Chapter 4

Introduction to Engineering Design

4.1 About This Chapter

Before beginning this chapter, look around you for a moment and notice how much of your environment has been designed by humans. Perhaps you are reading inside a building; people designed, engineered, and constructed it. This book has been designed; if you are reading it in a paper format, the paper, ink, and binding have been manufactured, while if you are reading it electronically, the computer on which you are reading has been designed and fabricated.

Almost every aspect of modern life depends on and is affected by technological **artifacts** such as bridges, buildings, vehicles, cell phones, computers, and so on. These technological artifacts are designed and created by engineers; the process by which engineers create is often called the engineering design process. ABET, the organization that accredits undergraduate university and college engineering programs, has developed the following definition of the engineering design process.

> Engineering design is the process of devising a system, component, or process to meet desired needs. It is a decision-making process (often **iterative**), in which the basic sciences, mathematics, and the engineering sciences are applied to convert resources optimally to meet these stated needs.

Chapter Learning Objectives

After working through this chapter, you should be able to do the following:

- Explain what a design process is.
- Explain how engineering design differs from other design processes.

- Explain the different steps in the engineering design process.
- Apply each step of the engineering design process to design a product or process.
- Describe how the implementation the design process affects the quality of the resulting design.

4.2 The Design Process

The word *design* has several meanings. One meaning is a plan or drawing that shows the look and function of an object or structure before it is made. This is the meaning of design that we consider in this chapter. Examples of this meaning for design include

- a team of architects may develop the design of a building, specifying the building's appearance and the layout of rooms, doors, and hallways;
- a team of engineers may develop the design for a new jet engine, specifying its structure and the materials from which it is built.

Figures 1 and 2 show examples of this type of design.

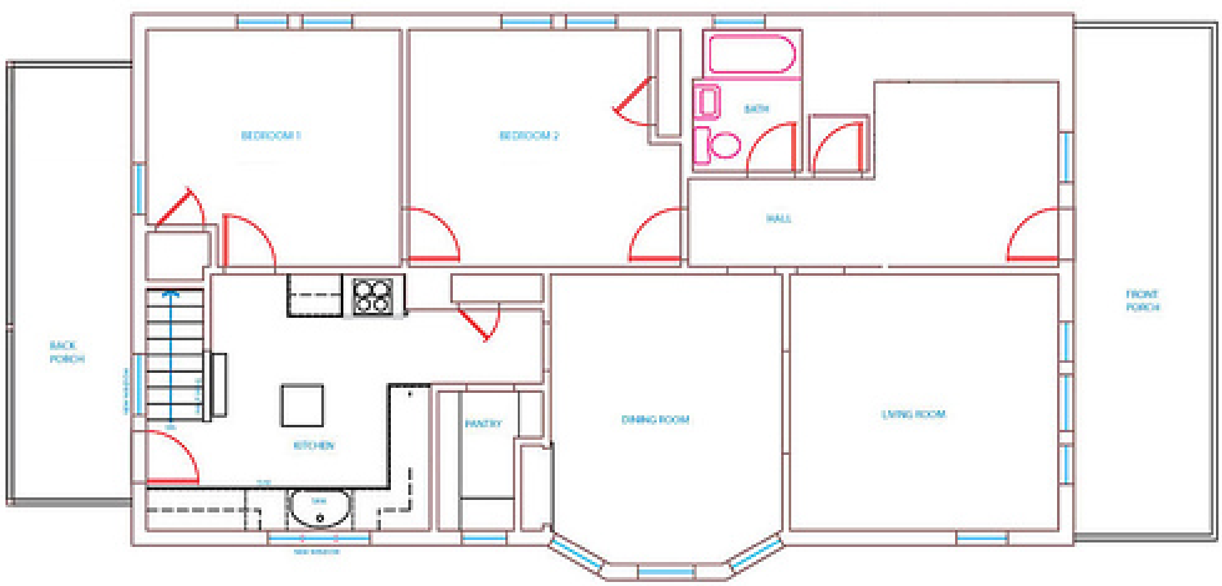

Figure 4.1: The floor plan of the first story of a house. Architects document their designs using such floor plans.

In general conversation, the word design is often used to mean "an arrangement of lines or shapes to form a pattern or decoration." Figure 3 shows an example of this meaning for design; this is *not* the meaning that we are considering in this chapter.

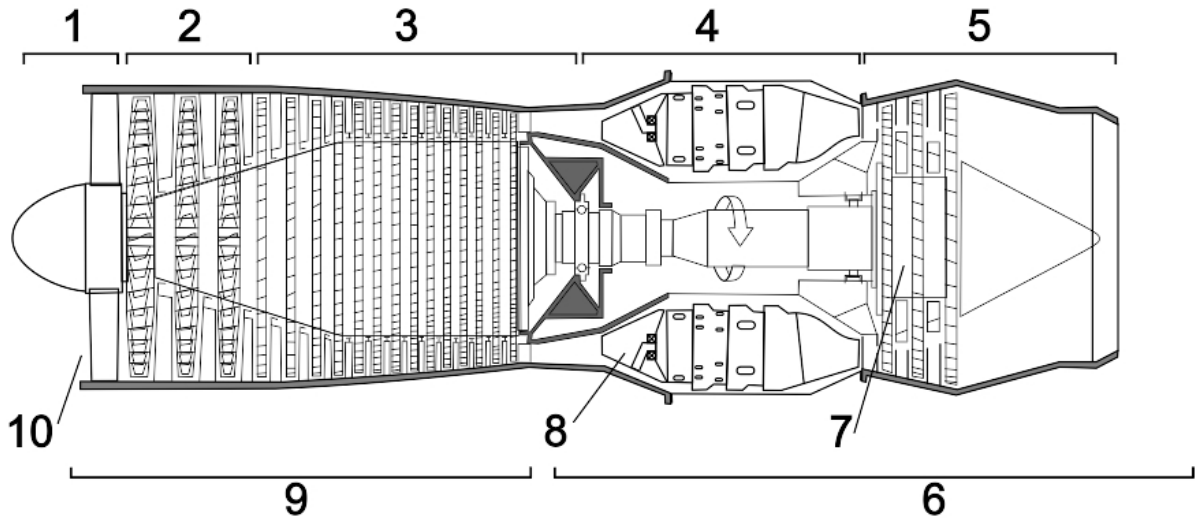

Figure 4.2: A design of a jet engine.

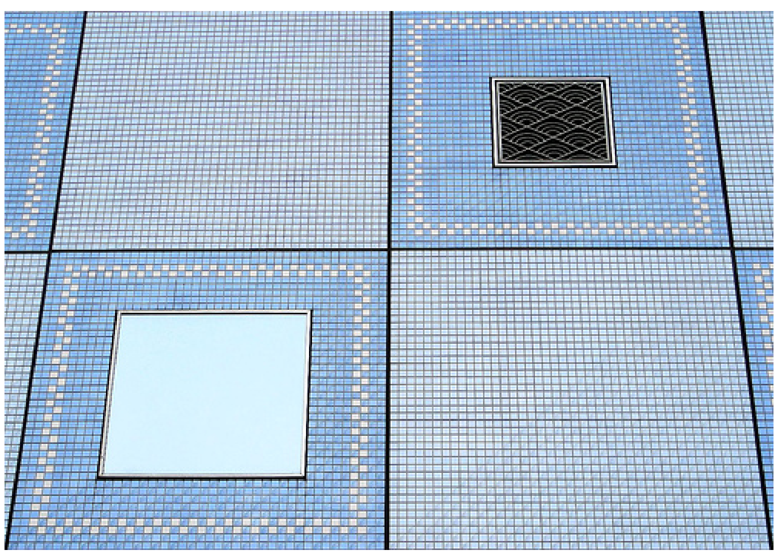

Figure 4.3: A design can be an arrangement of shapes and lines that forms a decorative pattern. This is the type of design that we will consider in this chapter.

A process by which a design for an object or a structure is created is called a *design process.* All design processes have similarities. They all involve creativity. They all involve making decisions. However, engineering design tends to require a more extensive and specialized knowledge of technology, math, and science than other types of design.

Engineering Design

Teams undertake several different types of engineering design projects. Most projects involve modifying or enhancing an existing product or process; these projects are described as **incremental design**. Sometimes a new product is developed from scratch. Such a project would be a new design. Both types of projects use the design process.

The purpose of most design projects is to develop an object, structure, or process that meets the needs of **customers** and **stakeholders**. A customer is someone who will use the designed object; customers usually pay for the product. A stakeholder is someone who has an interest in the product. Customers are stakeholders; other stakeholders may include government agencies, companies, and individuals. For example, stakeholders for a new automobile design might include the individuals who will purchase it, the mechanics who will maintain and repair it, the Environmental Protection Agency that will monitor its emissions, and the oil companies that will supply its fuel.

Design problems are almost always open ended—they rarely have a single correct solution. Instead, there are usually several solutions that will satisfy the desired needs. One of the challenges of design is to choose from the vast number of possible solutions. Indeed, engineered products may be very complex, and the design of such products may require that a design team make hundreds or thousands of decisions. Without a clearly defined process to follow, the team may not develop designs that meet the needs of customers or other stakeholders; the team may make poor decisions or lose sight of the important attributes of the product. Thus, it is important to use a structured design process. Structured design processes offer several advantages. They provide a framework in which the team decision-making is made explicit and the decision process can be well documented. They also reduce the likelihood that important issues will be forgotten or overlooked.

In this section, we describe "the engineering design process," which may give the impression that there is only one correct process. In reality, many processes have been successfully applied to engineering design. The design process discussed in this section may not always be the best for a given project or problem. The design process should not be applied blindly, but should be adapted to fit the circumstances of the design team and the particular project. The design process should also be subjected to a continuous improvement process so that the design team's performance improves over time.

The engineering design process may not result in a **viable** design for several reasons:

- Incorrect or unrealistic assumptions.

- A lack of understanding of the desired needs or underlying problems to be solved.
- Errors in design specifications or representations (e.g. **models** and drawings).
- Inadequate testing of **prototypes**.
- Poor design choices.

Sometimes, poor design decisions made early in the process will make it impossible to develop a design that successfully meets customers' needs.

A Design Process

In this section we present a typical engineering design process. Other descriptions of the design process may break the process into somewhat different steps and may use somewhat different terms to describe the steps, but most design processes are similar to this one. An example of how this design process could be applied is in The Design Process in Action section.

Figure 4.4: A design process.

Our basic engineering design process includes the steps shown in Figure 4. Note that Figure

4 shows each step being completed before the next step begins; this process is sequential. In many real-life situations, the design team may revisit a step several times to create the final design. We now describe the steps in more detail.

Define the problem. In the problem definition step, the needs of potential customers are investigated; potential competitors are identified and their market positions are **characterized**; **constraints** imposed by government regulations or technological limitations are identified; and constraints on the design effort such as available personnel, time, and money are established. The problem definition process results in a clear understanding of the scope of the design project and the resources available to solve the design problem. This understanding is often expressed in a **problem statement**. This understanding is also expressed in the form of criteria and constraints.

Identify criteria and constraints. **Criteria** and constraints are used to evaluate the quality of a design. Constraints describe conditions that must be met by the design and design process; a design must meet all constraints. Criteria are measurable values that can be used to compare several designs and determine which is better.

Generate ideas. Once criteria and constraints are identified, the design team generates ideas for designs. These ideas come from many different sources; these include existing products (including competitors' products), brainstorming and other creative activities, and market and technical research. Ideas are combined to generate potential designs; at this stage, designs are concepts without a significant level of detail.

Explore possibilities. After potential designs are generated, they are explored to understand their characteristics and likely advantages and disadvantages.

Select a design concept. Potential designs are evaluated relative to the constraints and criteria, and one or more is selected to be designed in detail and prototyped. This selection is made using a structured process that requires the constraints to be met and chooses the best design according to the criteria.

Develop a detailed design. The selected design is developed in more detail. The **design architecture** is established by identifying physical and functional chunks. Shapes and **dimensions** are determined, materials and fabrication processes are selected, and product components are identified. The design is developed in enough detail that prototypes and models of the design can be made.

Create models and prototypes. One or more prototypes are typically implemented to characterize various aspects of the design. Prototypes may be physical models of the design in which dimensions, materials, and fabrication processes emulate important aspects of the design. Increasingly, prototypes are implemented using computer modeling software that simulates mechanical, electrical, and other characteristics of the product.

Test and evaluate. Prototypes are tested to see whether the design meets all constraints and performs acceptably relative to the criteria.

Refine the design. Testing and evaluation may reveal weaknesses of the design or indicate ways in which the design may be improved. At this point, the design may be refined to better meet the criteria and constraints. Sometimes, testing and evaluation show that a design will not work, so that a different design concept must be selected; in this case, the process goes back to the "Select a design concept" step.

Implementation. Depending on the context, the design is produced or constructed.

Communicate process and results. The activities and results of the design process are documented. This documentation is communicated to the appropriate stakeholders in the design.

The design process in Figure 4 is often called a sequential process because each step follows the previous one in direct sequence. This model does not account for the iterative nature of many actual design projects; as designs are developed, prototyped, and evaluated, their strengths and weaknesses are better understood and changes are made to the design on the basis of this improved understanding. After changing the design, the process of prototyping and evaluating is repeated. The design process in which the processes are iterated is often called a spiral design process. A spiral design process is illustrated in Figure 5.

Figure 4.5: A spiral design process. Changes are made in the design, and then the improved design is evaluated.

The advantage of using a spiral design process is that the end design is often much better than the initial design. The significant disadvantage of the spiral design process is that time and resources are required for each loop in the spiral; if these are not planned for, the project may easily be late and over budget.

Review Questions

Multiple Choice

The following questions will help you assess your understanding of the Discovering Engineering section. There may be one, two, three, or even four correct answers to each question. To demonstrate your understanding, you should find all of the correct answers.

1. Which attributes describe the engineering design process?
   (a) Creativity
   (b) Specialized knowledge of math and science
   (c) Decision making
   (d) Specialized knowledge of technology
2. Incremental design means that the
   (a) design process is slow
   (b) an existing product or process is modified
   (c) design is done in pieces
   (d) an existing product or process is enhanced
3. The design process may not produce a good product because
   (a) the team was made up of different kinds of engineers
   (b) materials were delivered too late to use
   (c) the engineers focused on attributes of the product
   (d) prototypes were not tested adequately
4. Which of these is used to evaluate the quality of a design?
   (a) The number of prototypes tested
   (b) The spiral design process
   (c) Criteria and constraints
   (d) The size of the engineering firm
5. What is the first step in the design process?
   (a) Explore possibilities
   (b) Define the problem
   (c) Select a design
   (d) Generate ideas
6. What is the last step in the design process?
   (a) Communicate process and results

(b) Test and evaluate
(c) Refine the design
(d) Implement

7. A good design
   (a) does not have constraints
   (b) is not limited by criteria
   (c) meets constraints
   (d) develops criteria and constraints
8. **Free Response Questions**
9. Why are planning and evaluation as important as creativity in the design process?
10. What is the difference between engineering design and other types of design (architectural, fashion, etc.)?

Review Answers

The Design Process

1. a,b,c,d
2. b,d
3. d
4. c
5. b
6. a
7. c

4.3 The Design Process in Action

In this section, we go through an example of a team using the design process. This section provides more detail about the steps of the sequential design process.

Case Study

To provide concrete examples throughout this section, we will use a design case study. In this case study, we will follow the design process used by an intrepid team of engineers who work at a small manufacturing company to develop a product that solves some of the problems with current commuting options. At the beginning of their project, the team chose a suitable engineering name for their project: the **sustainable** commuter vehicle, or SCV for short.

According to the United States Department of Transportation, in 2000, over three-fourths of the trips made to and from work were made by individuals traveling alone in a car, sport utility vehicle, or truck. In some ways, jumping in the car and going is the hallmark of modern American life. Americans prize the convenience and comfort of the modern automobile, even though it creates some serious problems.

- Vehicles create 20% of **greenhouse gas** emissions in the United States and appear to be a significant contributor to future climate change. **Carbon dioxide** is one of the principle greenhouse gasses emitted by vehicles.
- A typical American household spends more money on driving costs than it spends on food.
- In most major metropolitan areas, “rush hour” (congested traffic conditions similar to those in Figure 6) now lasts six to seven hours a day.
- Traffic congestion costs $63.1 billion per year. Each year, commuters stuck in traffic jams waste 2.3 billion gallons of fuel, not to mention their time or frustration.

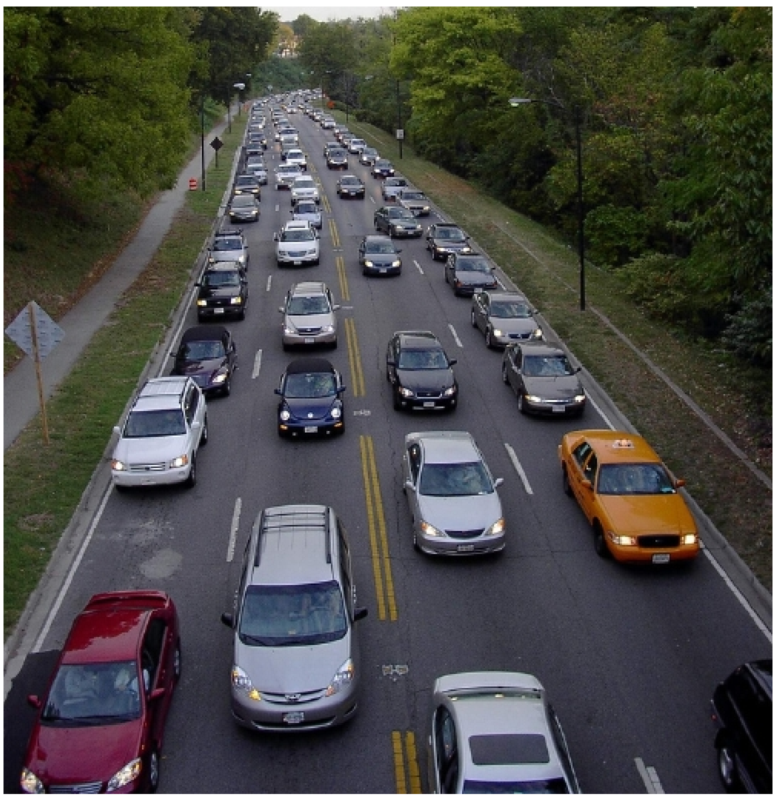

Figure 4.6: Rush hour traffic in Washington, D.C. Heavy traffic and long delays, as well as the associated air pollution and fuel consumption, are major problems for communities.

Is there a way to solve some of these problems without completely giving up the comfort and convenience that we have come to expect?

Activity

To increase understanding of the issues faced by the engineering team, complete one or more of the following exercises that involve problems associated with commuting.

- Research the issues associated with commuting in your area. These issues might include traffic congestion, accidents, and pollution.
- Do you know anybody who commutes regularly to work alone in their automobile? Talk to them about the benefits and drawbacks associated with this.
- Find information on transportation planning in your area. How much money is spent developing new roadways? How much money is spent upgrading and maintaining existing roads? Is the current road network effective?
- What problems do environmental activists in your area see with the current commuting **infrastructure**?

With your understanding, write a paragraph describing the commuter problem from the perspectives of the commuter, the city planner, and the environmental activist.

Activity

Spend an hour working with a team of classmates to develop a design solution to the commuter problem. Write a paragraph that describes what your team did during the hour. Then consider the following questions:

- Did your team find a solution? If not, why not?
- What processes did your team use to find solutions?
- How good is your solution? How do you know whether it is good or not?
- How well did you document your design process?

In this section, we will describe the (fictional) design process used by the SCV team to address the commuting problem.

Define the Problem

Problem definition is one of the most critical steps in the design process. Since the design team trying to solve this problem will expend a significant effort, it is very important that the problem being addressed is actually the problem that is important to potential customers. It is also important that the problem be clearly defined and understood by the design team.

Many techniques can be used to clearly define and understand the problem (see Fogler and LeBlanc, 1995). These techniques include

- gathering information from customers and other stakeholders,
- finding expert information (either in person or through books or other sources),
- doing a **root cause analysis** to identify what the real problem is.

The SCV design team began by gathering information about the issues associated with vehicular commuting and traffic congestion. They found and read several government reports. They interviewed various stakeholders in the commuting problem; these included people who commute to and from work in their car each day, officials from state and local departments of transportation, and representatives of environmental groups. They also used their own experience as commuters.

Activity

> Using your understanding of the issues associated with commuting, develop a problem statement to describe the problem that the design team should solve.

On the basis of the research that they performed, the design team defined their design problem to be "Design a commuter vehicle that is environmentally friendly, acceptable to a typical commuter, and compatible with existing transportation infrastructure."

The design team also expanded this problem statement to make it more informative as follows. Environmentally friendly means that the vehicle produces as little pollution and greenhouse gases as possible and uses sources of **renewable energy**. Acceptable to the commuter means that the vehicle is convenient (does not require the commuter to wait), comfortable, and affordable. Compatible with existing infrastructure means that the vehicle does not require changing roads, bridges, etc., and does not require the development of a new fuel distribution system.

Identify Criteria and Constraints

The problem statement is used as a starting point to develop an understanding of the characteristics of a good solution. These characteristics are described in terms of constraints and criteria. A constraint is a limitation or condition that must be satisfied by a design. A criterion is a standard or attribute of a design that can be measured. The constraints and criteria are used in subsequent steps of the design process to determine which of many possible designs should be implemented.

Activity

> Using your problem statement or the one developed by the design team, develop criteria and constraints that could be applied to decide whether a potential commuter vehicle design is good or not.

From the problem statement, the SCV design team identified criteria and constraints that would apply to their design. They identified the following constraint:

- Does not require new transportation infrastructure.

They identified the following criteria:

- The amount of pollution and greenhouse gases emitted per mile traveled by a commuter.
- The percent of the energy used from renewable sources.
- The convenience for the commuter.
- The comfort of the commuter.
- The cost to use the vehicle for five years (includes the purchase price, maintenance, and fuel).

Activity

> Compare your criteria and constraints with the ones developed by the design team. What are the strengths of your criteria when compared to the design team's? What are the weaknesses?
>
> Are each of your criteria measurable? Does each accurately reflect the problem statement?

Generate Concepts

With criteria and constraints identified, the design team begins to **generate concepts** for the design. This is the step in which creativity plays a very important role—good designs are often very different from existing solutions to a problem. In addition to creativity, the design team must use discipline to ensure that they explore enough options and potential solutions to guarantee a good design. Therefore, it is important to use a structured process to generate concepts for a design. Many different processes could be used. The one presented here is adapted and simplified from *Product Design and Development* by Eppinger and Ulrich. It includes the steps of problem decomposition, searching externally and internally for ideas, and systematically exploring possibilities.

Decompose the Problem into Subproblems

When a design problem is complex, it can be very beneficial to **decompose** the problem into subproblems. Subproblems are smaller problems that must be solved in order to solve the overall problem.

Activity

> Think of as many subproblems as you can for the SCV.

The SCV team broke the overall problem into subproblems as shown in Figure 7. Each of the subproblems is simpler to approach than the whole problem. The energy source is how the vehicle gets energy to move; for example, the energy source for a regular car is gasoline. The vehicle **configuration** is the number of wheels on the vehicle and where they are placed relative to the driver. The drive mechanism transforms energy into the locomotion of the vehicle.

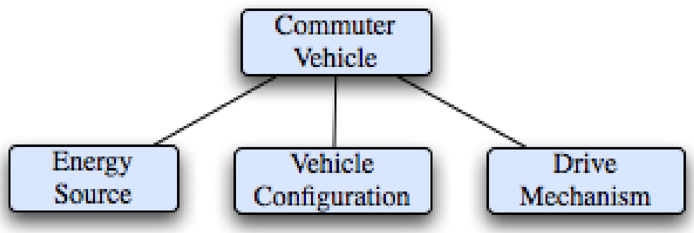

Figure 4.7: Decomposition of the commuter vehicle problem into three some problems: energy, configuration, and drive mechanism.

Search Externally for Ideas

Once the problem is decomposed into subproblems, the design team can begin to search for ideas to solve each subproblem. One source of ideas is to look at existing products and ideas to see whether there are already solutions to the overall problem or the identified subproblems. Sources of external information include interviews with potential customers or experts in the subproblem areas, patent and other technical databases, and existing products. Much of this information is now available on the World Wide Web.

Activity

> Identify sources of information that you could use to find ideas for your subproblems. Use one these resources to develop a list of potential solutions to one of your subproblems.

The design team researched externally to find potential energy sources for their commuter vehicle. They discovered the following energy sources:

- Solar energy converted into electricity using **photovoltaic solar cells**. This is the power source used by the Mars rover Sojourner (Figure 8).

- Nuclear energy
- Wind Energy converted into electricity using a turbine and generator. This might be a smaller version of a wind turbine such as that shown in Figure 9.
- Human power.
- Gasoline, a nonrenewable fossil fuel.
- A fuel cell that converts hydrogen and oxygen into electricity. Figure 10 shows the fuel cell that provides power to the Toyota Fuel Cell Hybrid Vehicle (FCHV).
- Ethanol made from corn or other plants; ethanol can typically be used like gasoline with only slight modification to the car's fuel system.

After some reflection, the team discarded nuclear energy and a fuel cell as being **unfeasible** given the current state of technology.

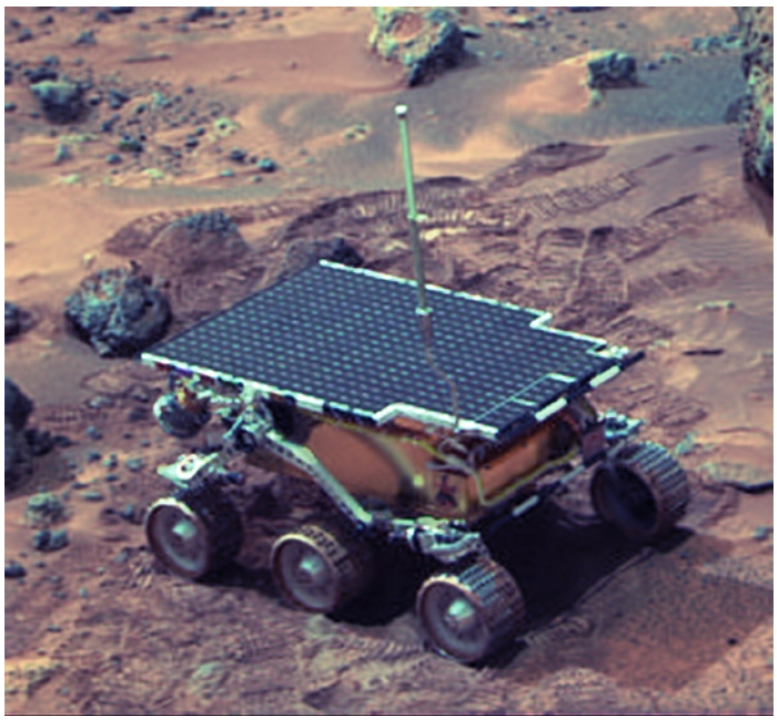

Figure 4.8: The rover Sojourner on the surface of Mars. The flat black panel on the rover's top is a panel of photovoltaic solar cells that provided power for 83 days.

The team also searched for possible drive mechanisms. They settled on three types:

- A clutch, gearbox, and drive shaft similar to the drive train used for most manual transmission, rear wheel drive automobiles.
- Electric motors that are located in the hubs of each wheel and drive each wheel directly. Figure 11 shows a bicycle hub that contains an electric motor; electric motors can also be put in the hubs of car wheels.

Figure 4.9: Large wind turbines on a wind farm in Iowa. These turbines use the wind's energy to generate electricity.

- A chain drive similar to that used in motorcycles and bicycles. Figure 12 shows a motorcycle chain drive.

Search Internally for Ideas

Searching internally for ideas is often called brainstorming; Figure 13 illustrates a group brainstorming. The goal of brainstorming is to develop as many ideas as possible without worrying whether they are feasible. Sketches are often good tools to capture ideas and to generate new ideas.

Activity

Brainstorm ideas that could solve one of your subproblems.

To solve the vehicle configuration subproblem, the design team brainstormed several possible configurations; a configuration is an arrangement of wheels around the passenger compartment. They brainstormed four different configurations, each have between one and four wheels. After brainstorming the configurations, they found photographs online to represent each configuration. These photographs are presented in Figure 14. After reflection, the team discarded the one wheel configuration as being unfeasible. They noted that both two-wheel configurations would require some method of balancing, but kept them both because there are existing vehicles that use each configuration.

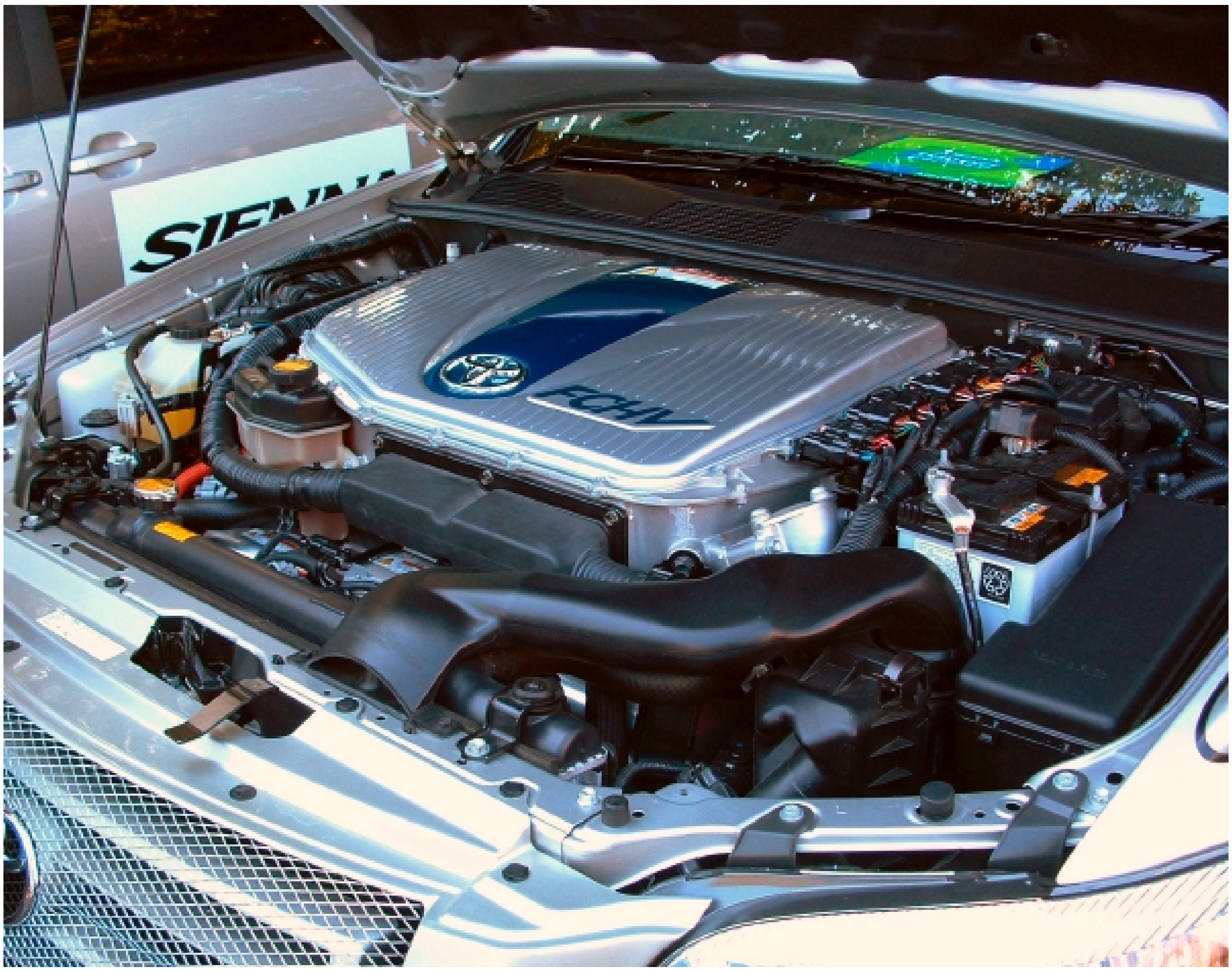

Figure 4.10: The Toyota Fuel Cell Hybrid Vehicle is powered by a fuel cell that generates electricity from hydrogen and oxygen. The fuel cell is still experimental technology that is currently extremely expensive, but shows promise for the future.

Figure 4.11: This bicycle hub contains an electric motor that moves the bicycle.

Figure 4.12: This chain drive transmits power from the motorcycle engine to its rear wheel.

Figure 4.13: Students write their ideas on white boards during a brainstorming session.

Explore Systematically

Searching externally and internally will generate many possible solutions for each of the subproblems. To ensure that good solutions are not left out of the set of possible designs, it is important to use a structured process to examine possible combinations of subproblem solutions. A tool for systematic exploration is the concept combination table. In this table, solutions for each of the subproblems are combined; Figure 15 shows a concept combination table for the commuter vehicle.

To use the table, a solution for each subproblem is combined, and then a sketch or description of the resulting concept is created. For example, if the concepts are combined as shown in Figure 16, then the possible design in Figure 17 results. This design could be very similar to a standard bicycle with an added solar cell canopy that shades the driver. The pedals of the bicycle would be removed and replaced by an electric motor that drives the vehicle forward.

Note that the combination of design elements often does not provide a complete design concept; decisions must be made to fill in the gaps. For example, if solar cells are included as part of a design, they could be placed on the vehicle or they could be part of a fixed charging station that charges a battery on the vehicle; the design team must decide which configuration would make the most sense.

Activity

Using the solutions to subproblems that you have developed in previous activities, create a concept combination table for the problem. Use your concept combination table to generate five or six design concepts. Sketch each of your

Figure 4.14: Possible solutions to the subproblem of configuring the wheels around the passenger.

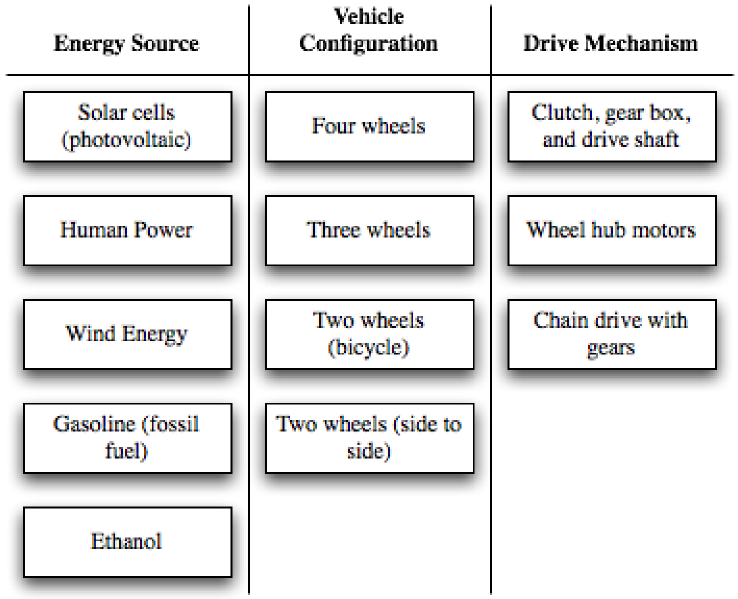

Figure 4.15: The concept combination table for the commuter vehicle.

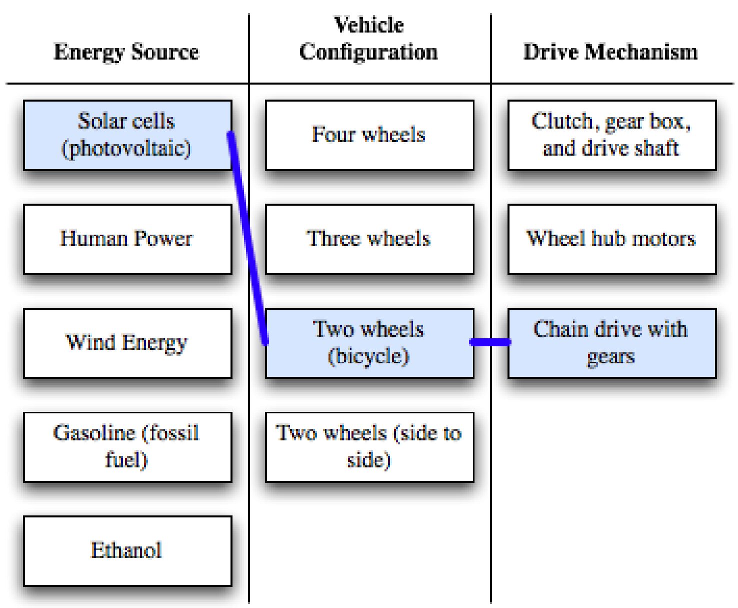

Figure 4.16: The concept combination table is used to generate a particular possible design.

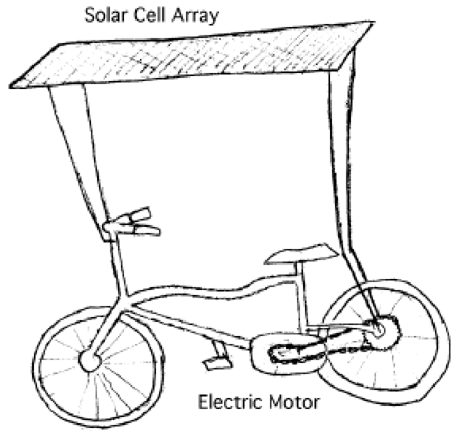

Figure 4.17: A sketch of the possible design obtained by from the concept combination table in Figure 16. Note that engineers often use rough, hand-drawn sketches at this point in the design process to understand design concepts and explore their strengths and weaknesses.

concepts.

The design team used the concept combination table to develop six concepts.

Concept 1: The design in Figure 17.

Concept 2: The energy source is a combination of solar cells and wind energy; the solar cells and wind turbines are installed at centrally located municipal charging stations and used to charge batteries. The vehicle configuration is a small, three-wheeled car with an enclosed passenger cabin that seats two people. The drive mechanism is wheel hub motors installed in the three wheels, with energy supplied to the motors from the charged batteries; these motors use **regenerative braking** to recover energy as the vehicle slows down.

Concept 3: This concept combines a gas engine with a four-wheeled configuration and a clutch, gearbox and drive shaft to form a traditional automobile. To be attractive as an alternative commuter vehicle, this design would be a two-seater subcompact.

Concept 4: This concept is the same as Concept 3, except that the engine is run on ethanol. Thus, Concept 4 is a small, two-seater alternative fuel vehicle.

Concept 5: The energy source is a combination of solar cells and human power. The vehicle configuration is three wheels, and the drive mechanism is a chain drive with gears. This is similar to a solar-assisted tricycle.

Concept 6: The energy source is a combination of solar cells mounted on the vehicle plus a battery; the battery can be charged at the user's home using a renewable energy source (wind or solar cells) or plugged into the user's home electricity system. The battery provides most of the energy, while the solar cells extend the life of the battery on sunny days. The configuration is two wheels side by side with room for a single passenger, and the drive mechanism is wheel hub motors. The motors are controlled to keep the vehicle balanced (similar to the Segway personal transport device in Figure 14).

Some combinations will not make sense or will result in a concept that is clearly unfeasible. For example, any concept that uses wheel hub motors must use an energy source that generates electricity.

Explore Possibilities and Select a Design

The design concepts are explored to understand their characteristics. For example, exploring Concept 1, the solar-powered bicycle in Figure 17, leads to the following conclusions:

- The design would use only renewable energy.
- The design would be relatively inexpensive to manufacture and would cost nothing to operate.
- The design may not be convenient for the commuter, since the motor will only run when sunlight falls on the solar array. This means that it is impossible to commute at night or on cloudy days.
- The design will not be particularly comfortable for the commuter, since they will be exposed to hot, cold, and rainy weather, and the seat appears to be uncomfortable.

Activity

> Explore the possibilities of one of the concept combinations developed in the previous activity.

When exploring the possibilities of a design concept, the team may discover ways in which the design can be improved. For example, Concept 1 might be improved by providing a more comfortable seat and by adding a battery that can store energy for use when it is dark or cloudy and the solar array does not generate electricity.

Once several design concepts have been developed and explored so that their advantages and disadvantages are understood, the design team must choose one concept that will be used to create the design for the product. It is usually best to choose the concept using a structured decision process. In a structured decision process, each of the concepts is evaluated to see whether it meets the constraints and is compared with the other concepts using the criteria; the best concept according to the criteria that meets the constraints is typically selected to implement the product.

In the case study, Concept 2 did not meet the constraint because it would require cities to build charging stations, so it was eliminated from consideration. Using the criteria as a guide, the design team determined that the two best designs were Concept 1 and Concept 5. They ranked high because of low pollution, using only renewable energy, and being low cost compared with other options. However, it is clear that these designs are the least comfortable for the consumer, and may therefore not be commercially successful. At this point, the design team could choose to use one of these designs and go forward in the design process; or, they may feel after seeing the outcome of the selection process that their criteria did not accurately capture their customers' desires. In this case, they may go back and improve their criteria, then repeat the decision process. Or, they may determine that better concepts may have been developed with different combinations of subproblem solutions or through different assumptions in the Explore Possibilities step, and thus repeat the Concept Generation and Explore Possibilities steps.

Sometimes, a design does not satisfy the constraints but could be easily modified to satisfy the constraints. For example, in Concept 2 if a battery charging station were to be built at each customer's house, the concept could be judged to meet the constraint. At other times, one design will score low because it has a particular flaw that can be corrected by combining it with characteristics of another design. Thus, the team should see if there are any designs that score low because of one aspect and can be corrected or if two designs can be combined to provide a better design.

Develop a Detailed Design

After concept selection, the team has a general design concept; they have decided how each subproblem will be addressed and have an overall understanding of the design. Before the design can be manufactured, the team needs to develop the details of the design. A detailed design includes

- The shapes and dimension of all physical components.
- An understanding of which components will be acquired from external vendors and which will be fabricated within the company and, if fabricated within the company, the materials and fabrication processes to be used.
- A detailed schematic diagram of any electrical subsystems and computer code for any embedded processors.
- Assembly processes.

The development of a detailed design from a design concept may occupy the majority of time allocated to a new product design project. This step will also have a significant impact on the success of the project; a poor detailed design can ruin a good design concept.

In the process of developing a detailed design, the team may use many or all of the subsequent design steps of prototyping, testing, and refinement. This process may require many iterations as the testing of prototypes reveals previously unknown characteristics of the design.

A major step in the process of going from a design concept to a detailed design is the development of the design architecture. The design architecture is "the assignment of the functional elements of the product to the physical building blocks of the product" (Eppinger and Ulrich, 2003).

For example, one architectural decision for the SCV design is how to incorporate the solar array into the design. Should the array be a separate physical block of the vehicle, for example creating the canopy structure in Figure 17, or should the array be created as an integral part of the frame? The first option represents a modular architecture, while the second option represents an integrated architecture.

Prototype, Test, and Refine

A prototype or model is a representation of some aspect of the design. The purpose of models and prototypes is to provide additional understanding of the design and its performance. A prototype may implement only a small portion of design or may be comprehensive and implement the whole design. For example, while developing a detailed design for Concept 1, the design team may initially wish to develop a prototype only of the electrical system (the solar cell array and the electric motor). Once the electrical system design is verified, they may implement a comprehensive prototype of the whole vehicle.

Prototypes may be physical or virtual. A physical prototype may be implemented out of materials that are very similar to those that will be used to manufacture the final design, or, to reduce cost or save time, the prototype may be implemented out of other materials. A virtual prototype may be created using a computer-aided design and drafting (**CADD**) program. Modern programs can simulate many aspects of a physical system, revealing flaws or promoting understanding of the design without the need to implement it physically.

One important function of a prototype is to test whether the design will work as expected. Understanding of the design and confidence that it will work is gained as prototypes are tested and evaluated relative to the constraints and criteria for the design. Testing procedures should be carefully planned to ensure that questions about the design are answered without requiring too much time and resources. The test results should be evaluated relative to specifications that reflect the constraints and criteria.

Testing and evaluation of the prototype may reveal weaknesses in the design or may provide information that can be used to improve the design. In this case, the design will often be refined, particularly if it does poorly with respect to some of the criteria or constraints. Sometimes, the chosen design concepts do not meet the criteria or constraints, and the design team must go back and perform more concept generation and then select another concept. This is an integral part of a spiral design process.

Communication and Implementation

As the design team has gone through the design process, they have kept records of the different processes that they used and results of these processes. Often, this information is used to create user manuals and maintenance manuals for the product. This information is important for team members who will be required to update or modify the design in the future. Lessons are learned in the design process that should be conveyed to other teams in the company or perhaps to external stakeholders in government or academia. An important part of the design process is to document these issues and communicate the results to the appropriate stakeholders.

As the design is completed, the effort to implement the design increases. If the design is of a product that is manufactured, a manufacturing system must be developed. For example, in the alternate commuter vehicle design, suppliers for components such as motors and solar cells must be located; facilities for manufacturing the frame are created; and a sales and marketing staff are identified.

Review Questions

Multiple Choice

The following questions will help you assess your understanding of the Discovering Engineering section. There may be one, two, three, or even four correct answers to each question. To demonstrate your understanding, you should find all of the correct answers.

1. Design problems are broken down into subproblems because
   (a) each design team member needs a specific problem to solve
   (b) the customer or stakeholders do not understand the overall problem
   (c) smaller problems must be solved in order to solve the overall problem
   (d) engineering companies make more money solving many smaller problems
2. When a design team searches externally for ideas they
   (a) interview customers
   (b) look at existing products
   (c) look at technical databases
   (d) talk to experts in the problem area
3. A concept combination table helps you to
   (a) explore design ideas systematically
   (b) see the complete design concept
   (c) identify the overall design problem
   (d) keep track of rejected designs
4. A concept screening matrix is used to

(a) select a design
(b) eliminate constraints
(c) develop a design
(d) eliminate criteria

5. A prototype can be
   (a) a physical representation
   (b) a scale model
   (c) a virtual representation
   (d) a final product
6. Implementation means that a
   (a) physical model is built
   (b) virtual model is built
   (c) prototype is built
   (d) product is manufactured
7. A design is refined because
   (a) it has met the constraints and criteria
   (b) testing has found weaknesses in the design
   (c) a product must go through the spiral design process
   (d) there are no further improvements to make
8. Communicating processes and results is done by
   (a) posting designs on a website
   (b) creating a users manual
   (c) text messaging team members
   (d) emailing manufacturers
9. A detailed design includes
   (a) a market analysis
   (b) shapes and dimensions of all physical components
   (c) computer code
   (d) assembly process
10. The step in the design process called Explore Possibilities is used to
    (a) make additional designs
    (b) improve the design
    (c) understand the design characteristics
    (d) test the prototype
11. Searching internally for ideas is called
    (a) mind searches
    (b) design sessions
    (c) idea dumps

(d) brainstorming

12. When engineers generate ideas in the design process they
    (a) use an unstructured approach
    (b) use a step by step approach
    (c) use a mathematical approach
    (d) use a structured approach
13. Which techniques are used to define the design problem?
    (a) Find expert information
    (b) Try to identify the real problem
    (c) Gather information from customers
    (d) None of the above
14. **Free Response Questions**
15. How can you tell the difference between a good design and a bad design?
16. What is the difference between engineering design and other types of design (architectural, fashion, etc.)?
17. How do you know that your design team has considered enough ideas to ensure that they develop a good design?
18. What are the characteristics of a good problem definition statement?
19. What are the steps of the design process? Why are they not always completed in order?
20. How do you use team decision-making tools in the design process?
21. How do you create a detailed design from a design concept?

Review Answers

The Design Process in Action

1. c
2. a,b,c,d
3. a
4. a
5. a,b,c
6. d
7. b
8. b
9. b,c,d
10. b,c
11. d
12. d
13. a,b,c