CHAPTER 3

The Design Loop

INTRODUCTION

Obtaining a viable solution to an engineering problem requires thought and action coordinated in a specific, iterative pattern. The method enables engineers to evaluate and refine potential solutions. Each step defines a specific action that propels the project forward to the next step. This process is shown in Figure 3.1.

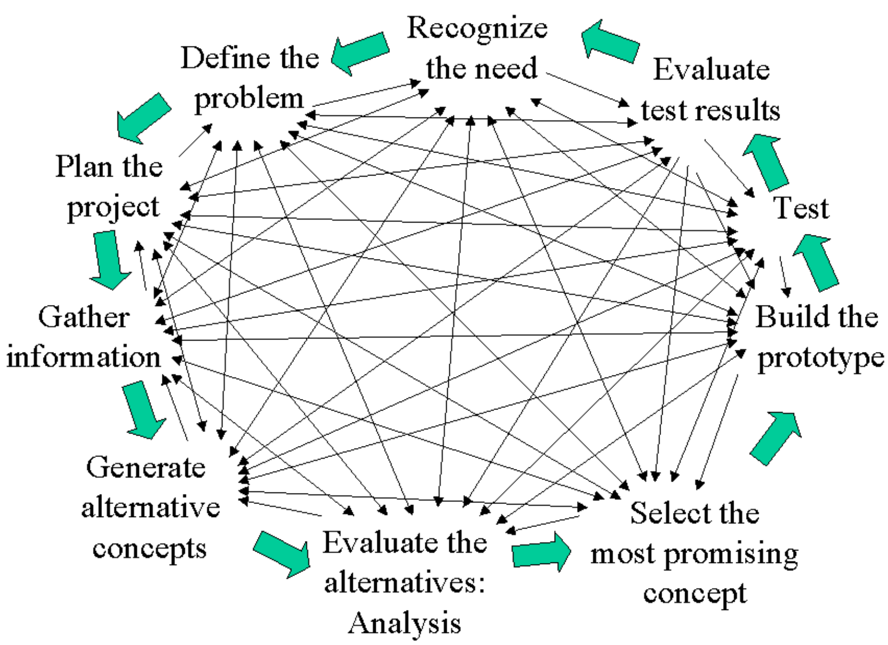

Figure 3.1. Schematic of the design process.

The process begins when a design engineer recognizes the need for a solution to a problem. A brief examination of the problem leads to defining and determining the requirements of the project. Although the full scope of the solution is still undefined, the design team begins to plan the project by estimating how much time each stage of the project should take. The team then gathers information to refine the objectives of the project.

Throughout these first stages of the design process, ideas for potential solutions representing alternative concepts will be generated. These concepts must be analyzed, so that an informed decision selecting the most promising concept can be made. These important analyses take the process out of the realm of pure "trial and error" into an "engineered" solution. Next a *prototype*, or first model, is constructed. The prototype is then tested to see if it fulfills the requirements. The outcome of the test is evaluated to determine whether modifications are needed or if new problems have been created. If so, the loop is started over (iterated). If not, the original problem has been solved.

This is an idealized model of the design process. In reality, events rarely proceed so smoothly. Instead, stages occur simultaneously, shortcuts around the loop are often taken, and sometimes the process goes in reverse. The following example illustrates some possibilities: the column on the right identifies the design process stages as they occur in the example.

EXAMPLE: DESIGN OF A CUP HEATER

Suppose that your small design team at Sunbeam Inc. was given the following task: *Design a better cup heater to heat 250 ml of tap water to boiling in 2 minutes.*	⇐ Problem statement
First, notice how simple—yet general—the problem statement is. There are no guidelines for the size or type of heater, except that it must fit inside a cup. Also, the shape of the heater is unclear. Your team also asks the questions: "To what is the heater compared? Better than what?" Your supervisor says that the heater should perform better than a microwave oven and plug into an electric wall socket. Then, your supervisor mentions that you have only one week to complete the design.	⇐ Problem definition
"One week!" Your team quickly realizes that the preliminary design must be completed today, and tested and refined tomorrow.	⇐ Planning
These first observations and questions are written in your design journal, but they remain unanswered. What is the next step in assessing the problem? A quick look in a physics textbook helps to further define the problem. Your team finds that it is possible to generate heat by passing a current through a wire.	⇐ Information gathering

Now the ideas start to flow. One team member remembers that her mother uses a small electric heater to heat cups of water. You remark that electric space heaters basically are made of long sections of thick wire, too. A suggestion is made to purchase a tea cup heater. Many team members speak at once. Someone suggests, obviously in jest, building a pocket-sized nuclear weapon. Another idea is to use the chemical packet that warms up feet in ski boots. All of these ideas are documented in your journal.

⇐ Brainstorming: generating alternative concepts

Your supervisor then requests that the heater be constructed from specialty wire located in the warehouse. You wonder what is so special about this particular wire. You wonder if the supervisor will continue to add more parameters.

⇐ Additional problem definition

Since heating wire is now required, your team decides to evaluate that concept further. A sketch is drawn in your design journal. The potential set-up looks something like the drawing in Figure 3.2.

⇐ Selection

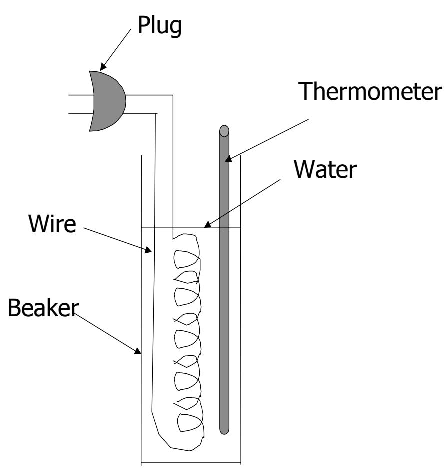

Figure 3.2. Design journal sketch.

A parts list prepared from the sketch includes wire, beaker, water and thermometer. Two team members state that they are ready to build the heater—but *are* they? Some members of the team want to build the heater immediately, but you say that the team needs more information before beginning. Another member returns from

⇐ Information gathering

the warehouse with a spool of the specialty wire. The label states that the material is NiCr, that the wire diameter is 22 gauge and that the resistance is 1.6 Ω per foot. One team member notes the thinness of the wire. Another team member says that the symbol “Ω” stands for the word “ohm.” How does the value of 1.6 Ω per foot relate to the heating of water? Your team realizes that it must perform an *engineering analysis* of the problem to understand the relationship between the heating wire and the temperature of the water.

⇐ Information gathering (cont.’d)

Together you discuss how a heater performs. Current flowing through the wire causes the wire to heat. The heat is transferred to the water. Your team estimates that the temperature of the water must be raised a maximum of 100°C, if the temperature comes out of the tap at close to 0°C (as a worst case scenario). How much heat is required to perform this feat? What equations apply to heating water? Someone digs out a first-year chemistry book, and the team finds that the heat absorbed by a volume of water is related to its heat capacity according to the following energy equation:

⇐ Engineering analysis

$$Q = C_p \Delta T,$$

where Q is the energy or heat absorbed by the water in watts, and $\Delta T = (T_2 - T_1)$, the difference between the beginning and ending water temperatures.

The reference tables in the back of the chemistry book give a value for C_p of water as approximately 1 cal/cc/°C.

$$Q = \left(1\frac{cal}{cc^{o}C}\right)(100°C - 0°C)\left(1\frac{cc}{ml}\right)\left(4.1868\frac{Joules}{cal}\right)\left(1\frac{Watt - \sec}{Joule}\right)$$

$$Q = 418.69\frac{Watts - \sec}{ml}$$

This is the amount of energy needed to heat one ml of water 100^{o}C. Heating a cup of water (250 ml) in 2 minutes will take $\frac{\left(418.68\frac{Watt - \sec}{ml}\right)(250ml)}{(2min)\left(60\frac{\sec}{min}\right)} = 873Watts$.

⇐ Engineering analysis (cont.'d)

This value, $Q = \frac{dQ}{dt} = 873Watts$ is the energy per unit time, or power, required. At this point, you perform a reality check. "If this were a light bulb, it would be pretty bright. Some hair dryers are only 800 watts. Some microwaves are around 1000 watts, but it does take a lot of energy to heat water."

Your next move is to determine how much wire is needed. The physics text states that for any material conducting electricity, Ohm's Law is given by the following formula:

V = IR,

where V is volts, I is current in amps, and R is resistance in ohms. You also read that the power P dissipated by the wire is given by this formula:

$$P = I^2 R = IV$$

Now, by using the above power equation, your team finds the current that is carried by the wire. The heater is to be plugged into a socket supplying common household electricity that has a voltage of 110 volts. From the power equation, the following expression is obtained for I:

$$I = \frac{P}{V} = \frac{873Watts}{110V} = 8amps$$

The required wire resistance is calculated from Ohm's Law:

$$R = \frac{V}{I} = \frac{110V}{8amps} = 14\Omega$$

Now, the length of the wire can be estimated. The length is found from the resistance characteristic stated on the label, or 1.6 Ω per foot, and the required resistance value for the heater, or 14 Ω:

Length = 14 Ω / 1.6 Ω per foot = 8.75 feet.

This seems like a reasonable amount to coil up in a coffee cup, since the wire is so thin.

Your team decides that the analysis supports the original design concept shown in Figure 3.1 and chooses to build it. The team gathers in the lab and locates a glass beaker, an alcohol thermometer, a pair of wire snips and an unwired electrical plug. One team member suggests using a 10-amp fuse "just in case." The wire is wound neatly around a 1-inch rod, and he ends of the wire are attached to the plug and the fuse. After filling the beaker with water, the coil of wire is submerged. You are ready to record the amount of time to heat the water while another team member prepares to record the temperature rise, and a third snaps a photograph of the experimental set-up. The plug is placed into the outlet.

⇐ Engineering analysis (cont.'d)

Everyone watches as the plug smokes and they hear the snap of the fuse. What happened to heater? Why has it shorted out?

⇐ Testing

The team evaluates the test procedure. The bare wire was placed in the beaker of water. The fuse is attached to one end of the wire. The other wire end and the fuse end were connected to the plug. A team member comments, "Doesn't water conduct electricity?"

⇐ Evaluation of test results

All of you simultaneously recognize that the water created a short circuit around the wire because the wire was not insulated from the water.

⇐ Problem re-definition

Your team decides to modify the configuration so that the wire is electrically insulated from the water. Scouting around the supplies in the warehouse, the team notices thin, small diameter tubing called shrink tubing. The tubing slides over uninsulated wire. A heat gun is used to shrink the tubing until a snug fit is obtained.

⇐ Concept selection

You apply the shrink tubing and then start the test again. After four minutes the temperature of the water reaches 50°C.

⇐ Prototype fabrication

After eight minutes the temperature is only 90°C. It takes 11 minutes to heat the water to boiling.

⇐ Testing

The team evaluates the data by plotting the temperature rise as a function of time (see Figure 3.3). Why does it take so long to heat the water to boiling?

⇐ Evaluation of test results

One team member muses on the possibility of the insulation affecting the rate of heat dissipating from the wire. You suggest that the plastic tubing acts as electrical and thermal insulation. The team decides that only electrical insulation is necessary. How can the design be changed to obtain the correct amount of heat transfer?

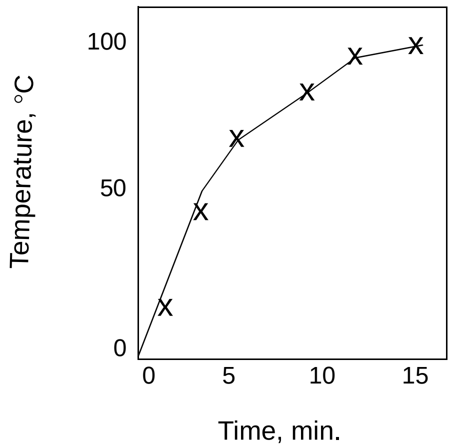

Figure 3.3. Plot of temperature vs. time.

One person proposes that thinner shrink tubing be found. Another team member suggests using a longer wire. How much longer should the wire be? Two team members suggest using at least four times as long, while another says it should be six times as long.

⇐ Generating alternative concepts

After much discussion, your team decides to try using more analysis to determine an appropriate length for the wire. You review the equations and realize that you need a heat transfer model to take the thermal insulating effect of the shrink tubing into account.

⇐ Engineering analysis

Conclusion

What do you think will happen in the next iteration of the design loop? The heat transfer analysis could lead to a new prototype with a much longer length of wire. Testing could show the same temperature response. Additional information gathering could reveal that a thick rod of NiCr could better heat the water. Additional brainstorming could lead the design team at Sunbeam Inc. to a completely different design. Many possibilities exist, most requiring substantial planning, problem definition, engineering analysis and testing to justify advancing a particular design choice.

The preceding example demonstrates the iterative process that a typical engineering design solution can follow. In this course your design team will find that many solution pathways can exist. Practicing the steps in the design loop will help determine the optimal solution for your design problem.