refer to the *Problem Statement* section), and have each team member think about the problem silently and write ideas on an index card. After a few minutes of individual thinking, the facilitator solicits an idea from each team member and writes it on a board or flip chart. Writing all ideas where everyone can see them is important because it can trigger new creative solutions or improvements to existing ideas. When the prepared solutions are exhausted, the facilitator solicits spontaneous ideas from the group in random order. A brainstorming session should be freewheeling and fun, lasting about 20-30 minutes.

Inversion

Inversion means turning something upside down or inside out. The basic idea of inversion is to imagine what would happen if the order in which various pieces of a system interact were changed. If Part A were fixed and Part B moves, what would happen if you fixed Part B and moved Part A? For example, in 1826, Oersted figured out that if a current is passed through a wire in a magnetic field, a lateral force is produced, the basic operating principle of an electric motor. In 1831, Faraday discovered an inversion to this concept: if a wire is forced through a magnetic field, it generates an electric current, which gives rise to a generator. And, in fact, an electric motor will generate electric current if it is forced to turn.

Another example is the contact lens cleaner case shown in Figure 7.7. In order to minimize irritation to the eyes after contact lenses are disinfected, a catalytic insert is placed in the cleaning solution at the bottom of the lens case. In an early design, the insert was wedged into the bottom of the case, which made it difficult to replace. A clever designer, perhaps stimulated by customer reaction to this design, came up with an inversion: fasten the catalytic insert to the lid instead of the case. Each time the contact lens wearer unscrews the lid to remove the lenses, the insert comes with it.

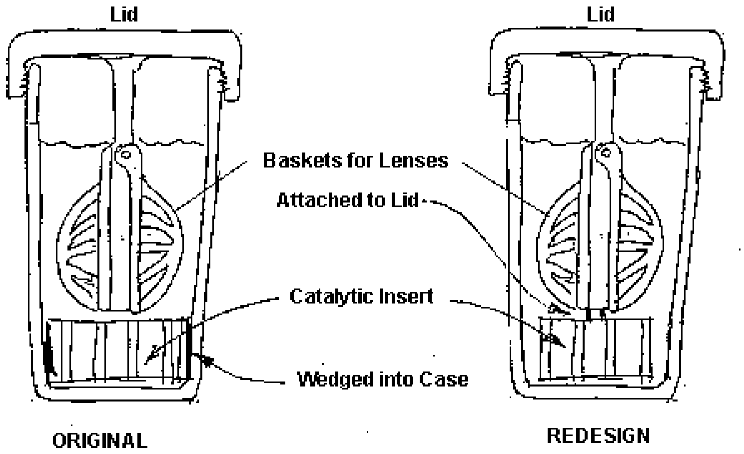

Figure 7.7. Two designs for a contact lens cleaning case.

Analogy

Many good design ideas are borrowed from other areas. Being aware of the surrounding world can stimulate creative solutions. For example, a toy store can be a rewarding source of new ideas. Examples of inventions and their source include:

Inspiration	→	**Invention**
Bat navigation		Sonar
Pistol grip		Hand power tool handles
Burrs		Velcro
Rattlesnake fangs		Hypodermic needles
Fireflies		Cold chemical light

Empathy

Imagine being an intimate part of the problem at hand. For example, if the challenge is to find a new way to clean CDs, imagine being about one inch tall standing on the CD. How could it be cleaned? A broom? A hose? These “crazy” ideas may lead to a cleaning brush or nozzle that is in fact very feasible, even though shrinking people is not! Or, if the problem is to design a new urban transportation system, imagine a giant straddling the entire city. How would that giant move people and goods across town?

Explain the Problem

People often get so entrenched in a problem they are attempting to solve that it is difficult to see it from a different perspective. Try explaining the problem to a friend or colleague who comes from a different viewpoint. Expressing the problem clearly to someone else can often help the designer see it in a new light.

SCAMPER

SCAMPER is a mnemonic device attributed to Bob Eberle [5], based on the ideas of Alex Osborn, the father of brainstorming. It was referenced in an excellent creativity book by Ed Sobey [6], who provided the example below. The word suggests different changes that could be made to an existing design to make the ideas start flowing. Each letter represents one or more ways to change the design:

S ubstitute

C ombine

A dapt

M odify, **M**agnify, or **M**inify

P ut to other uses

E liminate

R everse or **R**earrange

Example: suppose that your problem is how to keep your lunch cold until you eat it at noon. Running down the letters in SCAMPER, you might ask:

- Can I **substitute** the materials from which the lunch bag is made? Are there better insulating materials?
- Can I **combine** insulators? Is there something I could wrap around the lunch bag to keep it colder?
- Can I **adapt** an idea from somewhere else? What other products use insulation?
- Could I **modify** the lunch bag; for example, into a mini-cooler?
- What **other uses** could I make of a colder lunch bag? How about keeping freshly-caught fish cool on the way back to camp? Does that suggest any new ideas?
- Is there anything I can **eliminate** that might be transferring heat to the inside of the box?
- Could I **rearrange** anything? For example, could I make different arrangements for how or when my lunch gets made and gets to me at school?

Step 6: Evaluate the Alternatives — Engineering Analysis

One of the differences between engineering design and design in general lies in the use of *engineering analysis* to help make decisions and to guide the design process. For example, any good designer might choose steel as a material for an automobile drive shaft, but engineering analysis is used to size the shaft to transmit the torque from the engine and last the life of the vehicle.

Because many of the analytical tools necessary to perform appropriate engineering analysis are learned in the later stages of an engineering curriculum, it is often difficult for beginning engineering students to perform adequate analysis. Nevertheless, good analysis is essential for good design. Students should bear in mind that even in the “real world,” engineers are called upon to learn and apply new material constantly, often in a “just in time” manner. Given the estimate that knowledge doubles every seven years, engineers must cultivate a habit of lifelong learning.

Several chapters at the end of this book provide fundamental electrical and mechanical concepts that can aid beginning students in analysis. Other sources for guidance with analysis are engineering instructors with appropriate expertise, teaching assistants and upper division or graduate students.

Step 7: Select the Best Alternative

Engineering design always requires making decisions, since the design process generates alternative concepts from which to choose. While some decisions are easy to make, it is more typical to have a complex array of attributes that makes choosing the best alternative difficult. It may be useful to use a methodology to help with this process.

Like other design methodologies, this one is a process and forces decisions to be made based on rational evaluation of alternatives [7]. And, like other techniques, the result is only as good as what is put into it! The fundamental law of computer programming applies here as well:

Garbage In → *Garbage Out*

List Criteria

The design engineer should make a list of all the criteria s/he can think of to compare design solutions. Start with the original design requirements and add others that help compare competing design concepts. Some possibilities (not exclusive) are:

- Weight
- Appearance
- Ease of assembly
- Number of parts
- Time to produce
- Safety
- Estimated life before failure
- Size
- Ease of use
- Ease of repair
- Corrosion resistance
- Cost to produce
- Shelf life
- Environmental impact

Assign Priority Values to Criteria

There are two ways to set priorities. One way is to use a 1 (least important) to 10 (most important) scale, but any type of scale can be used. For example, if appearance is rated 10 and cost 8, that implies that appearance is 25% more important than cost. To reduce bias, have each group member assign priority values independently and average the results.

If there are a large number of people in the group, or if there are a large number of criteria to evaluate, an *interaction matrix* is an effective (and fast!) way to assess the relative importance of each criterion relative to all the other criteria. As shown in Table 7.1, make a matrix chart listing all the criteria both in rows down the left and in columns across the top. (A spreadsheet is an excellent, and easy, way to simplify this process.) Choose a facilitator, and poll the entire group for their opinion of the relative importance of a given criterion vs. each other criterion, one pair at a time. For example, the first non-blank cell in row 1 tallies the number of people who feel that Criterion 1 is more important than Criterion 2 (the diagonal cells are blank, for obvious reasons). After each vote, fill in the two appropriate off-diagonal cells (note that if there are N people in a group, and X people vote for Criterion 1 over Criterion 2, then the number of people who must favor Criterion 2 over Criterion 1 is simply N-X).

Table 7.1. Interaction matrix to assign design requirement priorities.

	Criterion 1	Criterion 2	Criterion 3	Criterion 4	Criterion 5	ROW TOTAL	NORMALIZED VALUE
Criterion 1		1 vs. 2	1 vs. 3	1 vs. 4	1 vs. 5	T_1	T_1/SUM
Criterion 2	2 vs. 1		2 vs. 3	2 vs. 4	2 vs. 5	T_2	T_2/SUM
Criterion 3	3 vs. 1	3 vs. 2		3 vs. 4	3 vs. 5	T_3	T_3/SUM
Criterion 4	4 vs. 1	4 vs. 2	4 vs. 3		4 vs. 5	T_4	T_4/SUM
Criterion 5	5 vs. 1	5 vs. 2	5 vs. 3	5 vs. 4		T_5	T_5/SUM
					COLUMN TOTAL	SUM	

Normalize the Priority Values

In order to get a better "feel" for the relative priority values, it is a good idea to *normalize* the values, which means to calculate each value as a proportion of a total that equals 1. Divide each value by the total sum of values. Each criterion will now have a priority value between 0 and 1, and the sum of all values will be 1 (i.e., 100%). A pie chart is a good way to visualize the overall results (Figure 7.8).

Example: Table 7.2 shows what the results might look like for a hypothetical problem in which a playground structure, with the following design requirements, is to be designed: light weight, low cost, long lasting, corrosion resistant and attractive. The bar graph in Figure 7.8 clearly displays the relative priority values.

Table 7.2. Interaction matrix for playground structure example

	Low Cost	Light Weight	Long Lasting	Attractive	Corrosion Resistant	Row Total
Low Cost		7	6	5	5	23
Light Weight	0		1	2	1	4
Long Lasting	1	6		4	2	13
Attractive	2	5	3		4	14
Corrosion Resistant	2	6	5	3		16
					COLUMN TOTAL	70

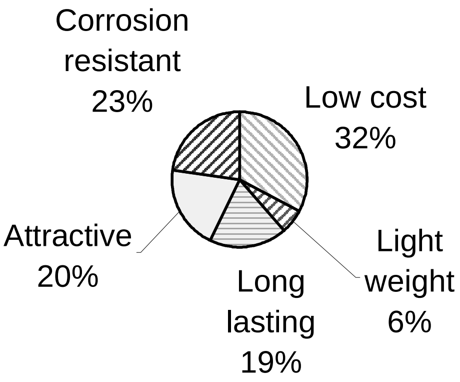

Figure 7.8. A pie chart clearly displays the relative priority values.

Analyze Alternative Designs

Rank each alternative design concept according to how well the group feels that concept could satisfy each of the design criteria identified in steps 1-3. Use a consistent scale, e.g., 0-5 or 0-10. A ranking of 0 means the concept does not meet that criterion at all, and a maximum score implies that the concept meets that criterion perfectly.

Compare Alternative Designs

Make a chart of the normalized criteria values, ordered from largest to smallest. This puts the most important criteria at the top of the list. Make a separate column for each idea being compared. Multiply each ranked value by the normalized criterion value factor, and sum them at the bottom (suggestion: use a spreadsheet).

Analyze Results

The concept with the highest value is the "best" one; i.e., it best meets the criteria as selected. Some concepts may have significantly lower totals than others, which suggests that they can be discarded. The concept with the highest score may be selected, or the chart can be studied for the highest score within each category and the concept with the majority of high rankings selected. Also, this method allows time and energy to be focused on the lowest ranked criteria of the "best" concept to see if improvements can be made. Yet another technique is to take the highest ranked concept from each criterion and generate a new idea that incorporates the better features of all concepts.

One caution: since the values are subjective, do not ascribe too much precision to the results. A score of 4.96 is not appreciably different from a score of 5.04.

Example (continued). Assume that a design group has identified four possible materials from which to construct the playground structure: wood, steel, aluminum and PVC (polyvinyl chloride, a type of plastic). Assuming that the structure will be outside, Table 7.3 shows what the results might be. Based on the priority values given the design criteria, wood is the clear choice. On the other hand, if the structure were going to be indoors, the relative priority values might change, giving the results shown in Table 7.4. Either aluminum or PVC now emerges as a possible candidate.

Table 7.3. Decision matrix for playground structure example—outdoor use.

Criteria	**Priority value**	**Normalized Priority Value**	**Wood**		**Steel**		**Aluminum**		**PVC**	
Low Cost	10	0.37	5	1.85	2	0.74	1	0.37	2	0.74
Corrosion Resistant	8	0.30	5	1.48	1	0.30	5	1.48	5	1.48
Long Lasting	5	0.19	3	0.56	3	0.56	5	0.93	5	0.93
Attractive	3	0.11	2	0.22	3	0.33	5	0.56	5	0.56
Light Weight	1	0.04	3	0.11	2	0.07	5	0.19	5	0.19
TOTALS	27	1.00		4.22		2.00		3.52		3.89

Table 7.4. Decision matrix for playground structure example—indoor use.

Criteria	**Priority value**	**Normalized Priority Value**	**Wood**		**Steel**		**Aluminum**		**PVC**	
Low Cost	10	0.34	3	1.03	2	0.69	5	1.72	5	1.72
Corrosion Resistant	8	0.28	2	0.55	3	0.83	5	1.38	5	1.38
Long Lasting	7	0.24	3	0.72	3	0.72	5	1.21	5	1.21
Attractive	3	0.10	5	0.52	1	0.10	5	0.52	5	0.52
Light Weight	1	0.03	5	0.17	2	0.07	1	0.03	2	0.07
TOTALS	29	1.00		3.00		2.41		4.86		4.90

Step 8: Communicate the Design

In days gone by, products were designed and fabricated by one creative and hard-working individual. Today's society is much more complex, and any given engineer or worker is responsible for only a small piece of the larger puzzle. In order for a complex project to be accomplished smoothly and effectively, good communication is vital.

Communication methods include written reports and instruction manuals, oral presentations and poster sessions. Details regarding written reports can be found in *Chapter 11: Writing.* Details regarding oral presentations can be found in *Chapter 12: Oral Presentations.* Engineering graphics communicate design intent efficiently and unambiguously, either through hand-drawn sketches or computer-aided design (CAD) methods; more information can be found in *Chapter 10: Engineering Drawing.*

Step 9: Implement the Design

It always works on paper! Only by creating a physical design can the unforeseen problems inherent in any design become apparent.

Models in Engineering Design

Modeling is an effective way to quickly answer questions about a design as a step toward final prototype production. As listed below, models can take many forms. The ideal model should answer the question being asked, but no more. In other words, models should be no more complex than necessary. For example, a complex, fully-rendered CAD model is a waste of time if the conceptual design stage is still being explored, when in fact good hand-drawn sketches will suffice. Some basic types of models that can help the engineering design process include:

Physical Model

Physical models can help answer questions of geometry, motion, interference, etc. Use any available material that is adequate for the task, such as cardboard, foam core, plastic, sheet metal, etc. One creative team of students answered many geometric questions about a complex 3D part by carving it from a block of soap. Heavy poster board and sewing eyelets can create complex movable mechanisms, but they will not transmit any significant forces.

Conceptual Model

A good hand-drawn sketch is the starting point for most engineering designs. For additional information, see *Chapter 10: Engineering Drawing.*

CAD Model

CAD models, especially fully-rendered solid models, are effective ways to depict issues of space, mobility, interference, etc., especially if they are parametrically based so that they can be easily changed. For more information, see *Chapter 10: Engineering Drawing.*

Free-Body Diagram

A simple diagram that shows all the forces and moments acting on a part under load is the starting point for analyzing most structures. But, many students do not realize that a free-body diagram can be an effective modeling tool, even if it is not solved explicitly. Just knowing the directions and approximate magnitudes of all the forces acting on a part can often provide good insight into what its design must be to perform the function. For additional information, see *Chapter 14: The Basics of Engineering Mechanics.*

Mathematical Model

The fundamental tool of engineering analysis is the mathematical model that represents the response of a component or system to external inputs such as force, voltage, temperature, etc. Care should be taken in using mathematical models to know the assumptions and simplifications that are implicit in any model.

Spreadsheet

A good spreadsheet is an excellent way to perform the mathematical computations quickly and efficiently. The user-friendly graphical capabilities of spreadsheets can help one visualize trends and correlations between variables. Also, spreadsheets are excellent at “what if” calculations that show the impact of changing one or more variables.

Computer Simulation

A powerful tool, computer simulations can be used to simulate the behavior of complex systems or components. Typical examples include computing the stresses and strains in a structure, the temperature distribution in a part, the flow of a fluid in a complex chamber, or the behavior of an electrical circuit. Some computer simulation tools, such as finite element stress analysis, link directly to CAD models of part geometry. *Care must be taken in using computer simulation to validate the results by separate, perhaps simpler calculations.* The results from a complicated finite element stress analysis are worthless if the wrong forces are applied.

Prototype Fabrication

The ultimate goal of the design process is to fabricate a prototype perfectly the first time. If done carefully, this can save tremendous amounts of time and energy. Perhaps the best example of this is the Boeing 777 aircraft, which underwent such sufficient modeling, simulation and analysis in the design phase that the very first airplane flown in 1995 was also the first one sold, saving millions of dollars and considerable time.

Final prototypes should be fabricated as professionally and carefully as possible, as they reflect all the previous work that has gone into them. Some prototypes can be fabricated with simple hand and power tools. More complex designs may require professional machine shop capabilities. Outside vendors can often do professional fabrication at a reasonable cost. For example, a piece of Plexiglas could be purchased from a vendor that is larger than what is actually needed. Then, the designer could cut it to specification him/herself. Alternatively, if the vendor is provided with the exact specifications, s/he can cut the piece to exact size, with a better quality. Using the best tool for the job generally produces the best results.

DESIGN FOR ??? (DFX)

The somewhat ambiguous title of this section refers to the fact that many aspects must be considered in any design. This includes Design for Manufacturability (DFM), Design for Assembly (DFA), Design for Serviceability (DFS) and universal design.

The Four Fs

The four Fs [8] are: *form, fit, function* and *finish;* they refer to detailed design aspects of components of a larger system.

Form refers to shape. Is the part shaped correctly to perform its function? If it is too thin, it may fail by breaking or by deforming excessively. If it is too large or too thick, it will be heavy and expensive. If it has a sharp external corner, it represents a safety hazard because sharp corners are cutting edges. If it has a sharp internal corner, high stresses will develop (which may lead to premature failure), and it will be difficult to produce.

Fit is involved when assembling two or more pieces to form a subsystem. Will the pieces fit together without gaps or discontinuities? If holes are drilled in a given component for bolts, are they in alignment so that bolts fit without interference? Fit becomes critical when dealing with rotating shafts that require bearings. If the bearing is to fit properly, tolerances required for the housing containing the bearing are very tight and require precise machining of the component parts. If the fit is too tight, the bearing will overheat and seize. If the fit is too loose, vibration will occur which detracts from performance, and shortens the life of the bearing and other components.

Function is the ability of the system to perform satisfactorily with its components. If a part fails in service, then the system cannot function. Suppose a crankshaft for an automobile vibrates excessively at an engine speed of 3800 RPM. It has the right form, it fits properly and it has the correct surface finishes on the bearing journals. But the crankshaft vibrates at or near highway cruising speed. The design fails because the performance of the auto has been severely compromised by the vibrations induced in the engine by the crankshaft. The crankshaft has not functioned correctly.

Finish refers to the surface finish of the part. Is the surface rough, smooth or polished? Does it matter? Some surfaces are important because of appearance. The sheet metal on an automobile is very smooth so that the paint will have a high gloss finish. Other surfaces are not important. The aluminum block on an automobile engine is die cast, and its outside surface reflects the finish of the die. An engine is rarely looked at in terms of beauty, and so a relatively rough surface finish is acceptable. Some surfaces are polished or ground to enhance their performance in bearing applications. When a part is designed, it is important to know how it will be used in service and specify the appropriate surface finishes on the detail drawing for that part.

Design for Manufacturability (DFM)

One of the intriguing aspects of engineering design is that alternative design concepts can be conceived which all perform the required function equally well, yet the cost to manufacture them can differ by a factor of ten or more. For example, one way to make a simple bracket is to machine it from a solid block of metal, a time-consuming and expensive process. Comparable function, *with no sacrifice in quality*, can be achieved by stamping and bending the bracket from a thin piece of sheet metal.

For parts that are produced in large quantities, the way in which each part will be manufactured is equally as important as function. The design engineer must carefully consider manufacturing methods such as die casting, injection molding, forging, casting, drawing, machining, stamping, etc.

in the detail design of mass-produced parts. Even one-of-a-kind prototypes can benefit from careful DFM consideration.

Bralla [9] has produced an excellent reference containing detailed DFM guidelines for a wide range of manufacturing processes, and Boothroyd et al. [10] have published general DFM guidelines to be followed in design. Storage Technology Corporation has outlined 12 fundamental concepts of DFM [11]:

1. *Reduce the Number of Parts.* Simplicity is the key. The ideal product has one part.
2. *Use Modular Design.* Use “building blocks.”
3. *Don’t Fight Gravity.* Design so that a product can be assembled from the top down.
4. *Reduce Processing Surfaces.* Avoid expensive part reorientation. Finish processing on one surface before moving to the next surface.
5. *Process in the Open.* Minimize restricted access and vision problems.
6. *Eliminate Fasteners.* Fasteners are expensive, difficult to handle and vibrate loose. Use snap fits, adhesives, etc.
7. *Optimize Part Symmetry.* Either design parts so that they can function in any orientation (e.g., a washer), or make the parts obviously asymmetrical. Design so that a product *cannot* be assembled incorrectly.
8. *Optimize Part Handling.* Provide gripping surfaces; avoid flexible parts or parts that tangle.
9. *Design for Easy Part Mating.* Provide “guide surfaces,” such as chamfers.
10. *Provide Nesting.* Design features to locate parts during assembly.
11. *Reduce, Simplify and Group Processes.* Group “like” processes.
12. *Optimize Process Sequence.* During design, think about how a product will be made!

Design for Assembly (DFA)

Most designs consist of assemblies of components. Once the components are individually manufactured, they must be assembled into the final system. Design engineers tend to focus on function while ignoring how components can be manufactured or how components can be assembled. While more extensive coverage of this topic can be found elsewhere [10], one of the fundamental DFA concepts is to minimize the number of parts. A part that is not there does not have to be manufactured, inspected, shipped, inventoried or assembled. It will not, therefore, ever vibrate loose or need to be replaced.

Design for Serviceability (DFS)

The perfect design would *never* require maintenance. However, this is not always possible. For example, an automobile oil filter keeps the oil clean by trapping small particles, preventing them from damaging the engine. But eventually, both the oil and the oil filter must be changed on a regular basis in order to prolong the life of the engine.

Changing the oil filter varies tremendously from car to car. On some cars, the body of the car must be raised; someone would have to crawl under the car and reach up to unscrew a horizontallyoriented filter. When the filter is loosened, it leaks, and oil runs down the side of the engine and onto the mechanic. Clearly, the design of this engine and the placement and orientation of the oil filter did not accommodate the need for periodic and scheduled maintenance. On other cars, the filter is replaced from the top without going under the car. The designers have also oriented the filter vertically so that the oil does not spill when the filter is loosened. This second filter is an example of design for serviceability. The designer recognized the need for periodic maintenance and developed the product to allow for easy access and rapid, inexpensive replacement of the required parts.

For a design project, design to minimize maintenance. However, if servicing is required, design the product so that it can be easily serviced, and provide clear, written instructions.

Universal Design

The concept of *universal design* means that products should be usable by as many people as possible, including a range of ages, abilities and disabilities. Seven principles should be considered as a part of design decisions:

1. *Equitable Use.* The design is useful and marketable to people with diverse abilities.
2. *Flexibility in Use.* The design accommodates a wide range of individual preferences and abilities.
3. *Simple and Intuitive Use.* Use of the design is easy to understand, regardless of the user’s experience, knowledge, language skills or current concentration level.
4. *Perceptible Information.* The design communicates necessary information effectively to the user, regardless of ambient conditions or the user’s sensory abilities.
5. *Tolerance for Error.* The design minimizes hazards and the adverse consequences of accidental or unintended actions.
6. *Low Physical Effort.* The design can be used efficiently and comfortably with a minimum of fatigue.
7. *Size and Space for Approach and Use.* Appropriate size and space is provided for approach, reach, manipulation and use regardless of user’s body size, posture or mobility.

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