CHAPTER 1

INTRODUCTION: STANDARDS, CODES, REGULATIONS

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1.1 THE DESIGNER AND THE DESIGNER'S PROBLEMS

1.1.1 Design and the Designer

Design and engineering, although sometimes viewed as distinct, are two facets of the same profession. Krick [1.1] states that engineering is a profession concerned primarily with the application of a certain body of knowledge, set of skills, and point of view in the creation of devices, structures, and processes used to transform resources to forms which satisfy the needs of society.

Design is the activity in which engineers accomplish the preceding task, usually by responding to a design imperative for the required task. The design imperative is the result of a problem definition and has the following general form [1.2]: "Design (subject to certain problem-solving constraints) a component, system or process that will perform a specified task (subject to certain solution constraints) optimally."

The end result of the engineering design process is a specification set from which a machine, process, or system may be built and operated to meet the original need.

The designer's task is then to create this specification set for the manufacture, assembly, testing, installation, operation, repair, and use of a solution to a problem. Although primarily decision making and problem solving, the task is a complex activity requiring special knowledge and abilities. A designer cannot effectively operate in a vacuum, but must know, or be able to discover, information affecting the design, such as the state of the art, the custom of the industry, governmental regulations, standards, good engineering practice, user expectations, legal considerations (such as product liability), and legal design requirements.

In addition, an effective designer possesses the ability to make decisions; to innovate solutions to engineering problems; to exhibit knowledge of other technologies and the economics involved; to judge, promote, negotiate, and trade off; and finally, to sell an acceptable problem solution which meets the imposed constraints.

The designer must also be an effective communicator, not only with design supervisors and peers, but also with the public, as represented by federal, state, and local governments, the courts, and the news media.

Most of the time design proceeds by evolution rather than revolution. Thus many of the requirements may have already been met by contributions of others, and most of the time the engineer has to work on only a small portion of the design, requiring only some of the requisites previously identified.

1.1.2 Design Criteria

Although the general criteria used by a designer are many, the following list addresses almost all concerns:

- Function
- Safety
- Reliability
- Cost
- Manufacturability
- Marketability

The inclusion of safety and reliability at or near the level of importance of function is a recent development that has resulted from governmental regulation, expansion in the numbers of standards created, and development of product liability law, all of which occurred in the late 1960s and early 1970s.

Although cost is explicitly fourth on the list, its consideration permeates all the criteria just listed and is part of all design decisions.

As taught and practiced in the past, design criteria emphasized function, cost, manufacturability, and marketability. Reliability was generally included as a part of functional considerations. If product safety was included, it was somewhere in the function-cost considerations.

Design critiques were accomplished at in-house policy committee meetings or their equivalent involving design engineers, a production representative, a materials representative, and possibly representatives of marketing and service.

In the current design climate, the traditional design criteria are still valid; however, the additional constraints of governmental regulations, standards, and society's desire for safety, as exemplified in product liability litigation, have to be included in the design process. In addition, engineers must now be prepared to have their designs evaluated by nondesigners or nontechnical people. This evaluation will not be in the inner confines of a design department by peers or supervisors, as in the past, but may be in a courtroom by a jury of nontechnical people and attorneys who have an ulterior motive for their approach or in the public arena.

Since such a design evaluation is generally a result of an incident which caused damage or injury, to mitigate the nontechnical evaluation, current design procedures should emphasize the following factors in addition to traditional design criteria:

1. *Safety* This is associated with all modes of product usage. In providing for safety, the priorities in design are first, if at all possible, to design the hazards out of the product. If this cannot be done, then shielding and guarding should be provided so that operators and bystanders cannot be exposed to the hazard. Otherwise, if a risk-benefit analysis shows that production and sale of the machine are still justified (and only as a last resort), effective warning should be given against the hazard present. Even though warnings are the least expensive and easiest way to handle hazards in the design process, there has never been a warning that physically prevented an accident in progress. Warnings require human action or intervention. If warnings are required, excellent reference sources are publications of the National Safety Council in Chicago and a notebook entitled *Machinery Product Safety Signs and Labels* [1.78].

2. *Failure analysis* If failure cannot be prevented, it is necessary that it be foreseen and its consequences controlled.

3. *Documentation* Associated with the evolution of the design, documentation is developed so that it can satisfy the involved nontechnical public as to the rationale behind the design and the decisions and tradeoffs that were made.

The designer is in a new mode which places safety on the same level of importance in design considerations as the function or the ability of the design to perform as intended.

Arguments may be made that cost considerations are the most important. This is true only if the cost of the design includes the costs of anticipated litigation. These costs include product liability insurance premiums; direct out-of-pocket costs of investigating and defending claims; and indirect costs in the loss of otherwise productive time used in reviewing the design involved, in finding information for interrogatories, in being deposed, and in developing defense testimony and exhibits. If a lawsuit is lost, the amount of the verdict and the probable increase in product liability insurance premiums must also be included.

No longer can product liability be considered after the design is on the market and the first lawsuit is filed. Product liability considerations must be an integral part of the entire design process throughout the function, safety, cost, manufacturing, and marketing phases.

Additional criteria, considerations, and procedures should be included in programs to address specifically the product safety, failure, or malfunction problems which have contributed significantly to the existing product liability situation. Some of the important considerations and procedures are

1. Development and utilization of a design review system specifically emphasizing failure analysis, safety considerations, and compliance with standards and governmental regulations
2. Development of a list of modes of operation and examination of the product utilization in each mode

3. Identification of the environments of usage for the product, including expected uses, foreseeable misuses, and intended uses
4. Utilization of specific design theories emphasizing failure or malfunction analysis and safety considerations in each mode of operation

Design reviews have been used extensively for improving product performance, reducing cost, and improving manufacturability. In the current product liability climate, it is very important to include, and document in the review, specific failure analysis and safety emphases as well as to check compliance with standards and governmental regulations.

An important consideration in the design review process is to have it conducted by personnel who were not involved in the original design work, so that a fresh, disinterested, competent outlook and approach can be applied in the review.

1.1.3 Influences on the Designer

While attempting to meet the general criteria discussed earlier, the designer's work and the results are affected by both internal and external influences. The external influences, shown in Fig. 1.1, reflect the desires of society as represented by economics, governmental regulations, standards, legal requirements, and ethics, as well as the items shown as human taste.

The other broad area of external influences reflects what is known and available for use in a design problem. The designer is limited by human knowledge, human skills, and, again, economics as to what can be made.

Another important external influence on the designer and the design is legal in nature. The designer is directly influenced by the in-house legal staff or outside attorney retained for legal advice on patents, product liability, and other legal matters and also is affected by product liability suits against the product being designed or similar products.

Internal influences also affect the design. Figure 1.2 identifies some of these. They are a result of the designer's environment while maturing, education, life experiences, moral and ethical codes, personality, and personal needs. These personal or internal influences help shape the engineer's philosophy of design as well as the approach and execution. Individual designs will vary depending on the most important local influences at any given time.

1.1.4 Design Procedure

The general procedure for design is widely available in the literature (see Refs. [1.3] to [1.12]). The following procedure is representative of those found in the literature and is discussed extensively by Hill [1.3]:

1. Identification of need
2. Problem statement or definition of goal
3. Research
4. Development of specifications
5. Generation of ideas
6. Creation of concepts based on the ideas

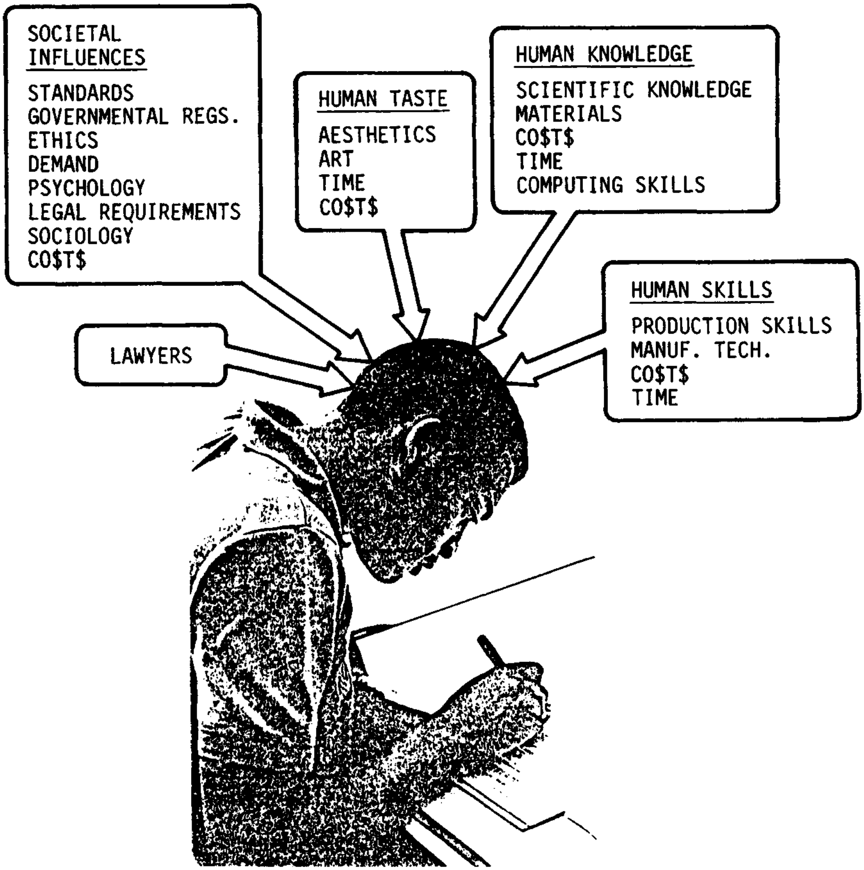

FIGURE 1.1 External influences on the engineering designer.

7. Analysis of alternative concepts
8. Prototype and laboratory testing
9. Selection and specification of best concept
10. Production
11. Marketing
12. Usage (maintenance and repair)

The flowchart in Fig. 1.3 (taken from Ref. [1.13]) illustrates the design process. Note that although not all feedback paths are shown, each step in the process can result in arresting progress and reverting to a prior step, emphasizing that product design is an iterative process.

Much of the design work done is in a small part of one of the feedback or feed-forward portions of the chart and thus is evolutionary. Rarely will an individual designer start at the beginning of the chart with a clean sheet of paper and go through the entire process.

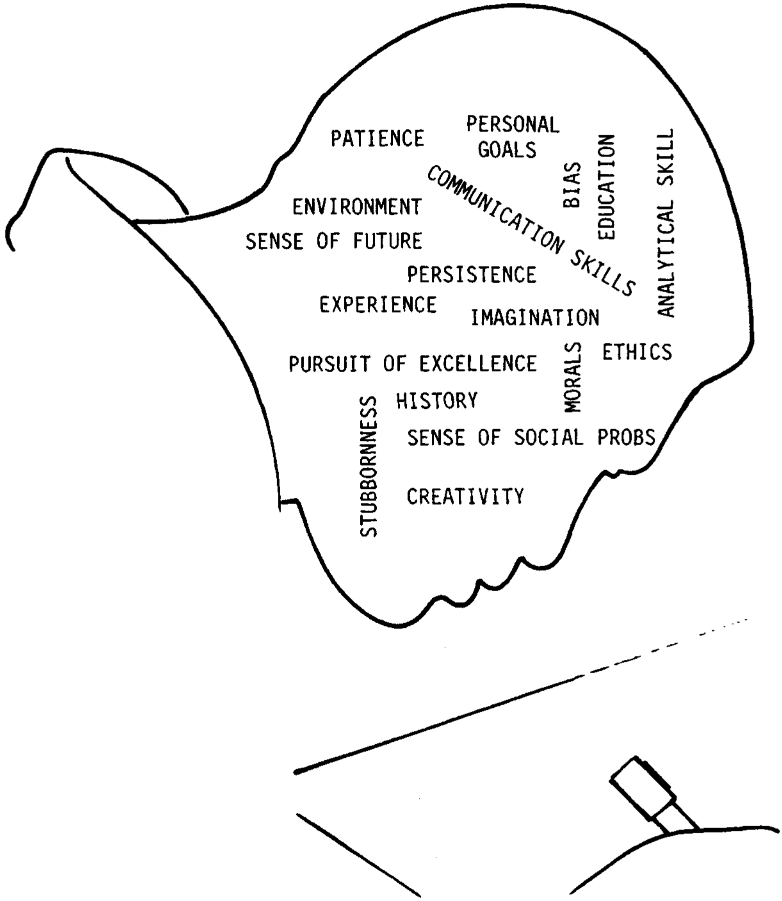

FIGURE 1.2 Internal influences on the engineering designer.

For those designers who do start at the beginning, the checklist in Table 1.1 is an example of one that may be used to organize the information required to define the design problem and aid in establishing design goals. An example list of information for a design specification based on the checklist in Table 1.1 is given in Table 1.2.

After defining the problem and setting the goals for the new design, as much search effort should be made as is feasible to gather all the information possible that applies to the design. This effort includes information on other competitive products or products of a similar nature, governmental regulations and codes, standards, field reports on failure and operation, recall, safety and accident reports, information from lawsuits, plus all the traditional technical information provided in design education (see Ref. [1.14]).

Some of these information sources have attained importance only recently. One example is governmental regulations which have been promulgated since the late 1960s and early 1970s with a major stated purpose of increasing safety both in the workplace (Occupational Safety and Health Act) and elsewhere (Consumer Prod-

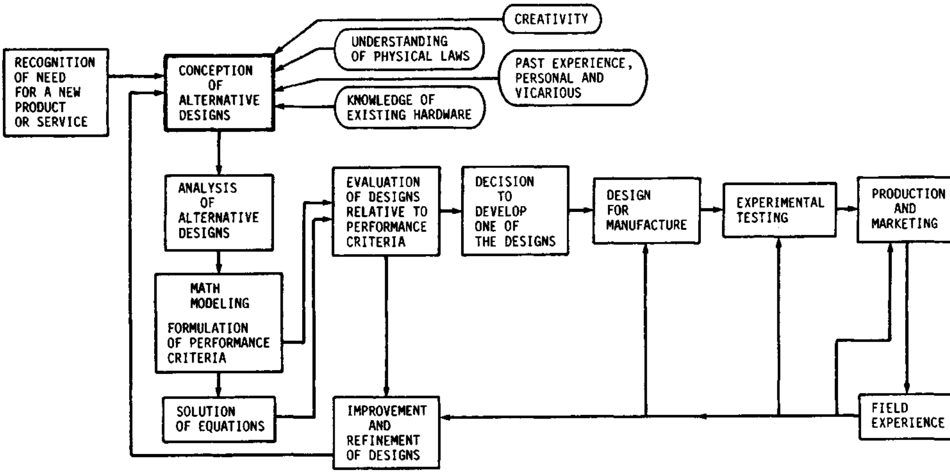

FIGURE 1.3 A flowchart for the design process. (*Adapted from Ref. [1.13]. Used by permission of Charles E. Merrill Publishing Co.*)

TABLE 1.1 Design Checklist

1. Function:	
A simple statement of the objective	
2. Detailed functional requirements:	
Required performance stated numerically	
3. Operating constraints:	
Power supplies	Life
Operating procedures	Reliability
Maintenance procedures	Other operating constraints
4. Manufacturing constraints:	
Manufacturing processes available	Labor available
Development facilities available	Delivery program
Permissible manufacturing cost	Number required
Other manufacturing constraints	
5. Environment:	
Ambient temperature	Installation limitations
Ambient pressure	Expected operators
Climate	Effect on other parts of the parent system
Acceleration	Vibration
Contaminants	Other environmental factors
6. Other constraints:	
Applicable governmental regulations	Applicable standards
Legal requirements—patents	Possible litigation

SOURCE: Adapted from Leech [1.14].

TABLE 1.2 Example of Information Provided on a Design Specification Form

1. Product or job identification number
2. Modification or change number and date
3. Function: In basic terms, what is the function to be performed by the item when designed?
4. Application: Include the system requiring this application.
5. Origin: When, how, and by whom was the requirement made?
6. Customer's specification: Identify the customer's specification and note whether it is in writing or was oral. If oral, who made it, who in your organization received it, and when was this done?
7. General related specifications: Identify all general specifications, definitions, standards, or other useful documents and information that contribute to the design specifications.
8. Safety: Identify standard and special safety precautions or requirements to be included in design considerations, manufacture, marketing, or usage.
9. Governmental regulations and standards applicable: Identify and list.
10. Environment: Identify and list the environmental specifications required using the items included under "Environment" in Table 1-1 as guidelines.
11. Number required and delivery schedule.
12. Desired cost or price information
13. Functional requirements:

Life	Performance requirements with acceptable tolerance limits
Reliability	Servicing, maintenance, or repair restrictions
Unacceptable modes of failure	Any other functional requirements

14. Additional relevant information:
    Limitations of manufacturing facilities
    Special procedural requirements
    Any other relevant information
15. Action required: For example, preparation of proposal, preparation of detail drawings, manufacture of prototypes, or manufacture of full production quantity.

SOURCE: Adapted from Leech [1.14].

uct Safety Act). Litigation has also provided additional emphasis on including safety considerations in design. Even so, the question of how safe a product has to be is very complex and ultimately can be answered only in the courts.

Including safety considerations in the design of a product requires knowledge of the types of hazards that can occur and the application of good design principles to the product involved. One of the appropriate considerations for including safety in design is to recognize that the product will ultimately fail. If this is done, then the product can be designed in such a way that the location and mode of failure are planned and the failure and consequences can be predicted, accommodated, and controlled.

Hazards can be classified as human-caused or non-human-caused. The listings in Tables 1.3 and 1.4 are not meant to be complete or all-inclusive, but they do provide a guide for designers to hazards that they should know, appreciate, and consider in any project. To reduce the effect of these hazards in designing a product, the designer should consider the possible modes of usage; the users, operators, or bystanders; the environment of use; and the functions or requirements of expected use.

TABLE 1.3 Hazards of Human Origin

Ignorance	Smoking
Overqualification	Physical limitations
Boredom, loafing, daydreaming	Sickness
Negligence, carelessness, indifference	Exhaustion
Supervisory direction	Emotional distress
Overproduction	Disorientation
Poor judgment	Personal conflicts
Horseplay	Vandalism
Improper or insufficient training	Physical skills
Alcohol, drugs	Shortcuts

TABLE 1.4 Hazards of Nonhuman Origin

Weight	Visibility	Cold
Flammability	Pinch and crush points	Pressure and suction
Speed (high or low)	Noise	Emissions (particulates/gaseous)
Temperature	Light, strobe effect, intensity	Explosions, implosions
Toxicity (poison)	Electric shock	Vibrations
Sharp edges	Radiation	Stored energy
Rotating parts	Chemical burn	High-frequency radiowaves
Reciprocating parts	Sudden actions	Slick surfaces
Shrapnel (flying objects)	Height	Surface finish
Stability, mounting	Heat	Flames or sparks

The word *expected,* instead of *intended,* is used intentionally because society, through the courts, expects the designer and manufacturer to know and provide for *expected* usage. This will be discussed in more detail in Sec. 1.5.

Table 1.5 lists some modes of usage to include in design deliberations. Considerations for each of the modes of usage are presented in Tables 1.6 and 1.7. Naturally, not all products require consideration of all the items listed in Tables 1.3 to 1.7, and some will require even more. Further information on procedure and other aspects of a designer's tasks can be found in the references cited at the end of this chapter.

TABLE 1.5 Modes of Product Usage

Intended operation or use	Commercial and industrial use	Repair
Unintended operation or use	Assembly	Cleaning
Expected operation or use	Setup	Packaging
Misuse	Installation	Storage
Abuse	Testing/certification	Shipping/transportation
Emergency use	Maintenance/service	Starting/stopping
Changing modes of operation	Isolation	Disposal
Salvaging	Recreational use	Inspection
Repair	Servicing	Modification

TABLE 1.6 Considerations during Each Mode of Usage†

Life expectancy	Observation of operation	Weight and size
Duration of length of use	Materials for cleaning	Speed of operation
Complexity	Materials handling devices	Pay/compensation plan
Operator position/station	Frequency of repair	Insertion/removal of workpiece
Nonoperator position/station	Test fixtures, ancillary equipment	Failure of workpiece
Labeling	Controls and human factors	Temperature of operation
Misuse	Operator comfort	Noise of operation
Material used	Ratings and loadings	Emissions (particulate/gaseous)
Operator education/skill	Guarding and shielding	Stability
Operator mental/physical condition	Warnings (audible, visual)	Social restrictions
Environment or surrounding condition	Types of failure	Weather
Type of tool required	Consequences of failure	Local specific operating procedure
Reliability	Ventilation	Leakage
Waste materials	Cost	Light/lighting
Operating instructions	Service instructions	Instructions, maintenance
Machine action	Power source/loss	Effects of usage/wear
Accessories/attachments	Appurtenant parts	Maintenance/repair/service
Aesthetics	Government regulation	Standards

†There is no significance to the order in the table; various products and situations will establish the relative importance in specific cases.

TABLE 1.7 Specific Design Concepts and Philosophies

K.I.S.S.†	Foreign material sensing/elimination	Deadman switches
Fail safe	Prevention of modification	Shield and guard interlocks
Design hazards out	Isolation of operators from point of machine operation	Avoid the use of set screws and friction locking devices
Positive lockouts	Controls user-friendly	Use self-closing lids/hatches/closures
Warnings	Provide proper safety equipment	Consider two-handed operation for each operator
Emergency shutoffs	Provide overload/overspeed alarms	Use load readouts when possible
Prevention of inadvertent actuation	Training programs	Control failure mode so consequences are predictable
Prevention of unauthorized actuation	High feasible factor of safety	
Shielding and guarding	Redundant systems	
Proper materials for operation	Proper use of components	
Accessibility for adjustments/service		

†Keep it simple, stupid!

1.2 DECISIONS AND THEIR IDENTIFICATION

1.2.1 General

Decision making is a key part of the design process in which the designer tries to provide a solution to a problem faced by a customer. The customer is interested primarily in performance (including safety), time (how soon the solution will be available and how long it will last), and cost (including price, maintenance cost, and, today, litigation and insurance costs).

The designer, in order to meet the requirements of the customer, generally uses as design criteria function, safety, economy, manufacturability, and marketability. To achieve these criteria, the designer may use as a problem statement the design imperative as presented in Mischke (see Sec. 1.1 or Ref [1.2]) and then make basic product decisions of the types listed in Table 1.8. From this point on, the decisions required to establish the solution to the design problem appear to be without bound. A second level of more detailed decisions then needs to be reached. Examples are shown in Table 1.9.

Neither Table 1.8 nor Table 1.9 is represented as being complete, all-inclusive, or in any order of priority, since priority is established on a job-by-job basis.

1.2.2 Approach to Problem Solving

To make decisions effectively, a rational problem-solving approach is required. The first step in problem solving is to provide a statement defining the problem to be solved. The essential ingredients as stated and discussed in Dieter [1.15] are

- A need statement
- Goals, aims, objectives
- Constraints and allowable tradeoffs
- Definitions of terms or conditions
- Criteria for evaluating the design

TABLE 1.8 Basic Product Decisions to Be Made by the Designer†

Anticipated market	Expected maintenance	Controls
Component elements	Types of loadings	Materials
Fabrication methods	Target costs	Expected life
Evolutionary design or original design	Energy source(s)	Permissible stresses
		Permissible distortions

†No significance is to be attached to order or extent.

SOURCE: J. P. Vidosic, *Elements of Design Engineering*, The Ronald Press Company, New York, 1969.

TABLE 1.9 Second-Level Decisions to Be Made by the Designer†

Strength of each element	Reliability of each element	Maintenance required
Allowable distortion	Style	Noise allowable
Governing regulations	Governing standards	Governing codes
Control requirements	Surface finish	Corrosion anticipated
Friction anticipated	Lubrication required	Wear anticipated
Geometry	Tolerances	

†No significance is to be attached to order or extent.

All these ingredients require evaluation of safety, potential litigation, and environmental impact. Establishing each of these ingredients includes decision making from the start of the design process.

1.2.3 The Decision Maker and Decision Making

Decision makers are concerned with the consequences of their decisions for both their employers and society, as well as for their own egos and professional reputations. By themselves, these concerns may cause faulty decision making.

The decision maker may operate in one of the following ways (Janis and Mann [1.15a] as discussed by Dieter [1.15]):

- Decide to continue with current actions and ignore information about risk of losses.
- Uncritically adopt the most strongly recommended course of action.
- Evade conflict by putting off the decision, passing it off to someone else.
- Search frantically for an immediate solution.
- Search painstakingly for relevant information, digest it in an unbiased way, and evaluate it carefully before making a decision.

Unfortunately, only the last way leads to a good, effective decision, and it may be compromised by time constraints.

The basic ingredients for a good, effective decision are listed in Table 1.10, along with substitutions that may have to be made in practice. The use of these items [1.15b] is discussed at length in Dieter [1.15].

An action of some type is implied after a decision is made and may be classified as a *must* action, a *should* action, a *want* action, or an *actual* action.

A *must* action is one that has to be done and differentiates between acceptability and unacceptability. A *should* action is what ought to be done and is the expected standard of performance for meeting objectives. A *should* action is compared with an *actual* action, or what is occurring at the time the decision is being made. A *want* action does not have to be implemented but may be negotiated as reflecting desires rather than requirements (discussed in Dieter [1.15]).

The steps in [1.15b] for making a good decision are summarized by Dieter [1.15] as follows:

TABLE 1.10 Basic Decision-Making Ingredients

Ingredient	Surrogate
Fact	Information
Knowledge	Advice
Experience	Ad hoc experimentation
Analysis	Intuition
Judgment	None

SOURCE: D. Fuller, *Machine Design,* July 22, 1976, pp. 64–68.

1. Establish the objectives of the decision to be made.
2. Classify objectives by importance, identifying *musts, shoulds,* and *wants.*
3. Develop alternative actions.
4. Evaluate alternatives for meeting the objectives.
5. Choose the alternative having the most promising potential for achieving the objectives as the tentative decision.
6. Explore future consequences of tentative decision for adverse effects.
7. Control effects of final decision by taking appropriate action while monitoring both the implementation of the final decision and the consequences of the implementation.

1.2.4 Decision Theory

The following discussion is adapted from and extensively quotes Dieter [1.15], who in turn cites extensive references in the area of decision theory.

Decision theory is based on utility theory, which develops values, and probability theory, which makes use of knowledge and expectations available. A decision-making model contains the basic elements listed in Table 1.11. Decision-making models are usually classified on the basis of the state of the knowledge available, as listed in Table 1.12.

In applying decision theory, a method of determining the *utility* of a solution must be established. The *utility* of a solution is defined as being a characteristic of the pro-

TABLE 1.11 Elements of a Decision-Making Model

1. *Alternative courses of action*
2. *States of nature:* The environment of operation of the decision model. The designer has very little, if any, control over this element.
3. *Outcome:* The result of a combination of an action and a state of nature.
4. *Objective:* The statement of what the decision maker wishes to achieve.
5. *Utility:* The satisfaction of value associated with each outcome.
6. *State of knowledge:* Certainty associated with states of nature, usually given in terms of probabilities.

SOURCE: Adapted from Dieter [1.15].

TABLE 1.12 Classification of Decision-Making Models with Respect to State of Knowledge

1. *Decision under certainty:* Each action results in a known outcome that will occur with a probability of 1.
2. *Decision under risk:* Each state of nature has an assigned probability of occurrence.
3. *Decision under uncertainty:* Each action can result in two or more outcomes, but the probabilities for the states of nature are unknown.
4. *Decision under conflict:* States of nature are replaced by courses of action, determined by an opponent who is trying to maximize his or her objectives function; this is also known as *game theory.*

SOURCE: Adapted from Dieter [1.15].

posed solution that relates to a value in use or a goal of the solution that has meaning in the marketplace. Utility can be cost, price, weight, speed of performance, statistical reliability (probability of failure), factor of safety, or other like attributes. Another name for utility is *merit,* which is also discussed in Sec. 1.3.4 and is extensively presented in Ref. [1.2].

The occurrence of specific states of nature, such as those expressed as materials properties, part geometries, loadings, odors, aesthetics, or taste, may be expressed deterministically, probabilistically, or not at all. If the desired state-of-nature variable can be quantified deterministically, then the utility or merit of a given course of action (problem solution) may be determined and compared to the values of utility or merit for other solutions, allowing the decision maker to choose the better solution for each comparison and, ultimately, the best solution.

If the variables are known only probabilistically, either as a probability distribution or as a mean and variance, statistical expectation techniques as described in Haugen [1.16] or propagation of uncertainty techniques as described in Beers [1.17] have to be used to determine the statistical expectation of the value of the utility for a given course of action (solution). Decisions are then made on the basis of comparisons of expected values of utility or merit. Utility is discussed additionally in Dieter [1.15].

Decision making under risk and decision making under uncertainty are two extremes where, respectively, one does or one does not know the probabilities involved to determine the expected value of utility. Realistically, one can usually estimate the probabilities that affect the outcome, but often without much confidence.

The Bayesian theory of decision making uses the best estimate of the values of utility involved and then bases the decision on the outcome with the maximum expected utility. If probabilities are unknown or cannot be estimated, a weighting function may be established using factors developed from experience or opinion to aid in estimating the utility value for various solutions.

Decision matrices may be used to assist in making decisions where the design goals establish several measures of utility to be evaluated simultaneously for proposed solutions. An example might be a situation where low cost, small weight, and high strength are all important. Dieter [1.15] discusses creation of decision matrices, also known as *payoff matrices* or *loss tables,* and provides several examples of their use in decision making. If a utility function can be created for these cases, optimization theory (as discussed in Ref. [1.12]) may be applied through available digital computer techniques to maximize utility (or merit) functions of many variables to aid in determining the best course of action (solution).

Sometimes the utility of a given course of action cannot be quantified. One way of proceeding in this situation is to establish an arbitrary numerical scale ranging from most unacceptable to most desirable. Evaluations may then rate beauty, fragrance, odor, or whatever the utility is defined to be, on the numerical scale. The ratings may then be evaluated to assist in making the appropriate decision based on the subjective utility.

Another useful technique for exhibiting the results of a decision matrix for the case where decisions must be made in succession into the future is the *decision tree.* This technique, which appears to be an adaptation of fault-tree analysis, where utility is taken to be probability of failure, is described in an example in Dieter [1.15] and as fault-tree analysis in Scerbo and Pritchard [1.18], which also references as sources Larson [1.19], Hammer [1.20], and others. More discussion of decisions, their identification, and decision theory can be found in Wilson [1.7], Dixon [1.5], and Starr [1.10].

1.3 ADEQUACY ASSESSMENT

An *adequacy assessment* is any procedure which ensures that a design is functional, safe, reliable, competitive, manufacturable, and marketable. Usually, in the formative stages, matters of marketability, manufacturability, and competitiveness are addressed and built in, and the principal attention is focused on sustaining function, safety, and reliability. This is why quantitative concepts such as factor of safety and reliability are prominent in examining a completed design.

1.3.1 General

The designer's task is to provide a documented set of specifications for the manufacture, assembly, testing, installation, operation, repair, and use of a solution to a problem. This task may be started by considering several solution concepts, selecting one to pursue, and then generating schemes for meeting the requirements. Usually there are many iterative steps throughout such a process. At each step, decisions must be made as to which concept or detailed specification should be pursued further. This section identifies tools and other considerations necessary to assess adequacy and presents methods of rationally providing and combining information so that informed decisions can be made.

1.3.2 Criteria for Adequacy Assessment

Effective adequacy assessment requires a knowledge of all persons and organizations involved in any way with the product and an understanding of what is important to those involved. Table 1.13 lists factors to be considered and the cast of people involved in engineering adequacy assessment. The order of priority in engineering practice depends on the specific case considered.

The roles in adequacy assessment of the courts, governmental bodies, and to some extent the public as well as the criteria of governmental regulations, standards, and public expectations are addressed in some detail in Secs. 1.5 and 1.6.

TABLE 1.13 Considerations and the Cast of Characters Involved with Design Adequacy Assessment

Important considerations	Criteria	Those involved
Personal reputation	Maintainability	The designer
Keeping one's job	Serviceability	Design peers
Function	Marketability	Design supervisors
Cost	Aesthetics	Users and operators
Safety	Factor of safety	Maintenance and service personnel
Size	Manufacturability	The courts
Reliability	Standards	Governmental bodies
Factor of safety	Public expectations	The public
Government regulations		

1.3.3 Suitability-Feasibility-Acceptability Method

The suitability-feasibility-acceptability (SFA) method of evaluation (as presented in Ref. [1.2]) may be used to evaluate several proposed solutions or compare the desirability of various courses of action. The method is based on determining, in turn, the suitability, feasibility, and acceptability of the proposed solution using the following procedure and then evaluating the results:

Step 1. Develop a problem statement that is as complete as possible.

Step 2. Specify a solution as completely as possible.

Step 3. Answer the question: Is this solution suitable? In other words, with no other considerations included, does the proposed solution solve the problem?

Step 4. Answer the question: Is this solution feasible? In other words, can this solution be implemented with the personnel available, the time available, and the knowledge available without any other considerations included?

Step 5. Finally, answer the question: Is the proposed solution acceptable? In other words, are the expected results of the proposed solution worth the probable consequences to all concerned?

The results of the SFA test can only be as good as the effort and information put into the test. Done casually with inadequate information, the results will vary. Done with care and skill, it can be very effective in assessing the adequacy of proposed problem solutions.

An example of the application of the SFA test (adapted from Ref. [1.2]) is presented below:

Step 1 (Problem Statement). Metal cans as originally designed require a special tool (can opener) to open. This was true in general, but was especially burdensome to people using beverage cans away from a kitchen or immediate source of a can opener. A method was needed to provide metal beverage cans that could be opened without a can opener or other tool.

Step 2 (Solution). Design a can for beverages that will meet all the requirements of the original cans and, in addition, will have the top manufactured so that a ring is attached to a flap of metal that is part of the top, but is scored so that a person pulling on the ring can pull the flap out of the top of the can, thus opening the can without a tool.

Step 3. Is this solution suitable—i.e., will it solve the stated problem? The answer is yes. For the described solution, the can may be opened generally by the user's fingers without any special tool.

Step 4. Is this solution feasible—i.e., can it be done using available personnel, finances, facilities, time, and knowledge? The answer is yes. The state of manufacturing techniques and materials is such that the design could be produced. The additional cost appears to be reasonable. Thus this solution is feasible.

Step 5. Is the proposed solution acceptable to all concerned? The initial decision was that the solution was acceptable to the designer, the manufacturer, the marketing organizations, and to the consumer, and so it was put into production.

However, as later events revealed, the consequences of having the ring and flap removable from the can were not generally acceptable to the public because of the consequences of the discarded flaps and rings, and so a new design, retaining the flap to the can, evolved.

1.3.4 Figure of Merit or Weighting Function Method

The *figure of merit* (FOM), also known as the *merit function* or weighting function, is applicable in problems where the important parameters can be related through a function that can be evaluated to find the "best" or "highest merit" solution to a problem. This approach differs from the SFA approach in that the SFA approach is based on more subjective factors.

The FOM lends itself well to attaining or approximating the optimal solution sought by the design imperative discussed in Sec. 1.1. Customarily, the merit function is arbitrarily written so that it is maximized in obtaining the best (highest) value of merit.

Comparing the values of the merit variables obtained for the different alternatives examined should consist only of determining which value is the largest. For situations such as the case where minimum weight or minimum cost is desired, customarily the expression for weight or cost is written either as a negative function or as a reciprocal function, thus allowing maximization techniques to be used.

Although any variable can be used as the merit variable (including an arbitrary variable which is the sum of other disparate variables), the most useful equations are written so that the function represents a characteristic of the product used as a criterion by both engineers and the marketplace. Since safety, reliability, cost, and weight are all important characteristics, useful merit variables, for example, could be the weight, cost, design factor, safety factor, reliability, or time. Equations can be either deterministic or probabilistic in nature.

Where such subjective characteristics as taste, beauty, innovation, or smell are the important characteristics, the FOM approach does not work unless some method of quantifying these characteristics is developed that will allow their mathematical representation.

Two examples will be presented to illustrate the technique involved and identify terms used in the figure-of-merit process.

Example 1. Design and develop a package for a fragile device that will allow the packaged device to drop through a substantial distance onto concrete without the impact causing the device to fail or break. The package must be of small weight, cost, and size.

Several designs were proposed, built, and tested, and some protected the fragile device adequately. A method was then needed to determine the best of the surviving designs.

A merit function was set up which combined the three design requirements as follows:

$$M = -(A_1 w + A_2 c + A_3 d)$$

where M = merit, the sum of the three terms
w = weight, ounces (oz)
c = cost, cents
d = longest dimension, inches (in)

A_1, A_2, and A_3 are factors selected to weight each of the terms consistent with the importance of the associated variable. The minus sign is used to allow the maximum value of M to be attained when the sum of the three design requirement terms is at a minimum.

The first equation relating merit (which may be a factor of safety, cost, weight, or other desired attribute) to the other variables is known as the *merit function.* It is usually expressed in the form $M = M(x_1, x_2, \ldots, x_n)$. Regional (inequality) constraints are described limits of values that each of the variables may attain in the given problem. Function (equality) constraints are relationships that exist between variables that appear in the merit function. Both types of constraints are specified as a part of the construction of the merit function.

A detailed discussion and description of the preceding method and terms can be found in Mischke [1.2]. Other discussions of this technique with somewhat different terminology may be found in Wilson [1.7] and Dixon [1.5]. A short example will be set up to illustrate the preceding terms.

Example 2. A right-circular cylindrical container is to be made from sheet steel by bending and soldering the seams. Management specifies that it wants the least expensive gallon container that can be made from a given material of a specified thickness. Specify the dimensions for the least expensive container.

Solution. If the bending and soldering are specified, then a fabrication cost per unit length of seam can be estimated. In addition, for a given material of a specific thickness, the material cost is directly proportional to the surface area. A merit function is constructed as follows:

$$M = -\,(\text{cost of material} + \text{cost of fabrication})$$

If h = height (in) and d = diameter (in), then

$$M = -\left[\left(\frac{2\pi d^2}{4} + \pi dh\right)k_1 + (2\pi d + h)k_2\right]$$

where k_1 = material cost (dollars/in^2) and k_2 = fabrication cost (dollars/inch of seam).

The functional constraint for this problem is the relationship between the volume of the container and the dimensions:

$$V = 1 \text{ gal} = 231 \text{ in}^3 = \frac{\pi d^2 h}{4}$$

where V = volume of container (in^3). The regional constraints are $0 < d$ and $0 < h$, which shows that we are interested only in positive values of d and h.

The next step would be to substitute the functional constraint into the merit function, which reduces the merit function to a function of one variable which may be easily maximized. A robust method such as golden section (see Mischke [1.2]) can be used for optimization.

1.3.5 Design Factor and Factor of Safety

The design factor and the factor of safety are basic tools of the engineer. Both play a role in creating figures of merit, parts and materials specifications, and performance criteria for products being designed. Both may be defined generally as the ratio of the strength or capacity to the load expected, or allowable distortion divided by existing distortion of the object or system in question. Both the design factor and the factor of safety are used to account for uncertainties resulting from manufacturing tolerances, variations in materials properties, variations in loadings, and all other unknown effects that exist when products are put into operation.

The distinction between the design factor and the factor of safety is that the first is the goal at the start of the design process and the latter is what actually exists after the design work is completed and the part or object is manufactured and put into use. The changes occur because of discreteness in sizes of available components or because of compromises that have to be made as a result of materials processing and availability, manufacturing processes, space availability, and changes in loadings and costs.

A simple example would be the design of a rigging system using wire rope to lift loads of 10 tons maximum. The designer could preliminarily specify a design factor of 5, which would be the ratio of the wire rope breaking strength to the expected load, or

$$\text{Design factor} = 5 = \frac{\text{desired breaking strength}}{\text{load}}$$

Using this criterion, a wire rope having a breaking strength of 50 tons would be selected for this application.

The engineer would then evaluate the wire rope selected for use by determining the effect of the environment; the diameters of the sheaves over which the wire rope would be running; the expected loadings, including effects of impact and fatigue; the geometry of the wire rope ends and riggings; and any other factors affecting the wire rope strength to arrive at the final strength, knowing all the application factors. The factor of safety would then be

$$\text{Factor of safety} = \frac{\text{actual breaking strength in application}}{\text{load}}$$

Mischke [1.2], Shigley and Mischke [1.21], and other machine design books discuss the design factor and the factor of safety extensively, including many more complex examples than the one presented here.

A major danger in the use of both the design factor and the factor of safety is to believe that if either is greater than 1, the product having such a factor is safe. However, Fig. 2.5 points out that the factor of safety has a statistical distribution, and that even though the mean value exceeds 1, a fraction of the devices can fail.

1.3.6 Probabilistic Techniques

Propagation-of-error techniques, as described in Chap. 3 and Beers [1.17], can be used to determine the uncertainty of the value of the factor of safety to allow the designer to better assess the adequacy of the factor of safety finally determined. The techniques of Chap. 2 and Haugen [1.16] work directly with the reliability goal.

Another method of adequacy assessment uses the load strength and geometry variables combined to form a quantity called the *stimulus parameter* and the material strength for a given design. If the mean values and the standard deviation are known for any two of the variables (i.e., load, geometry, and materials strength), the threshold value of the third variable can be estimated to provide a specified reliability. The actual value present in the design or part can then be compared to the threshold value to see if the part meets the desired reliability criteria and is then adequate for the specifications provided.

1.4 COMMUNICATION OF ENGINEERING INFORMATION

The output of an engineering department consists of specifications for a product or a process. Much of the output is in the form of drawings that convey instructions for the manufacturing of components, the assembly of components into machines, machine installations, and maintenance. Additional information is provided by parts lists and written specifications for assembly and testing of the product.

1.4.1 Drawing Identification

Drawings and machine components are normally identified by number and name, for example, Part no. 123456, Link. Each organization has its own system of numbering drawings. One system assigns numbers in sequence as drawings are prepared. In this system, the digits in the number have no significance; for example, no. 123456 would be followed by numbers 123457, 123458, etc., without regard to the nature of the drawing.

A different system of numbering detail drawings consists of digits that define the shape and nominal dimensions. This eases the task of locating an existing part drawing that may serve the purpose and thus reduces the likelihood of multiple drawings of nearly identical parts.

The generally preferred method of naming parts assigns a name that describes the nature of the part, such as piston, shaft, fender, or wheel assembly. Some organizations add descriptive words following the noun that describes the nature of its part; for example:

Bearing, roller, or bearing, ball

Piston, brake, or piston, engine

Shaft, axle, or shaft, governor

Fender, LH, or fender, RH

Wheel assembly, idler, or wheel assembly, drive

A long name that describes the first usage of a part or that ties the part to a particular model can be inappropriate if other uses are found for that part. A specific ball or roller bearing, for example, might be used for different applications and models.

1.4.2 Standard Components

Components that can be obtained according to commonly accepted standards for dimensions and strength or load capacity are known as *standard parts.* Such components can be used in many different applications, and many organizations assign part