CHAPTER 6

Understanding the Problem and the Development of Engineering Specifications

6.1 INTRODUCTION

The *Mariner IV* satellite was to be packaged in a rocket, its solar panels folded against its sides. After launch the satellite was to spin so that the solar panels would unfold by centrifugal force and be locked in a straight-out position. Because these panels were quite large and very fragile, there was concern that they would be damaged when they hit the stops that determined their final position. To address this problem, the major aerospace firm that had the *Mariner* contract initiated a design project to develop a retarder (dampener) to gently slow the motion of the panels as they reached their final position. The constraints on the retarders were quite demanding: they would have to work in the vacuum and cold of space, work with great reliability, and not leak, since any foreign substance on the panels would harm their capability of capturing the sun's energy during the satellite's nine-month mission to Mars. Millions of dollars and thousands of hours were spent to design these retarders, yet after extensive design work, testing, and simulation, no acceptable devices evolved. With time running out, the design team ran a computer simulation of what would happen if the retarders failed completely; to the team's amazement, the simulation showed that the panels would be safely deployed without any dampening at all. In the end, they realized that there was no need for retarders, and *Mariner IV* successfully went to Mars without them.

This story is an example of how a lot of time and money can be wasted designing the wrong product. Surveys show that poor product definition is a factor in 80 percent of all time-to-market delays. Further, getting a product to market late is more costly to a company than being over cost or having less than optimal performance. Finding the "right" problem to be solved may seem a simple task; unfortunately, often it is not.

Besides finding the right problem to solve, an even more difficult and expensive problem for most companies is what is often called "creeping specifications." Creeping specifications change during the design process. It is estimated that fully 35 percent of all product development delays are directly caused by such changes. There are three factors that cause creeping specifications. First, as the design process progresses, more is learned about the product and so more features can be added. Second, since design takes time, new technologies and competitive products become available during the design process. It is a difficult decision whether to ignore these, incorporate them (i.e., change the specifications), or start all over (i.e., decide that the new developments have eliminated the market for what you are designing). Third, since design requires decision making, any specification change causes a readdressing of all the decisions dependent on that specification. Even a seemingly simple specification change can cause redesign of virtually the whole product. The point is that when specification changes become necessary, they should be done in a controlled and informed manner.

The importance of the early phases of the design process has been repeatedly emphasized. As pointed out in Chap. 1, careful requirements development is a key feature of concurrent engineering. In this chapter the focus is on understanding the problem that is to be solved. The ability to write a good set of engineering specifications is proof that the design team understands the problem. The methodology developed in this chapter for finding requirements helps

- ***Ensure that the requirements are discriminatory.*** Requirements need to reveal the differences between alternatives to help distinguish one from the other during an evaluation. If you said your ideal mate must have hair, this would be a poor requirement as nearly all people have the feature "hair." Thus, this requirement is useless because it does not allow for discrimination between people. If another requirement is that your ideal mate should be between 1 and 2 meters tall, this does not allow for discrimination either, yet for a different reason. The height of your potential mate may be a key feature to you. However, the target for this feature does not discriminate since most people are between these limits.
- ***Ensure that the requirements are measurable.*** Ideally, all identified requirements are measurable. Because of its importance, this is a major topic of this chapter.
- ***Ensure that the requirements are orthogonal.*** Each requirement should identify a unique feature of the alternative. There should be no overlapping of requirements. This is often difficult because overlapping is so hard to identify. For example, in the initial list of criteria for choosing a new product, a company proposed two criteria:
  - Product must give smooth ride over rough roads.
  - Product should reduce shocks from bumps.

  Although these both seem important, in many ways they are not orthogonal, as smoothing the ride and reducing the shocks are not independent. It is important for the team to refine these, eliminating one or defining them so they describe independent features of alternatives.

- ***Ensure that the requirements are universal.*** A universal requirement characterizes an important attribute of *all* the proposed alternatives. If only some of the alternatives have the feature measured by the requirement, then it is not universal and either the issue is not well defined or some of the alternatives have features not consistent with the issue being addressed.
- ***Ensure that the requirements are external.*** The difference between internal and external requirements is best introduced by this example. You want to buy a car. Some of your requirements will be on the performance of the car. For instance, say you want a car that can go from 0 to 60 mph (100 kph) in under 5 seconds. The acceleration feature of the car is discriminatory, measurable, and universal. Now, to ensure that you get the performance you want, say you add another requirement: it must have a six-cylinder engine. This feature, the number of cylinders, has a series of problems. First, it is clearly not orthogonal to the acceleration feature. In many ways, it may measure the same thing, yet the number of cylinders may be important for some other reason. Even more telling, the number of cylinders is an internal feature and probably not important to the selection of a car. This statement will be explained in a moment, but first, this brings us to the definition of internal and external features. Every system or object considered has a boundary. Users of the product are outside this boundary, that is, external to the system or object. Thus, the only sense of the performance of the system or object is what decision-makers discern through the boundary. Everything that happens inside the boundary, the internal workings of the system or object, is not observable. Returning to the car example, we see that the number of cylinders is internal. Cars with four, six, or eight cylinders may be able to meet the acceleration target. Thus, itemizing the number of cylinders, an internal feature, does not help unless it affects or is needed for some other requirement.

There are many techniques used to generate engineering specifications. One of the best and currently most popular is called *quality function deployment (QFD)*. What is good about the QFD method is that it is organized to develop the major pieces of information necessary to understanding the problem:

1. The specifications or goals for the product
2. How the competition meets the goals
3. What is important from the customers' viewpoints
4. Numerical targets to work toward

Regardless of whether this technique or some other is used, the important information that must be developed is the same. It is the information developed that is emphasized in this chapter.

The QFD method was developed in Japan in the mid-1970s and introduced in the United States in the late 1980s. Using this method, Toyota was able to

All design problems are poorly defined.

reduce the costs of bringing a new car model to market by over 60 percent and to decrease the time required for its development by one-third. It achieved these results while improving the quality of the product. A recent survey of 150 U.S. companies shows that 69 percent use the QFD method and that 71 percent of these have begun using the method since 1990. A majority of companies use the method with cross-functional teams of ten or fewer members. Of the companies surveyed, 83 percent felt that the method had increased customer satisfaction and 76 percent indicated that it facilitated rational decisions.

Before itemizing the steps that compose this technique for understanding a design problem, consider some important points:

1. No matter how well the design team thinks it understands a problem, it should employ the QFD method for all original design or redesign projects. In the process the team will learn what it does not know about the problem.
2. The customers' requirements must be translated into *measurable design targets for identified critical parameters.* You cannot design a car door that is "easy to open" when you do not know the meaning of "easy." Is easiness measured by force, time, or what? If force is a critical parameter, then is "easy" 20 N or 40 N? The answer has to be known before much time and resources are invested in the design effort.
3. The QFD method can be applied to the entire problem and any subproblem. (Note that the design of a door mechanism in item 2 here is a subproblem in automobile design.)
4. It is important to first worry about *what* needs to be designed and, only after that is fully understood, to worry about *how* the design will look and work. Our cognitive capabilities generally lead us to try to assimilate the customers' functional requirements (what is to be designed) in terms of form (how it will look); these images then become our favored designs and we get locked onto them. The QFD procedure helps overcome this cognitive limitation.
5. This method takes time to complete. In some design projects, about one-third of the total project time is spent on this activity. Ford spends 3–12 months developing the QFD for a new feature. Time spent here saves time later. Not only does the technique help in understanding the problem, it also helps set the foundation for concept generation.

The QFD method helps generate the information needed in the engineering specifications development phase of the design process (Fig. 4.1). That phase is reproduced in Fig. 6.1. Each block in the diagram is a major section in this chapter and a step in the QFD method.

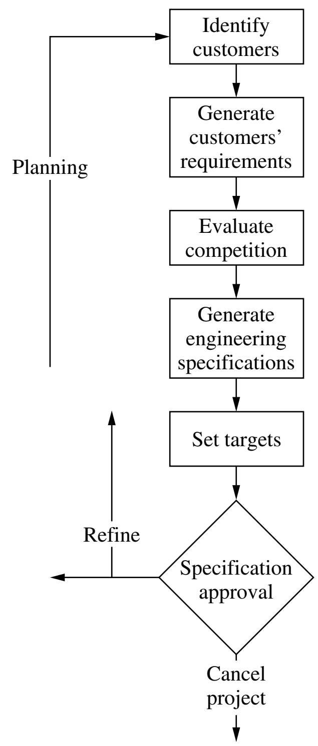


Figure 6.1 The engineering specifications development phase of the design process.

Applying the QFD steps builds the *house of quality* shown in Fig. 6.2. This is a house of many rooms, each containing valuable information. This figure will be completed in detail for the bicycle suspension system as a running example. Before we describe each step for filling in Fig. 6.2, a brief description of the figure is helpful. The numbers in the figure refer to the steps that are detailed in the sections below. Developing information begins with identifying *who* (step 1) the customers are and *what* (step 2) it is they want the product to do. In developing this information, we also determine to whom the what is important—*who versus what* (step 3). Then it is important to identify how the problem is solved *now* (step 4), in other words, what the competition is for the product being designed. This information is compared to what the customers desire—*now versus what* (step 4 continued)—to find out where there are opportunities for an improved product. Next comes one of the more difficult steps in developing the house, determining *how* (step 5) you are going to measure the product's ability to satisfy the customers' requirements. The hows consists of the engineering specifications, and their correlation to the customers' requirements is given by *whats versus hows*

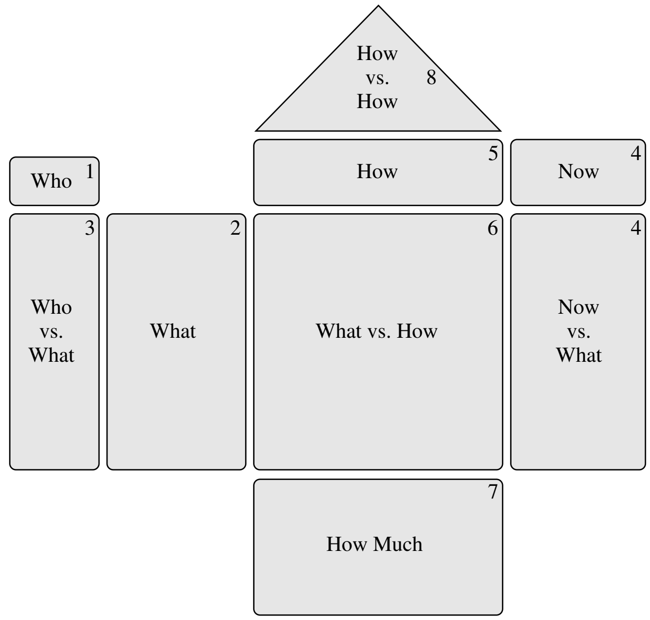
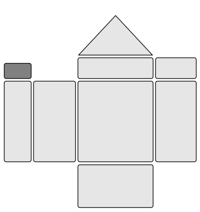


Figure 6.2 The house of quality, also known as the QFD diagram.

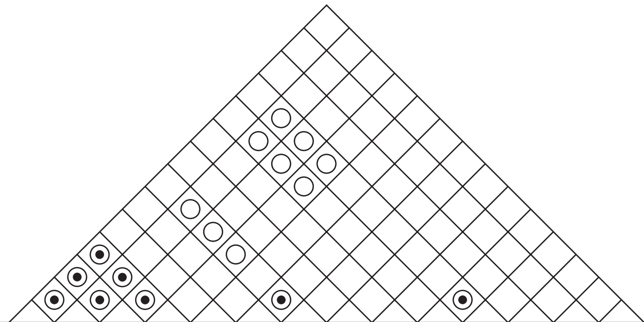
(step 6). Target information—*how much* (step 7)—is developed in the basement of the house. Finally, the interrelationship between the engineering specifications are noted in the attic of the house—*how versus how* (step 8). Details of all these steps and why they are important are developed in Sections 6.2 through 6.9. Postage stamp-size versions of Fig. 6.2, tie the steps together.

The QFD method is best for collecting and refining functional requirements hence the "F" in its name. However, in the material presented here, it will be used to help ensure that all requirements are collected and refined. In each step, the BikeE suspension system will be used as an example. The completed QFD for this problem is shown in Fig. 6.3.



6.2 STEP 1: IDENTIFY THE CUSTOMERS: *WHO* ARE THEY?

The goal in understanding the design problem is to *translate customers' requirements into a technical description of what needs to be designed.* Or, as the Japanese say, "Listen to the voice of the customer." To do this, we must first determine exactly who the customers are. For most design situations there is more than one customer; for many products the most important customers are the consumers, the people who will buy the product and who will tell other consumers about its quality (or lack thereof). Some products—a space shuttle or an oil drill



NOW: ◇ BikeE CT ○ Recumbent □ Mountain Bike

Street rider	Sales-repair person			BikeE Suspension Example	Energy transmitted on std road	Max acceleration on std street	Max acceleration on 2.5 cm std pothole	Max acceleration on 5 cm std pothole	Riders that notice pogoing	Rider weight range	Rider height range	# of tools to adjust	# of tools to adjust	Amount of change in spring rate	Amount of change in damping	Mean time between suspension maintainance	People liking suspension's looks	Added assembly time	NOW 1	2	3	4	5
				Direction of Improvement	↓	↓	↓	↓	↓	↑	↑	↓	↓	↓	↓	↓	↑	↓					
				Units	%	gs	gs	gs	%	lbs	in	#	#	%	%	dys	%	min					
13	14	WHAT	Performance	Smooth ride on streets	⦿	⦿	○	○											◇		□○		
18	12	WHAT	Performance	Eliminate shock from bumps	○	○	⦿	⦿											◇	○		□	
11	12	WHAT	Performance	No pogoing	△				⦿										□	○			◇
6	8	WHAT	Adjustability	Easy to adjust for different weights						⦿		⦿								□	○		◇
4	11	WHAT	Adjustability	Easy to adjust for different heights							⦿	⦿									□○		◇
10	6	WHAT	Adjustability	Easy to adjust ride hardness									⦿						◇○		□		
6	4	WHAT	Environment	No noticeable temperature effect										⦿	⦿							□○	◇
4	3	WHAT	Environment	No noticeable dirt effect										⦿	⦿							□○	◇
8	2	WHAT	Environment	No noticeable water effect										⦿	⦿								◇○□
15	5	WHAT	Other	Easy to maintain						○	○	⦿				⦿					□	○	◇
4	15	WHAT	Other	Looks like a suspension													⦿		◇		○		□
1	8	WHAT	Other	Easy to manufacture														⦿		□	◇○		
				BikeE CT	95.	0.4	1.6	3.0	0.0	100	6.0	0.0	0.0	0.0	0.0								
				Mountain Bike	35.	0.1	0.4	0.5	20.	30.	4.0	2.0	1.0	0.0	0.0	30.		20.					
				Recumbent	50.	0.1	0.7	0.9	40.	40.	6.0	1.0	1.0	0.0	0.0	45.		10.					
				Target (delighted)	30.	0.1	0.4	0.5	100	100	6.0	0.0	1.0	0.0	0.0	60.	90.	10.					
				Target (disgusted)	50.	0.2	0.7	1.0	50.	50.	3.0	1.0	1.0	0.0	0.0	30.	70.	20.					

Figure 6.3 House of quality for suspension system.

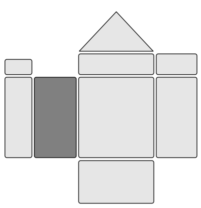
head—are not consumer products but still have a broad customer base. For example, the consumer, the designer's management, manufacturing personnel, sales staff, and service personnel must also be considered as customers. Additionally, standards organizations should be viewed as customers, as they too may set requirements for the product. For many products there are five or more classes of customers whose voices need to be heard.

It was only in the 1980s that we began to regard the people involved in manufacturing and assembly as customers. Their inclusion helps reduce the over-the-wall design discussed in Chap. 1.

For the BikeE suspension system, the main customers are bicycle riders; they are generally both the purchasers and the users. In interviewing current riders of BikeE products, the team realized that there were two types of riders for the new product. First is the rider who rides solely on streets. The BikeE was initially designed as a road or commuting bicycle. However, there were some few riders who wanted to take it off-road and so the second group of rider-customers is those who want to ride on rough roads or trails.[1]

Additional customers considered are bicycle shop sales people and mechanics (often the same people). These people have to be enthusiastic to sell the product, answer questions about it, and repair it.

Within the company, manufacturing, assembly and shipping personnel are also customers. In fact, concern for these "customers" is the primary focus of Chap. 12. In Fig. 6.3 the only customers shown are the street rider and bike shop sales-repair person as examples.



6.3 STEP 2: DETERMINE THE CUSTOMERS' REQUIREMENTS: *WHAT* DO THE CUSTOMERS WANT?

Once the customers have been identified, the next goal of the QFD method is to determine *what* is to be designed. That is, what is it that the customers want?

- Typically, as shown by the customer survey in Table 1.1, the *consumers* want a product that works as it should, lasts a long time, is easy to maintain, looks attractive, incorporates the latest technology, and has many features.
- Typically, the *production customer* wants a product that is easy to produce (both manufacture and assemble), uses available resources (human skills, equipment, and raw materials), uses standard parts and methods, uses existing facilities, and produces a minimum of scraps and rejected parts.
- Typically, the *marketing/sales customer* wants a product that meets consumers' requirements; is easy to package, store, and transport; is attractive; and is suitable for display.

[1] It is interesting to note that the product that resulted from this design project was so successful off-road that it was further refined to the FX model, the first purpose-designed off-road recumbent bike (see www.bikee.com).

You only think you know what your customers want.

Sections 6.3.1 through 6.3.2 give some important background information on collecting other customers' requirements.

6.3.1 The Kano Model of Customer Satisfaction

Our goal is to find requirements that not only satisfy the customers but also excite them to want to purchase the product and recommend it to others. Kano's[2] model of customer satisfaction plots customer satisfaction—from disgusted to delighted versus product function—from absent to fully implemented as shown in Fig. 6.4. This plot shows three lines representing basic features, performance features, and excitement features.

Basic features refer to customers' requirements that are not verbalized as they specify assumed functions of the device. The only time a customer will mention them is if they are missing. If they are absent in the final product, the customer will be disgusted with it. If they are included, the customer will be neutral. Requirements for basic features should not be included in the QFD. An example is the requirement that a bike should have brakes. If there are no brakes, then the customer is going to be disgusted with the product (and maybe injured also). Brakes are expected on bikes and so, just being there is not a cause for delight, just a neutral reaction from the customer. However, how well the brakes perform is clearly a concern, as discussed in the next paragraph.

Requirements for *performance* features are verbalized in the form that the better the performance, the better the product. This type of requirement is a major part of the QFD. For example, a requirement on brake stopping distance is clearly a performance requirement. Generally, the shorter the distance, the more delighted the customer.

A prime goal in determining the voice of the customer is to find the requirements that result in a product of *excitement features.* These requirements are often unspoken because customers do not expect them to be met in the product. If they are absent, the customers are neutral. However, if the customers' reactions to the final product are surprise and delight at the additional functions, then the product's chance of success in the market is high. Requirements for excitement-quality features are often called "wow requirements." If you went to a bike store and test rode a bike with voice activated brakes, this would be unexpected. Your reaction to the system would be "wow." If the system worked well you would be delighted, if it were not there at all you wouldn't know the difference and so would be neutral. (This assumes that the designers left the brake handles on the bike as a backup system.)

[2]The Kano model was developed by Dr. Noriaki Kano in the early 1980s to describe customer satisfaction.

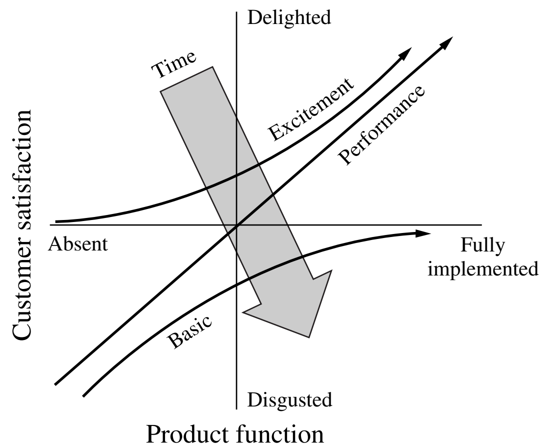


Figure 6.4 The Kano diagram for customer satisfaction.

Over time, excitement level requirements become performance level requirements and, ultimately, basic requirements. This is true for most features of home entertainment systems, cars, and other consumer products. When first introduced, a new feature is special on one brand and consumers are surprised and delighted. The next year every brand has the feature and some perform better than others. After a few years the feature is not even mentioned in advertising because it is an expected feature of the product.

In the QFD method you want to collect performance and excitement requirements.

6.3.2 Collection Methods for Customers' Requirements

The key to this QFD step is collecting information from customers. There are essentially three methods commonly used: observations, surveys, and focus groups.

Fortunately, most new products are refinements of existing products, so many requirements can be found by *observing* customers using the existing product. For example, automobile manufacturers send engineers into shopping center parking lots to observe customers putting purchases into cars to better understand one aspect of car door requirements.

Surveys are generally used to gather specific information or ask people's opinions about a well-defined subject. Surveys use questionnaires that are carefully crafted and applied either through the mail, over the telephone, or in face-to-face interviews. Surveys are well suited for collecting requirements on products to be redesigned or on new, well-understood product domains. For original products or to gather the customers' ideas for product improvement, focus groups are best.

The *focus-group* technique was developed in the 1980s to help capture customers' requirements from a carefully chosen group of potential customers. The method begins by identifying seven to ten potential customers and asking if they will attend a meeting to discuss a new product. One member of the design team acts as moderator and another as note taker. It is also best to electronically record the session. The goal in the meeting is to find out what is wanted in a product that does not yet exist, and so it relies on the customers' imaginations. Initial questions about the participants' use of similar products are followed with questions designed to find performance and excitement requirements. The goal of the moderator is to use questions to guide the discussion, not control it. The group should need little intervention from the moderator, because the participants build on each other's comments. One technique that helps elicit useful requirements during interviews is for the moderator to repeatedly ask "Why?" until the customers respond with information in terms of time, cost, or quality. To elicit good information takes experience, training, and multiple sessions with different participants. Usually the first focus group leads to questions needed for the second group. It often takes as many as six sessions to obtain stable information.

Later in the design process, surveys can be used to gather opinions about the relative merit of different alternatives. Observation and focus groups can be used both to generate ideas that may become alternatives and to evaluate alternatives. All these types of information gathering rely on questions formulated ahead of time. With a survey the questions and the answers must be formalized. Both surveys and observations usually use closed questions (i.e., questions with predetermined answers); focus groups use open-ended questions.

Regardless of the method used, these steps will help the design team develop useful data:

Step 2.1: Specify the Information Needed Reduce the problem to a single statement describing the information needed. If no single statement represents what is needed, more than one data-collecting effort may be warranted.

Step 2.2: Determine the Type of Data-Collection Method to Be Used Base the use of focus groups, observations, or surveys on the type of information being collected.

Step 2.3: Determine the Content of Individual Questions A clear goal for the results expected from *each question* should be written. Each question should have a single goal. For a focus group or observation, this may not be possible for all questions, but it should be for the initial questions and other key questions.

Step 2.4: Design the Questions Each question should seek information in an unbiased, unambiguous, clear, and brief manner. Key guidelines are

Do not assume the customers have more than common knowledge.
Do not use jargon.
Do not lead the customer toward the answer you want.
Do not tangle two questions together.
Do use complete sentences.

Questions can be in one of four forms

- Yes–no–don't know. (Poor for focus groups.)
- Ordered choices (1, 2, 3, 4, 5; strongly agree, mildly agree, neither agree nor disagree, mildly disagree, strongly disagree; or A = absolutely important, E = extremely important, I = important, O = ordinary, or U = unimportant [AEIOU]). Be sure that any ordered list is complete (i.e., that it covers the full range possible and that the choices are unambiguously worded). Scales with five gradations, as in the examples here, have proven best.
- Unordered choices (a, b, and/or c).
- Ranking (a is better than b is better than c).

The best questions ask about attributes, not influences. Attributes express what, where, how, or when. *Why* questions should lead to what, where, how, or when as they describe time, quality, and cost.

Step 2.5: Order the Questions Order the questions to give context. This will help participants in focus groups or surveys follow the logic.

Step 2.6: Take Data It usually takes repeated application to generate usable information. The first application of any set of questions should be considered a test or verification experiment.

Step 2.7: Reduce the Data A list of customers' requirements should be made in the customers' own words, such as "easy," "fast," "natural," and other abstract terms. A later step of the design process will be to translate these terms into engineering parameters. The list should be in positive terms—what the customers want, not what they don't want. We are not trying to patch a poor design; we are trying to develop a good one. (Even so, as we will see shortly, negative statements are sometimes needed to convey a requirement.)

To gather information for the BikeE suspension system, the team developed a survey and distributed it to some of the current BikeE owners. A sample of the questions included in the survey are:

Q1. How many miles do you ride your BikeE each week? (Circle the best choice.)
1. <5 miles
2. 5–10 miles
3. 10–30 miles
4. >30 miles

Q2. What surfaces do you often ride on? (Circle all that apply.)
1. Smooth pavement
2. Rough pavement
3. Gravel
4. Packed dirt paths
5. Forest trails

Q3. If your BikeE had a rear suspension system, what types of surfaces would you ride on? (Circle all that apply.)
1. Smooth pavement
2. Rough pavement
3. Gravel
4. Packed dirt paths
5. Forest trails

Q4. If your BikeE had a rear suspension system, how often would you expect to adjust or maintain it? Consider the maintenance similar to checking and adding air to your tires. (Circle the most frequent acceptable time period.)
1. Never
2. Once every 3 months
3. Once a month
4. Once a week
5. Every ride

Q5. What is most important to you? (Rank 1 through 5.)
______ Smoothing road surface bumps (e.g., rough surfaces, manhole covers)
______ Absorbing pothole shocks
______ Low maintenance
______ Cool looks
______ Maintenance ease

Q6. What is your weight? __________

Q7. Describe your experience using your BikeE to go to work or school. (Note that this is not a question, yet it leads the customers to describe their activities and can lead to many questions that hone in on time, cost and quality.)

6.3.3 The Types of Customers' Requirements

A checklist of the major types of requirements is given in Table 6.1. Comparing this list with the list of requirements developed for a product can reveal missing information. It is also useful in developing questions to ask in surveys and focus groups and as a key to information that needs to be found before design begins. The major types of requirements in this list are detailed next.

Functional performance requirements are those elements of the performance that describe the product's desired behavior. Although the customers may not use technical terms, function is usually described as the flow of energy, information, and materials or as information about the operational steps and their sequence. In Chap. 7 we develop concepts by building a functional model, based on the flow of energy, information, and materials. We will see that *developing functional requirements with the QFD and building a functional model of the product are often iterative*. The more the function is understood, the more complete are the requirements that can be developed.

Table 6.1 Types of customer requirements

Functional performance	Life-cycle concerns (continued)
Flow of energy	Diagnosability
Flow of information	Testability
Flow of materials	Repairability
Operational steps	Cleanability
Operation sequence	Installability
Human factors	Retirement
Appearance	Resource concerns
Force and motion control	Time
Ease of controlling and sensing state	Cost
Physical requirements	Capital
Available spatial envelope	Unit
Physical properties	Equipment
Reliability	Standards
Mean time between failures	Environment
Safety (hazard assessment)	Manufacturing requirements
Life-cycle concerns	Materials
Distribution (shipping)	Quantity
Maintainability	Company capabilities

Any product that is seen, touched, heard, tasted, smelled, or controlled by a human will have *human factors requirements* (see App. D for details on human factors). This includes nearly every product. One frequent customers' requirement is that the product "looks good" or looks as if it has a certain function. These are areas in which a team member with knowledge about industrial design is essential. Other requirements focus on the flow of energy and information between the product and the human. Energy flow is usually in terms of force and motion but can take other forms as well. Information flow requirements apply to the ease of controlling and sensing the state of the product. Thus, human factors requirements are often functional performance requirements.

Physical requirements include needed physical properties and spatial restrictions. Some physical properties often used as requirements are weight, density, and conductivity of light, heat, or electricity (i.e., flow of energy). Spatial constraints relate how the product fits with other, existing objects. Almost all new design efforts are greatly affected by the physical interface with other objects that cannot be changed.

In the *Time* magazine survey on quality quoted in Chap. 1, the second most important consumer concern was "Lasts a long time," or the product's *reliability.* It is important to understand what acceptable reliability means to the customer. The product may only have to work once with near-absolute certainty (e.g., a rocket), or it may be a disposable product that does not need much reliability. As discussed in Chap. 12, one measure of reliability is the *mean time between failures.*

A part of reliability involves the questions, What happens when the product does fail? What are the *safety* implications? Product safety and hazard assessment are very important to the understanding of the product, and they are covered in Chap. 8.

An often overlooked class of requirements is the class of those relating the product life cycle other than product use. All life-cycle phases listed in Table 6.1 were taken from Fig. 1.8. In designing the first BikeE, one of the design requirements set by sales/marketing was that the bicycle had to be shipped by a commercial parcel service. Such services have weight and size limits, which greatly affected the design of the product. If the advantages of distributing the product by commercial parcel service had not been realized early, extensive redesign might have been necessary. The same applies to the other life-cycle phases listed in Table 6.1 and Fig. 1.8.

A limited resource on every design project is time. *Time requirements* may come from the consumer; more often they originate in the market or in manufacturing needs. In some markets there are built-in time constraints. For example, toys must be ready for the summer buyer shows so that Christmas orders can be taken; new automobile models traditionally appear in the fall. Contracts with other companies might also determine time constraints. Even for a company without an annual or contractual commitment, time requirements are important. As discussed earlier, in the 1960s and 1970s Xerox dominated the copier market, but by 1980 its position had been eroded by domestic and Japanese competition. Xerox discovered that one of the problems was that it took it twice as long as some of its competitors to get a product to market, and Xerox put new time requirements on its engineers. Fortunately, Xerox helped its engineers work smarter, not just faster, by introducing techniques similar to those we talk about here.

Cost requirements concern both the capital costs and the costs per unit of production. Included in capital costs are expenditures for the design of the product. For a Ford automobile, design costs make up 5 percent of the manufacturing cost (Fig. 1.2). Many product ideas never get very far in development because the initial requirements for capital are more than the funds available. (Cost estimating will be covered in detail in Section 12.2.)

Standards spell out current engineering practice in common design situations. The term *code* is often used interchangeably with *standard.* Some standards serve as good sources of information. Other standards are legally binding and must be adhered to—for example, the ASME pressure vessel codes. Although the actual information contained in standards does not enter into the design process in this early phase, knowledge of which standards apply to the current situation are important to requirements and must be noted from the beginning of the project.

Standards that are important to design projects generally fall into three categories: performance, test methods, and codes of practice. There are *performance standards* for many products, such as seat-belt strength, crash-helmet durability, and tape-recorder speeds. The *Product Standards Index* lists U.S. standards that apply to various products; most of those referenced are also covered by ANSI (American National Standards Institute), which does not write standards but is a clearinghouse for standards written by other organizations.

Test method standards for measuring properties such as hardness, strength, and impact toughness are common in mechanical engineering. Many of these are developed and maintained by the American Society for Testing and Materials

> If you haven't set your targets at what the customers want, you only know you are done when you run out of time.

(ASTM), an organization that publishes over 4000 individual standards covering the properties of materials, specifying equipment to test the properties and outlining the procedures for testing. Another set of testing standards that are important to product design are those developed by the Underwriters Laboratories (UL). This organization's standards are intended to prevent loss of life and property from fire, crime, and casualty. There are over 350 UL standards. Products that have been tested by UL and have met their standards can display the words "Listed UL" and the standard number. The company developing the product must pay for this testing. Consumer products are usually not marketed without UL listing because the liability risk is too high without this proof of safe design.

Codes of practice give parameterized design methods for standard mechanical components, such as pressure vessels, welds, elevators, piping, and heat exchangers.

Standards information is given in the Sources section at the end of the chapter; most technical libraries carry an up-to-date set of ASME codes, ANSI standards, and UL standards.

It is important for the design team to ensure that requirements imposed by *environmental concerns* have been identified. Since the design process must consider the entire life cycle of the product, it is the design engineer's responsibility to establish the impact of the product on the environment during production, operation, and retirement. Thus, requirements for the disposal of wastes produced during manufacture (whether hazardous or not), as well as for the final disposition of the product, are the concern of the design engineer. This topic is further discussed in Chap. 12.

Some of the *manufacturing/assembly requirements* are dictated by the quantity of the design to be produced and the characteristics of the company producing the design. The quantity to be produced often affects the kind of manufacturing processes to be used. If only one unit is to be produced, then custom tooling cannot be amortized across a number of items and off-the-shelf components should be selected when possible (see Chap. 10). Additionally, every company has internal manufacturing resources whose use is preferable to contracting work outside the company. Such factors must be considered from the very beginning.

6.3.4 The BikeE Suspension Requirements

The design team used the results of the survey plus interviews with bike shop personnel to develop the list of requirements shown in Table 6.2. Note that this list tells *what* is needed in the product not *how* it will look or work. This is important, if there was a requirement "air shock must be easy to fill," then it is implied that there is an air shock in the system.

Table 6.2 Preliminary list of customers' requirements for the BikeE suspension system

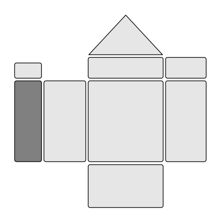
Smooth ride on streets
Eliminate shocks from bumps
Easy to adjust suspension system for different weight riders
Easy to adjust suspension system for different height riders
Easy to adjust suspension system for ride hardness
Easy to maintain
Looks like a suspension
Not noticeably affected by temperature
Not noticeably affected by dirt
Not noticeably affected by water
No pogoing[1]
Easy to assemble
Cost less than $50 to manufacture over the rigid rear fork
Weigh less than 400 grams over the rigid rear fork
Does not change bike height

[1]A bike that pogos moves up each time a pedal is pushed so it bounces up and down twice for each pedal revolution. Pogoing results from a poor design where the chain tension interacts with the suspension.

In Fig. 6.3 only those requirements that are related to function or are hard to measure have been listed in the "what" area. Others such as "cost" are directly measurable and the QFD would add little to its clarification.

Although the list in Table 6.2 is a good first try, it is hard to tell if it is complete. Therefore the team organized the items on the list into the major areas of concern that appear in Table 6.1. Many of the requirements for functional performance could, alternatively, be considered human factors requirements because the rider or mechanic supplies the energy and control (see App. D). By utilizing the checklist in Table 6.1, the design team could refine customers' requirements for completeness. The original requirements were then transformed into a more uniform listing, and in this way some omissions were brought to light. It is important to identify all requirements as early as possible. Partial results of the refinement are shown in Fig. 6.3, the sample suspension QFD diagram.

6.4 STEP 3: DETERMINE RELATIVE IMPORTANCE OF THE REQUIREMENTS: *WHO VERSUS WHAT*



The next step in the QFD technique is to evaluate the importance of each of the customers' requirements. This is accomplished by generating a weighting factor for each requirement and entering it in Fig. 6.2. The weighting will give an idea of how much effort, time, and money to invest in achieving each requirement. Two questions are addressed here: (1) To whom is the requirement important? and (2) How is a measure of importance developed for this diverse group of requirements?

Since a design is "good" only if the customers think it is good, the obvious answer to the first question is, the customer. However, we know that there may be more than one customer. In the case of a piece of production machinery, the desires of the workers who will use the machine and those of management may not be the same. This discrepancy must be resolved at the beginning of the design process, or the requirements may change partway through the job. Sometimes a designer's hardest job is to determine whom to please.

The region of the house of quality labeled "who vs. what" in Fig. 6.2 is for the input of the importance of each requirement. It is important to understand which requirements each type of customer thinks is important. Note that, in most cases, less than half of the requirements have most of the importance. The best way to represent importance is with a number showing its *weight* relative to the other requirements.

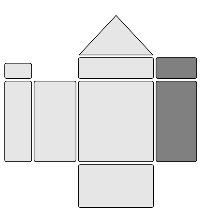
Traditionally, weighting has been done by instructing the customers to rate the requirements on a scale of 1 to 10 with 10 being important and 1 being unimportant. Unfortunately, often these methods result in everything being extremely or absolutely important.

A better method, the fixed sum method, is to tell each customer that they have 100 points to distribute among the requirements. Using the fixed sum of 100 forces the customer to rate some of the requirements low if they want others to be high. This method works much better than just telling them to rate requirements on a scale of 1 to 10.

To aid in weighting, write each requirement on a piece of self-stick note paper, put the notes on a wall, and ask each customer to arrange them in order of importance. If two or more requirements seem to be equally important, be sure that they don't measure the same thing, that they are orthogonal. Once the notes are in order, allocating the 100 points should be easier.

If there are more than 30 requirements, allocating weights can be very difficult. It is suggested that the large group of requirements be broken into two smaller groups, those that are most important and those that are least important. For the least important, give each a weight of 1 and use the fixed sum method on the rest. When done, normalize the weights to 100 total points.

The results of weighting the requirements for the suspension system are shown in Fig. 6.3 for each of the customers. The fixed sum method was used to set the weights.



6.5 STEP 4: IDENTIFY AND EVALUATE THE COMPETITION: HOW SATISFIED IS THE CUSTOMER *NOW*?

The goal here is to determine how the customer perceives the competition's ability to meet each of the requirements. Even though the suspension system is a new design, there is competition. The purpose for studying existing products is twofold: first, it creates an awareness of what already exists (the "now"), and second, it reveals opportunities to improve on what already exists. In some companies this process is called *competition benchmarking* and is a major aspect of understanding a design problem. In benchmarking, each competing product must be compared with customers' requirements (now versus what). Here we are only concerned with a subjective comparison that is based on customer opinion. Later, in step 8, we will do a more objective comparison. For each customer's requirement, we rate the existing design on a scale of 1 to 5:

1. The product does not meet the requirement at all.
2. The product meets the requirement slightly.
3. The product meets the requirement somewhat.
4. The product meets the requirement mostly.
5. The product fulfills the requirement completely.

Though these are not very refined ratings, they do give an indication of how the competition is perceived by the customer.

This step is very important as it shows opportunities for product improvement. If all the competition rank low on one requirement, this is clearly an opportunity. This is especially so if the customers ranked that specific requirement highly important in step 3. If one of the competitors meets the requirement completely, this product should be studied and good ideas used from it (note patent implications, Section 7.2.3).

If you included your current product as one benchmark (you should) and it ranks high on an important requirement, don't mess with the features that helped it meet that requirement.

In the 1980s there was a commercial on television for a family van in which the manufacturer bragged that its product was so good that one of its competitors bought and studied it. The commercial showed the competitor's technicians in white coats disassembling the van. What the commercial did not say was that the advertiser also bought and studied its competitor's product and that this is just good design practice.

The results of this step for the suspension system are shown in Fig. 6.3. The team decided to use three benchmarks. The first is the current cantilever product shown in Fig. 4.12 (BikeE CT). The second is a traditional mountain bike system, shown in Fig. 6.5, and the third is a recumbent competitor's system also shown in Fig. 6.5. Although there are many mountain bike configurations to choose from, only one was used here.

To determine how well the competitors met the requirements, the design team used questionnaires to evaluate them. The average results from street riders are shown in the "now vs. what" section of Fig. 6.3.

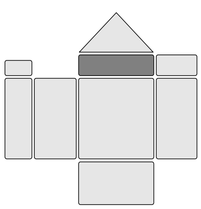
Important points to note are that

1. The BikeE CT gives a poor ride on streets, but even the competition is not very highly thought of by the street riders.
2. The BikeE CT, with its semirigid rear stay, does little to eliminate bumps but can handle different rider weights and heights.

Figure 6.5 Competitive mountain bike and a recumbent system (VR54 Courtesy of Vision Bikes).

3. Neither the mountain bike nor the competitive recumbent do a good job of not pogoing, or adjusting for rider height or weight.
4. None are easy to adjust.

These are all important factors to consider in the design, especially those that are considered very important to the customers (see step 3).



6.6 STEP 5: GENERATE ENGINEERING SPECIFICATIONS: *HOW* WILL THE CUSTOMERS' REQUIREMENTS BE MET?

The goal here is to develop a set of *engineering specifications* from the customers' requirements. These specifications are the restatement of the design problem in terms of parameters that can be measured and have target values. Without such information the engineers cannot know if the system being developed will satisfy the customers. The parameters are developed in this step, and the target values for these parameters are developed in step 8.

In this step, we develop parameters that tell *how* we know if customers' requirements have been met. These parameters are the measures of the customers' requirements. Some customers' requirements are directly measurable; this step does not apply to them. For example, the requirement that a new device be able to lift 100 kg or that a paper tray hold size A paper is clearly measurable. Abstract requirements, like “easy to attach,” must be refined in order to be measurable. It is toward these more abstract requirements that we now direct our attention.

We begin by finding as many engineering parameters as possible that indicate a level of achievement for customers’ requirements. For example, a requirement for “easy to attach” can be measured by (1) the number of steps needed to attach it, (2) the time to attach it, (3) the number of parts, and (4) the number of standard tools used. Note that a set of units is associated with each of these measures—step count, time, part count, and tool count. *If units for an engineering parameter cannot be found, the parameter is not measurable and must be readdressed.* Each engineering parameter must be measurable and thus must have units of measure. However, “time to attach” may not be a reliable measure as it will be dependent on the skill and training of the customer. Either the customer’s skill level needs to be defined or this parameter eliminated.

An important point here is that every effort must be made to find as many ways as possible to measure customers’ requirements. If there are no measurable engineering parameters for customers’ requirements, then the customer’s requirement is not well understood. Possible solutions are to break the requirement into finer independent parts or to redo step 2 with specific attention to that specific requirement.

When developing the engineering specifications, carefully check each entry to see what nouns or noun phrases have been used. Each noun refers to an object that is part of the product or its environment and should be considered to see if new objects are being assumed. For example, if one specification in the suspension problem was for “easy to adjust suspension system for different-weight riders,” then an adjustable suspension system (a noun phrase) has been assumed as part of the solution. If the design team has made a decision that there is to be a suspension system and it is to be adjustable, this is acceptable. However, if no such assumption has been made, the product solution has been unknowingly limited. Paying attention to the objects that are part of the product is a major topic in concept generation.

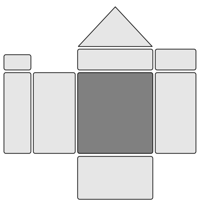
The engineering specifications for the BikeE suspension are shown in Fig. 6.3. Some important points about these are

1. In order to measure the “energy transmitted on a standard road,” a standard road and a method of measuring the energy content of the road and that transmitted need to be devised. By listing this specification, the team is either claiming they have a test method developed or are planning on developing one.
2. Some specifications are subjective. For example, it may be possible to actually measure “pogoing” and “looks” but, it may be easier to use a test panel and note percentage of subjects who notice pogoing or like the looks.
3. The “# of tools to adjust” is listed twice. The first time, for weight and height, will have a target of 0 (see step 7). This could have been listed as two different measures, but was combined as the target is the same. The second, for adjusting the ride hardness, will have a target of 1.

Find the target before you empty your quiver.

4. Measures for environmental effects are given in terms of both stiffness and damping, the two primary measures of a suspension system.

Also shown on Fig. 6.3 are the units for each specification and the direction of improvement, more is better (↑) or less is better (↓). A third option, not shown in the example is nominal is best, where a specific target is known. Targets will be further discussed in step 7.

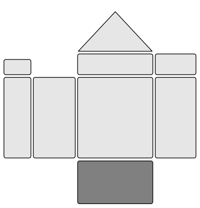


6.7 STEP 6: RELATE CUSTOMERS' REQUIREMENTS TO ENGINEERING SPECIFICATIONS: *HOW* TO MEASURE *WHAT*?

To complete this step, we fill in the center portion of the house of quality. Each cell of the form represents how an engineering parameter relates to a customer's requirement. Many parameters will measure more than one customer's requirement. The strength of this relationship can vary, with some engineering parameters providing strong measures for a customer's requirement and others providing no measure at all. The relation is conveyed through specific symbols:

◉ = strong relationship
○ = medium relationship
△ = weak relationship
Blank = no relationship at all

Figure 6.3 shows the results of this step for the suspension system.



6.8 STEP 7: SET ENGINEERING TARGETS: *HOW MUCH* IS GOOD ENOUGH?

The next step in the QFD technique is to determine a target value for each engineering measure. As the product evolves, these target values are used to evaluate the product's ability to satisfy customers' requirements. There are really two actions here. The first is to ascertain how the competition, examined in step 4, meets the engineering specifications, and the second is to establish the target for the new product.

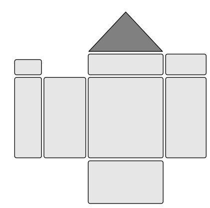
In step 4 competition products were compared to customers' requirements. In this step they will be measured relative to engineering specifications. This ensures that both knowledge and equipment exist for evaluation of any new products developed in the project. Also, the values obtained by measuring the competition give a basis for establishing the targets. This usually means obtaining actual samples of the competition's product and making measurements on them in the same way that measurements will be made on the product being designed.

Setting targets early in the design process is important; targets set near the end of the process are easy to meet but have no meaning as they always match what has been designed. However, setting targets too tightly may eliminate new ideas. Some companies refine their targets throughout concept development and then make them firm. Their initial targets, set here, may have ±30 percent tolerance on them.

Most texts on QFD suggest that a single value be set as a target. However, once the design process is underway, often it is not possible to meet these exact values. Additionally, if a more-is-better target is set at, for example, 50, then is a value of 49 unacceptable? A more robust method for setting targets is to establish the levels at which the customers (choose the most critical) will be delighted and disgusted. For example, in Fig. 6.3, for the engineering specification "energy transmitted on std road," a less-is-better requirement, the BikeE CT transmits 95 percent of the energy. This is not surprising as it has a semirigid rear stay. The mountain bike tested transmits 35 percent and the recumbent that was benchmarked transmits 50 percent. Based on these values and interview with customers, the team set the delighted target at 30 percent and the disgusted target at 50 percent. Similar logic was used to set the other targets.

A final comment on target setting is that if a target is much different than the values achieved by the competition, it should be questioned. Specifically, what do you know that the competition does not know? Do you have a new technology, do you know of new concepts, or are you just smarter than your competition?

6.9 STEP 8: IDENTIFY RELATIONSHIPS BETWEEN ENGINEERING REQUIREMENTS: HOW ARE THE *HOWS* DEPENDENT ON EACH OTHER?



Engineering specifications may be dependent on each other. It is best to realize these dependencies early in the design process. Thus, the roof is added to show that as you work to meet one specification, you may be having a positive or negative affect on others.

In Fig. 6.3 the roof for the suspension system QFD shows diagonal lines connecting the engineering specifications. If two specifications are interdependent, a symbol is noted in the intersection. Typically these symbols are used:

⋇	Negative	–1
×	Strong Negative	–3
⊙	Strong Positive	9
○	Positive	3

These relationships can be used to develop analytical relationships between the specifications.

6.10 FURTHER COMMENTS ON QFD

The QFD technique ensures that the problem is well understood. It is useful with all types of design problems and results in a clear set of customers' requirements and associated engineering measures. It may appear to slow the design process, but in actuality it does not, as time spent developing information now is returned in time saved later in the process.

Even though this technique is presented as a method for understanding the design requirements, it forces such in-depth thinking about the problem that many good design solutions develop from it. No matter how hard we try to stay focused on the requirements for the product, product concepts are invariably generated. This is one situation where a design notebook is important. Ideas recorded as brief notes or sketches during the problem understanding phase may be useful later; however, it is important not to lose sight of the goals of the technique and drift off to one favorite design idea.

The QFD technique automatically documents this phase of the design process. Diagrams like Fig. 6.3 serve as a design record and also make an excellent communication tool. Specifically, the structure of the house of quality makes explaining this phase to others very easy. In one project a member of the sponsoring organization was blind. A verbal description of the structure helped him understand the project.

Often, when working to understand and develop a clear set of requirements for the problem, the design team will realize that the problem can be decomposed into a set of loosely related subproblems, each of which may be treated as an individual design problem. Thus, a number of independent houses may be developed.

The QFD technique can also be applied during later phases of the design process. Instead of developing customers' requirements, we may use it to develop a better measure for functions, assemblies, or components in terms of cost, failure modes, or other characteristics. To accomplish this, review the steps, replacing customers' requirements with what is to be measured and engineering requirements with any other measuring criteria.

A final comment about developing the engineering specifications is that since much learning occurs during the design process, the QFD is considered a working document that is reviewed and updated as needed. The formality and complexity of the technique forces any change to be carefully considered and thus keeps the project moving toward completion. Without a system like QFD, changes in specifications can occur at the whim of a manager or without the design team even realizing it. These changes lead to a failure to meet the schedule and a potentially poor product.

6.11 SUMMARY

- Understanding the design problem is best accomplished through a technique called quality function deployment (QFD). This method transforms customers' requirements into targets for measurable engineering requirements.

- Important information to be developed at the beginning of the problem includes customers' requirements, competition benchmarks, and engineering specifications complete with measurable benchmarks.
- Time spent completing the QFD is more than recovered later in the design process.
- There are many customers for most design problems.
- Studying the competition during problem understanding gives valuable insight into market opportunities and reasonable targets.

6.12 SOURCES

Adams, J. L.: *Conceptual Blockbusting,* Norton, New York, 1976. The story about the *Mariner IV* satellite comes from this book on creativity.

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Roberts, V. L.: *Products Standards Index,* Pergamon, New York, 1986. A sourcebook for standards.

Salant, P., and D. Dillman: *How to Conduct Your Own Survey,* John Wiley & Sons, New York, 1994. A very complete book on how to do surveys to collect opinions.

Software packages

QFD/CAPTURE, version 2.2.1, International TechneGroup Inc. (ITI), Milford, Ohio. Software support for QFD diagrams. Fig. 6.3 was developed on this software.

QFD Designer, Qualisoft, **www.qualisoft.com.**

6.13 EXERCISES

6.1 For the original design problem (Exercise 4.1), develop a house of quality and supporting information for it. This must include the results of each step developed in this chapter. Make sure you have at least three types of customers and three benchmarks. Also, make a list of the ideas for your product that were generated during this exercise.

6.2 For the features of the redesign problem (Exercise 4.2) to be changed, develop a QFD matrix to assist in developing the engineering specifications. Use the current design as a benchmark. Are there other benchmarks? Be careful to identify the features needing change before spending too much time on this. The methods in Chap. 7 may be used iteratively to help refine the problem.

6.3 Develop a house of quality for these objects.

a. The controls on an electric mixer.

b. An all-terrain bicycle.

c. An attachment for electric drills to cut equilateral-triangle holes in wood. The wood can be up to 50 mm thick, and the holes must be adjustable from 20 mm to 60 mm per side.

d. A tamper-proof fastener as used in public toilet facilities.