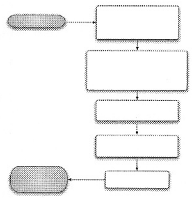
CHAPTER 2

THE DESIGN PROCESS

Is there a way to do engineering design? And can you give me a roadmap of where is this book is going?



HAVING DEFINED engineering design and its attendant vocabulary, we go on to explore the activity of doing a design, that is, the *process* of design. Some of this may seem abstract because we are trying to describe a very complex process by breaking it down into smaller, more detailed *design tasks*. Further, as we define those design tasks, we will identify places in the design process where we can use the design tools and methods we present in Chapters 3–5. Please keep in mind, however, that *we are **not** presenting a recipe* for doing design. Instead, we are outlining a framework within which we can *articulate and **think*** about what we are doing as we design something.

2.1 THE DESIGN PROCESS AS A PROCESS OF QUESTIONING

Imagine you are working in a company that makes diverse consumer projects, and your boss calls you into her office and says, "Design a safe ladder." You wonder to yourself, Why does anyone need still another ladder? Aren't there a lot of safe ladders already on the market (including those we saw in Figure 1.5)? And what does she mean by a "safe ladder"?

This scenario is clearly contrived, so its not a big surprise that a whole bunch of questions immediately come to mind. Typically, however, design projects or problems begin with a verbal statement that talks about a client's intentions or goals, the design's form or shape, its purpose or function, and perhaps some things about legal requirements. The designer's first task is to *clarify* what the client wants so as to be able to translate those wishes into meaningful *objectives* (goals) and *constraints* (limits). This clarification task proceeds as the designer asks the client to be more precise about what she really wants.

In fact, asking questions is an integral part of the entire design process. To paraphrase an observation made long ago by Aristotle, *knowledge resides in the questions that can be asked and the answers that can be provided.* Thus, it is important to think about the questions that should be asked and to identify others in the designer-client-user triangle who may have answers (and may also have other useful questions). Further, by looking at the kinds of questions that can be asked throughout the design process we can develop and articulate that process as a sequence of *design tasks.* In fact, the following array of questions we might ask about designing a ladder suggests a sequence of design tasks (in italics) that we will consider later.

Questions such as:

- Why do you want another ladder?
- How will the ladder be used?
- How much can it cost?

help *clarify and establish the client's objectives* for the design.

Questions such as:

- What does "safe" mean?
- What's the most you're willing to spend?

help *identify the constraints* that govern the design.

Questions such as:

- Can the ladder lean against a supporting surface?
- Must the ladder support someone carrying something?

help *establish functions* that the design must perform and suggest *means* by which those functions can be performed.

Questions such as:

- How much weight should a safe ladder support?
- How high should someone on the ladder be able to reach?

help *establish requirements* for the design.

Questions such as:

- Could the ladder be a stepladder or an extension ladder?
- Could the ladder be made of wood, aluminum, or fiberglass?

help *generate design alternatives.*

Questions such as:

- What is the maximum stress in a step supporting the "design load"?
- How does the bending deflection of a loaded step vary with the material of which the step is made?

help *model* and *analyze* the design.

Questions such as:

- Can someone on the ladder reach the specified height?
- Does the ladder meet OSHA's safety specification?

help *test* and *evaluate* the design against its objectives and its constraints.

Questions such as:

- Are there other ways to connect the steps?
- Can the design be made with less material?

help *refine* and *optimize* the design.

Finally, questions such as:

- What is the justification for the design decisions that were made?
- What information does the client need to fabricate the design?

help *document* the design process and *communicate* the completed design.

Thus, the questions we asked about the ladder design establish steps in a process that move us from an abstract statement of a client's desires through increasing levels of detail toward an engineering solution. The early design tasks move toward translating the client's wishes into a set of *requirements* that state in engineering terms how the design is to function or perform. These requirements, also called *design specifications*, serve as benchmarks against which the design's performance is measured. Design specifications are typically stated in one of three forms, so the requirements might: *prescribe* values for attributes of the design; *specify procedures* for calculating attributes or behavior; or they might *specify the performance* of the design's behavior. (We discuss this further in Chapter 4.) Continuing on, as we generate different *concepts* of how the design might work or function, we also create *design alternatives*. Then we choose one concept (say, here, a stepladder) and *build and analyze a model* of that ladder's design; *test and evaluate* the design; *refine and optimize* some of its details; and then *document* the justification for the stepladder's final design and its fabrication specifications. In Section 2.2 we will present *all* of the tasks of the engineering design process in greater detail.

Some of the early questions asked (to clarify the client's wishes) clearly connect to later tasks in the process where we make choices, analyze how competing choices interact, assess tradeoffs in these choices, and evaluate the effect of these choices on our top-level goal of designing a safe ladder. For example, the ladder's *form* or shape and layout are strongly related to its *function*: We are more likely to use an extension ladder to rescue a cat from a tree and a stepladder to paint the walls of a room. Similarly, the weight of the ladder has an impact on the efficiency with which it can be used: Aluminum extension ladders have replaced wooden ones largely because they weigh less. The material of which a ladder is made affects not only its weight, but also its cost and its feel: Wooden extension ladders are much stiffer than their aluminum counterparts, so users of aluminum ladders feel a certain amount of "give" or flex in the ladder, especially when it is significantly extended.

There are no equations for safety, color, marketability. . . .

Some of the questions in the later design tasks can be answered by applying the mathematical models such as those used in physics. For example, Newton's equilibrium law and elementary statics can be used to analyze the stability of the ladder under given loads on a specified surface. We can use beam equations to calculate deflections and stresses in the steps as they bend under the given foot loads. But there are no equations that define the meaning of "safe," or of the ladder's marketability, or that help us choose its color. Since there are no equations for safety, marketability, color, or for most of the other issues in the ladder questions, we must find other ways to think about this design problem.

It also seems clear that we will face a vast array of choices as our design evolves. At some point in our ladder design, for example, we have to choose a *type* of ladder, say a stepladder (for painting) or an extension ladder (for rescuing cats). We then have to decide how to fasten the steps to the ladder frame. The choices will be influenced by the desired behavior (e.g., although the ladder itself may flex, we don't want individual steps to have much give with respect to the ladder frame), as well as by manufacturing or assembly considerations (e.g., would it be better to nail in the steps of a wooden ladder, use dowels and glue, or nuts and bolts?). Note that we are now decomposing the complete ladder into its components and selecting particular types of components.

We should also note that as we work through these questions (and design tasks), we are constantly communicating with others about the ladder and its various features. When we question our client about its desired properties, for example, or the laboratory director about evaluation tests, or the manufacturing engineer about the feasibility of making certain parts, we are interpreting aspects of the ladder design in terms of *languages* and parameters that these experts use in their own work: We draw pictures in graphical languages; we write and apply formulas in the language of mathematics; we ask verbal questions and provide verbal descriptions; and we use numbers all of the time to fix limits, describe test results, and so on. Thus, the design process can't proceed without recognizing different design languages and their corresponding interpretations.

This simple design problem illustrates how we might *formalize* the design process to make explicit the design tasks that we are doing. We are also *externalizing* aspects of the process, moving these aspects from our heads into a variety of recognizable languages to be able to communicate with others. Thus, we learn two important lessons from our ladder design project:

Clarifying objectives and translating them into the right "languages" are essential elements of design.

- *Clarifying* the client's objectives is a crucial part of an engineering design project. The designer must fully understand what the client wants (and the users need) from the resulting design. Good communication among all three parties in the designer-client-user triangle is essential, and we must be very careful when eliciting the details of what the client really wants.
- Performing the design tasks in the design process requires *translating* the client's objectives into the kinds of words, pictures, numbers, rules, properties, etc., that are needed to characterize and describe both the object being designed and its behavior. The tasks of analyzing and modeling, testing and evaluating, and refining and optimizing cannot be done just with words. And the documentation of the final design cannot be done with words alone. We need pictures and numbers, and likely other

ways of representing the desired design. Thus, the designer translates the client's verbal statement into whatever languages are appropriate to completing the various design tasks at hand.

2.2 DESCRIBING AND PRESCRIBING THE DESIGN PROCESS

We have just seen that asking increasingly detailed questions exposed several design tasks. We will now formalize such design tasks into a design process. Many design process models are *descriptive*: they *describe* the elements of the design process. Other models are *prescriptive*: they *prescribe* what must be done during the design process. After introducing some descriptive models, we will introduce an extended set of our design tasks into one of them and so convert that (chosen and revised) descriptive model into a prescriptive model.

2.2.1 Describing the design process

The simplest descriptive model of the design process defines three phases:

1. *Generation*: the designer *generates* or creates various design concepts.
2. *Evaluation*: the designer *tests* the chosen design against metrics that reflect the client's objectives and against requirements that stipulate how the design must function.
3. *Communication*: the designer *communicates* the final design to the client and to manufacturers or fabricators.

Another three-stage model splits up the design process differently: *Doing research*, *creating*, and *implementing* a final design, with the contexts providing meanings for these three steps. While these two models have the virtue of simplicity, they are so abstract that they provide little useful advice on how to do a design. They also assume that the designer understands the client's objectives and the users' needs, and they both accept that the identification of the design problem has already occurred (and is, implicitly, not a part of the design process). Further, and perhaps most importantly, these models tell us nothing about *how* we might generate or create designs.

We show another, widely accepted descriptive model of the design process in Figure 2.1(a), with three "active" stages shown in boxes with rounded corners. It also shows the client's problem statement, sometimes identified as the *need* for a design, as the starting point. The final design (or its fabrication specifications) is the endpoint. The model's first phase is *conceptual design*, in which different *concepts* (also called *schemes*) are generated to achieve the client's objectives. Thus, the major functions and the means for achieving them are identified, as are the spatial and structural relationships of the principal components. Enough details have been worked out so that we can estimate costs, weights, and overall dimensions. For the ladder project, for example, conceptual designs might be an extension ladder, a stepladder, and a rope. The evaluation of these concepts will depend on the client's objectives, such as its intended use, its allowable cost, and even the client's aesthetic values.

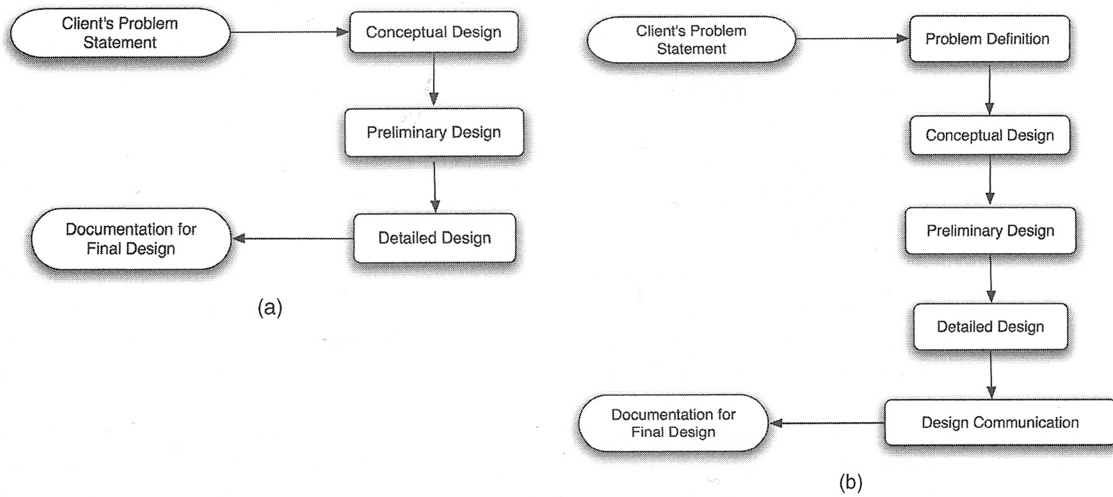


FIGURE 2.1 Two descriptive, "linear" models of the design process: (a) three stages; (b) five stages. Both models show the design process as simple, linear sequences of objects (*need* and *final design*) connected by three (*conceptual, preliminary,* and *detailed design*) or five (*problem definition, conceptual design, preliminary design, detailed design,* and *design communication*) design phases. As descriptive models, they provide very little guidance on how to do the various stages.

With its focus on tradeoffs between high-level objectives, conceptual design is clearly the most abstract and open-ended part of the design process. The output of the conceptual stage may include several competing concepts. Some argue that conceptual design *should* produce two or more schemes since early commitment to or fixation on a single design choice may be a mistake. This tendency is so well known among designers that it has produced a saying: "Don't marry your first design idea."

The second phase in this model of the design process is *preliminary design* or the *embodiment of schemes*. Here proposed concepts are "fleshed out," that is, we hang the meat of some preliminary choices upon the abstract bones of the conceptual design. We embody or endow design schemes with their most important attributes. We select and size the major subsystems, based on lower-level concerns that take into account the performance and operating requirements. For a stepladder, for example, we size the side rails and the steps, and perhaps decide on how the steps are to be fastened to the side rails. Preliminary design is more technical in nature, so we might use various back-of-the-envelope calculations. We make extensive use of rules of thumb about size, efficiency, and so on, that reflect the designer's experience. And, in this phase of the design process, we solidify our final choice of design concept.

The final stage of this model is *detailed design*. We now refine the choices we made in preliminary design, articulating the final choice in far greater detail, down to specific part types and dimensions. This phase typically follows design procedures that are quite well understood by experienced engineers. Relevant knowledge is found in design codes (e.g., the ASME Pressure Vessel and Piping Code, the Universal Building Code), handbooks, databases, and catalogs. Design knowledge is often expressed in specific rules, formulas and algorithms. This stage of design is typically done by component specialists who use libraries of standard pieces.

The classic model just outlined can be extended to a five-stage model that delineates two additional sets of activities that precede and follow the three-stage model sequence:

- *Problem definition*: a pre-processing stage that *frames the problem* by clarifying the client's original problem statement *before* conceptual design begins.
- *Design communication*: a post-processing phase that identifies the work done *after* detailed design to collect, organize, and present the final design and its fabrication specifications.

Note that in practice much of the documentation will have been developed along the way (e.g., a designer might write out the design rationale behind her choice for some details when the choice is actually made, rather than at the end), so the communication phase is as much about tracking and organizing work products as it is about writing a "new" report from scratch.

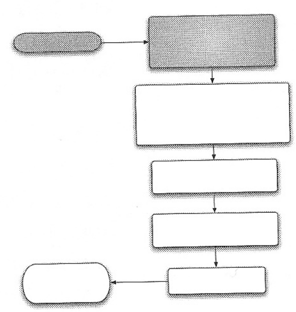
This five-stage model of the process, displayed in Figure 2.1(b), is more detailed than the three-stage models discussed above, but it does not bring us much closer to knowing *how* to do a design because it too is *descriptive*. In the next section we present a process model that prescribes what ought to done.

2.2.2 Prescribing the design process

In Figure 2.2 we show the descriptive model of Figure 2.1(b) converted into a five-phase *prescriptive* model that prescribes or specifies what is done in each phase in terms of fifteen design tasks, as delineated in the five charts below. It begins with the client's problem statement (chart 1) and ends with design documentation (chart 5). Each phase requires *input(s)*, has *design tasks* that must be performed, and produces *output(s)* or product(s). Thus, charts 1–5 detail the five phases of design with their inputs, tasks and output. Each chart is followed by a brief listing of the *sources of information*, *design methods*, and *means* relevant to the design tasks in that phase. (The sources of information and the corresponding means are discussed in Section 2.3; the design methods identified here will be outlined in Section 2 and discussed in detail in Chapters 3–5.) Note, too, that the output for each phase serves as the input to the following phase.

1. During *problem definition* we *frame the problem* by clarifying the client's objectives and gather the information needed to develop an unambiguous statement of the client's wishes, needs and limits.

   Input: *client's problem statement*
   Tasks: *clarify design objectives (1)*
   establish metrics for those objectives (2)
   identify constraints (3)
   revise client's problem statement (4)
   Outputs: *revised problem statement*
   list of final objectives
   metrics for final objectives
   list of final constraints



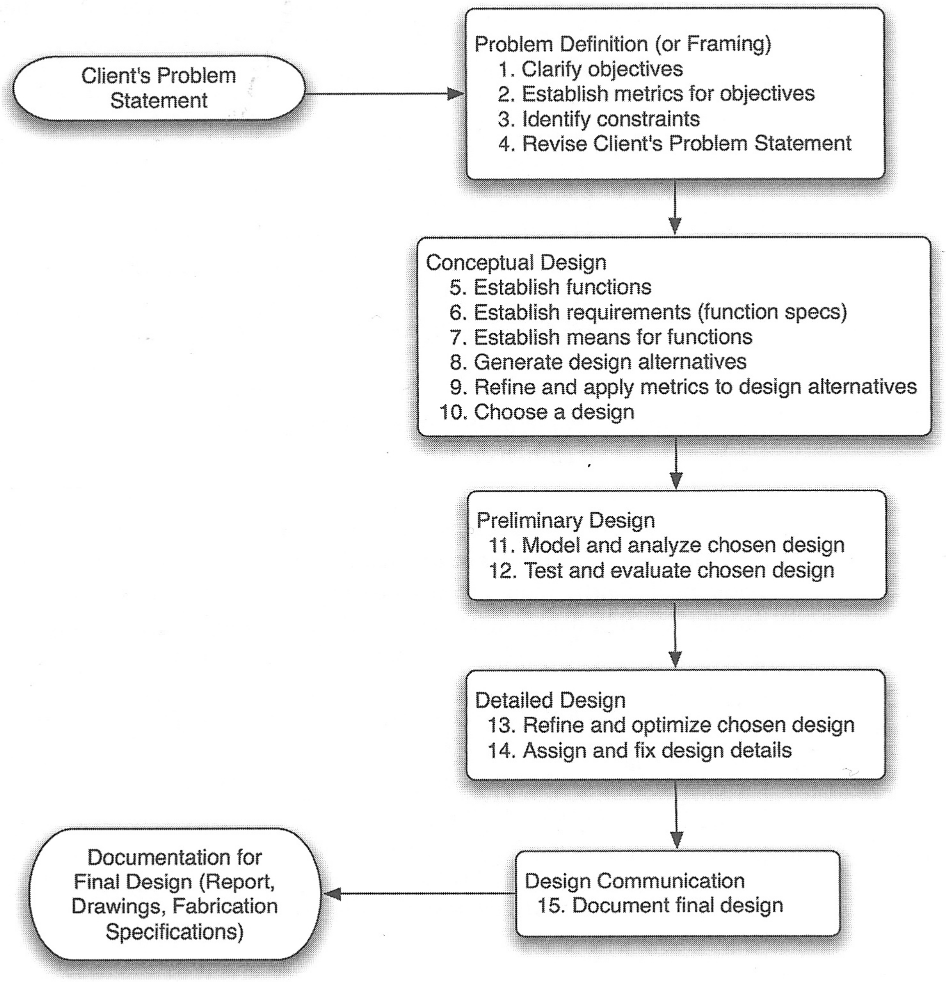


FIGURE 2.2 A five-stage *prescriptive* model of the design process. Like the descriptive model of Figure 2.1 (b), this model also styles the process as a linear sequence of objects (*need* and *final design*) and design phases, within which are situated the design tasks.

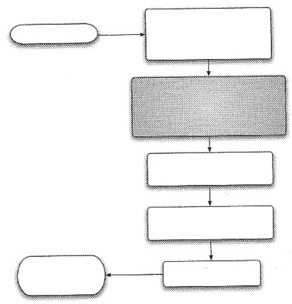
The *sources of information* for problem definition include current technical literature, codes, regulations and experts. *Design methods* include objectives trees and pairwise comparison charts. The *means* include literature reviews, brainstorming, user surveys and questionnaires, and structured interviews.

2. In the *conceptual design* stage of the design process we generate *concepts* or *schemes* of *design alternatives* or possible acceptable designs.

Inputs: *revised problem statement*
list of final objectives
metrics for final objectives
list of final constraints

Tasks: *establish functions (5)*
establish requirements (function specs) (6)
establish means for performing functions (7)
generate design alternatives (8)
refine and apply metrics to design alternatives (9)
choose a design alternative (10)

Outputs: *requirements (specifications for functions)*
a chosen design



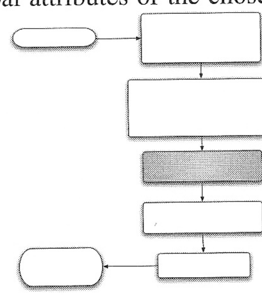
Competitive products are the additional principal *sources of information* for conceptual design. *Design methods* include functional analysis, function-means trees, morphological charts, requirements matrices, the performance specification method, and quality function deployment (QFD). *Means* include brainstorming, synectics and analogies, benchmarking, and reverse engineering (dissection).

3. In the *preliminary design* phase we identify the principal attributes of the chosen design concept or scheme.

Inputs: *requirements or specifications for functions*
the chosen design

Tasks: *model, analyze chosen design (11)*
test, evaluate chosen design (12)

Output: *an analyzed, tested, evaluated design*



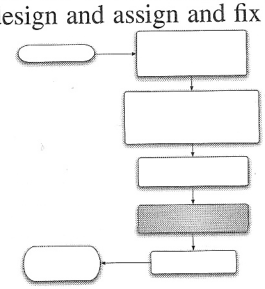
The *sources of information* during preliminary design include heuristics (rules of thumb), simple models and known physical relationships. *Design methods* include appropriate physical modeling and verifying that design requirements are met. *Means* include computer modeling and simulation, prototype development, laboratory and field tests, and proof-of-concept testing.

4. During *detailed design* we refine and optimize the final design and assign and fix the design details.

Input: *the analyzed, tested, evaluated design*

Tasks: *refine, optimize the chosen design (13)*
assign and fix the design details (14)

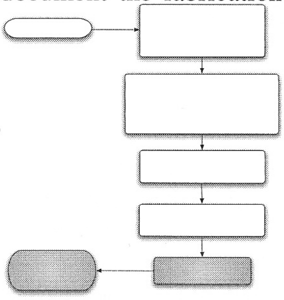
Output: *proposed design and design details*



The *sources of information* for detailed design include design codes, handbooks, local laws and regulations, and suppliers' component specifications. *Design methods* include discipline-specific CADD (computer-aided design and drafting). *Means* include formal design reviews, public hearings (if applicable), and beta testing.

5. Finally, during the *design communication* phase we document the fabrication specifications and their justification.

   Input: *proposed design and design details*
   Task: *document the final design (15)*
   Outputs: *final written, oral reports to client containing.*
   (1) description of design process
   (2) drawings and design details
   (3) fabrication specifications



The *sources of information* for the design communication phase are feedback from clients and users, and itemized lists of required deliverables.

We now have a checklist we can use to ensure that we have done all of the required steps. Lists like this are often used by design organizations to specify and propagate approaches to design within their firms. However, we should keep in mind that this and other detailed elaborations add to our understanding of the design process only in a limited way. At the heart of the matter is our ability to model the tasks done within each phase of the design process. With this in mind, we will present some means and formal methods for doing these 15 design tasks in Section 2.3.

2.2.3 Feedback and iteration in the design process

All of the models presented so far have been "linear" or sequential. The design process is not linear or sequential, however, and two very important elements must be added. The first of these is *feedback*, that is, the process of feeding information about the output of a process back into the process so it can be used to obtain better results. Feedback occurs in two notable ways in the design process, as illustrated in Figure 2.3:

- First, there are *internal feedback loops* that come *during the design process* and in which the results of performing the test and evaluation task are fed back from the preliminary design phase to *verify* that the design performs as intended. As noted in Section 1.3, feedback comes from internal customers, such as manufacturing (e.g., can it be made?) and maintenance (e.g., can it be fixed?).
- Second, there is an *external feedback loop* that comes *after the design reaches its intended market* and in which user feedback then *validates* the (presumably successful) design.

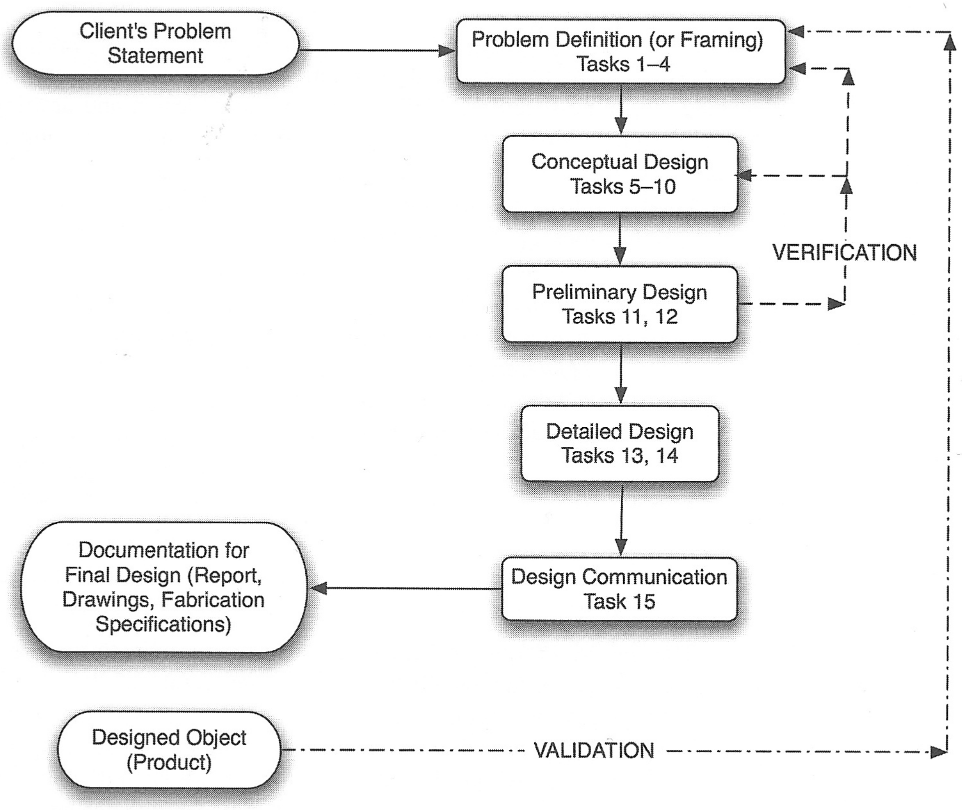


FIGURE 2.3 A five-stage prescriptive model of the design process that shows (in dashed lines) feedback loops for: (a) *verification*, internal feedback *during* the design process; and (b) *validation*, external feedback obtained after the design process when the designed object or device is in actual use.

The second element that we have thus far left out of our process models is *iteration*. We iterate when we repeatedly apply a common method or technique at different points in a design process (or in analysis). Sometimes the repeated applications occur at a different *levels of abstraction* wherein we know different degrees of detail, so we might use different scales. Thus, as we fix more detail, we become less abstract. Such iterations or repetitions typically occur at more refined, less abstract points in the design process (and on a finer, more detailed scale in analysis). In terms of the linear five-stage model depicted in Figure 2.2, we should anticipate repeating tasks 1–3 and 5 in some form in conceptual, preliminary, and detailed design. That is, we always want to keep the original objectives in mind to ensure that we have not strayed from them as we get deeper and deeper into the details of our final design. Of course, this may also mean that we may have reason to do some redesign, in which case we will certainly repeat tasks 11 (analyzing the design) and 12 (testing and evaluating the design) as well.

Iteration and feedback are integral parts of the design process.

Given that there are feedback loops and that we will repeat or reiterate some tasks, why did we present our process models as linear sequences? The answer is simple. We noted in Chapter 1 that "design is a goal-directed activity, performed by humans." As important as the feedback and iterative elements of design are, it is equally important not to be overly distracted by these adaptive characteristics when learning about — and trying to do — design for the first time. It is also true that, in some sense, feedback loops and the need to repeat some design tasks will occur naturally as a design project unfolds. When we are doing a design for a client, it is only natural to go back and ask the client if the original project statement was properly revised. And it is just as natural to show off emerging design concepts, and to refine these schemes by responding to feedback and by reiterating objectives, constraints, and requirements.

2.2.4 On opportunities and limits

The primary focus of this book is conceptual design, the first phase of the design process. As a result, we will often be dealing with some very broad themes and approaches in ways that are logical, but not as neat and tidy as a set of formulas or algorithms. In fact, conceptual design tools lend themselves to answering questions that are not easily posed in formal mathematical terms. It is ironic that this seeming lack of rigor of the tools we will present for use in conceptual design also makes them very useful more generally for *problem solving*.