MATHEMATICAL MODEL BUILDING

AN INTRODUCTION TO ENGINEERING

PREFACE

This book was written to introduce engineering students to their fields through the vehicle of mathematical model building. This route was chosen in preference to other alternatives because it appears to be more relevant to students, their questions, and their needs.

First, the author is still convinced that design ideas, methods, and mores are best left largely to the senior year of study, when the student and the instructor can call on a significant body of knowledge upon confronting the demanding task of synthesis.

Second, students are not usually convinced that all the courses in chemistry, physics, mathematics, statics, dynamics, strength of materials, thermodynamics, heat-mass-momentum transfer, electrical circuits and field theory, instrumentation, and the design of experiments are really necessary to their preparation to innovate. Their interest often lags, partly because of the lack of any coordinated effort to convince them on rational grounds of the necessity of the ordering of their educational events. This volume represents a first step in this direction.

Third, in disciplinary courses in the engineering sciences, the emphasis is on *subject matter*. The tool used to teach, organize, and utilize it is the mathematical model. Unfortunately, few instructors take the time to talk about the modeling process itself, sans subject matter. The modeling process must be understood in order to interpret the results properly. Too often students are absorbing disciplinary material and trying to learn the modeling techniques concurrently. Faltering in the modeling process leads to poorer understanding of the disciplinary elements. This volume is addressed principally to deterministic, deductive mathematical modeling before the disciplinary material becomes important. Thereafter students can, in later courses, observe modeling techniques in action at the same time they are absorbing disciplinary material.

The prerequisites to the understanding of the material are high school physics (mechanics and heat) and calculus (simple differentiation and integration). Freshmen who have high school science preparation can benefit. The better the student preparation, the more telling will be the impact of a course embodying the material of this book.

The material in this volume is suitable to all disciplines of engineering and others that depend on or study the application of mathematical modeling. The material, the course, and the students require the viewpoint and experience of mature staff. When good students are challenged with meaty material that is relevant to their goals, they respond with interest and enthusiasm. Their questions are searching, challenging, and occasionally profound. Answers should be in kind, promptly delivered, and to the point, with examples at their level of understanding.

Freshman (or sophomore, for that matter) students can appreciate and contribute to some carefully chosen larger issues and decisions in the engineering design process. What they cannot do is make meaningful microdecisions. They cannot design a shaft, select a motor or a pump, design an automobile door or an airbag, specify a production process, choose a material, or design a wave guide or a bubble tower. Generally they cannot contribute to the small decisions. If we get too involved with the small tools and technology, the student who likes them and stays in engineering may be staying for the wrong reason. The student who is not intrigued by them or assimilates too much, too fast, in the wrong discipline, and leaves engineering may be leaving for the wrong reason. A profession is chosen because solving its larger problems is the basis for a lifelong motivation and interest. The tools that are required, whatever they happen to be or are later discovered to be needed, are mastered simply to make the larger effort possible.

After many sections the vital points are summarized or identified. These constitute the essential ideas. The author has provided a little more detail than necessary, on the average, and some sections that are surplus for course objectives. When an instructor omits a section, it is still worthwhile to have the students read the summary of the omitted sections for background. Instructors are encouraged to extend some of the ideas presented here even further, augmenting with emphasis tailored exactly to their objectives.

Mathematical model building is based on equalities (and/or inequalities), the authority for which is to be found in empirical evidence. Chapter 1 constitutes an introduction to the nature of engineering and to the engineering designer's problem and the need for predictive ability. Since mathematical models provide this predictive ability, the motivation to examine them is established. Chapter 2 plunges into the use of mathematical models on an intuitive basis. The experience raises questions whose answers must be at hand before mathematical models are formulated. This experience establishes the pattern for the remainder of the book.

Chapter 3 describes figures of merit and gives some clues as to the parameters of which they are constructed. Some figures of merit are developed through examples and the mathematical model building involved is simple and intuitive. The chapter does not detail how to create a figure of merit because considerable background information remains to be developed. The distinction between tactical and formal figure of merit is drawn. The design factor and some of its *raison d'être* is offered. Cost as a figure of merit is introduced as well as some ideas concerning expectation. Reliability as a figure of merit is examined and problems associated with constraints are identified by encounter. A noncontinuous variable example is offered. Time as an element in a figure of merit is examined. The question of trade-off functions is raised as well as how qualitative parameters that should be in a figure of merit can be handled.

Chapter 4 considers how a digital computer fits into the engineering design regimen. An organized approach, IOWA CADET, is explained and its rationale examined. The necessity for documentation, error messaging, and testing is considered. The chapter is substantially *not* programming and devotes most of its attention to considerations at a broader perspective. Students may have had a programming course or be taking one concurrently. For those students, problems are provided at the end of this chapter and in the remainder of the book. For those who have not yet had a programming experience, examples can be read to illustrate the usefulness of the computer and provide motivation for their future programming experience.

Chapter 5 begins the process of building the rationale and empirical basis for mathematical model building. It considers the continuous and discrete conceptions of matter and indicates how models based on the former concept can be useful even when evidence supports the latter viewpoint. Effective empiricism is a carefully structured process and attention must be given to the proper definition of entities and measurable attributes of entities. The reasons for insisting on operational definitions are given. Given proper definition and the opportunity thus afforded for meaningful measurement, the effectiveness of graphical displays is explored and the authority for depicting loci on graphs is examined. As effective as the graph is as a communicative tool, it is awkward in the calculation process; therefore the motivation for fitting equations to experimental data is considered and some simple and reasonable schemes for curve fitting are examined.

The enormous expenditure of time and effort associated with experimental work (so that conclusions may be reached with high degrees of confidence) is noted and the capital contribution of E. Buckingham to the reduction in the number of experimental variables is examined in some detail. A method is presented for the routine establishment of a complete set of dimensionless variables.

The agreement to an international system of units is noted; subsequent to this section the text uses SI units heavily, in sharp contrast to the prior use of the familiar English system. The chapter continues with further simplification and reduction of effort made possible by some properties of partial derivatives. The next topic is the realization that physical models are possible, based on the ideas just examined, and an example is given. The final section indicates the importance of our ability to communicate variability and to be aware of some of its implications.

The structure of empiricism and its achievements have borne fruit. Chapter 6 is concerned with the recognition of reproducibility in cause, effect, and extent. The precise communication afforded by ideas and terminology associated with system and control region concepts is indicated. It becomes possible to speak of heat and work effects; surface effects; charge effects; magnetic effects; and other effects such as chemical, ballistic, and even impossible effects. The mathematical models (*system* statements) of some of these effects are displayed.

Chapter 7 is the prelude to modeling circumstances under which control region definition is the natural approach. Accountability ideas are examined in situations in which countables are discrete and continuous. The enunciation of first principle for conservation of charge, mass, energy, and momentum for systems is made; then corresponding statements for control regions are made. The nonuniqueness of the control region statements means that such statements must be tailor-made by the engineer for each control region of interest. Next the importance of delineating a system or control region for mathematical model building purposes is discussed. The origin of deterministic deductive mathematical models is indicated by example. A six-step procedure is followed, forming a routine yet rigorous plan of attack. The problem of checking results is addressed. Assertive deductive and simulative models and some introductory probabilistic modeling ideas are introduced.

Chapter 8 examines the optimization problem through a frustrating example; then the three kinds of optima are identified. The realization that simple calculus methods (locating places of zero slope) address but one kind of optimum is made. Edelbaum's sufficient conditions for stationary point maxima and minima are introduced. The method of Lagrange incorporates a second kind of optimum, increasing the power of calculus methodology. Sensitivity analysis is examined. The formal statement of an optimization problem is examined.

Direct search methods, exhaustive, interval-halving, and golden section (all one-independent variable methods) are rationally developed. Gradient sensitive multidimensional searches are introduced. Applications follow, including computer implementation.

Chapter 9 is mathematical modeling in action, and the instructor is encouraged to spend as much time as possible, right here where the action is. Many instructors will have their own problems particularly suited to the disciplinary complexion of their classes. The first eight chapters are the background against which the engineering art of mathematical model building can be practiced. Class treatment of the first eight chapters may be subordinated to the final model building experiences. Most of an engineer's subsequent course work will be rich in detail. Strategic understanding tends to be presumed by upper division instructors.

A bonus can be realized at no additional cost. Encourage the students on completion of this course to retain this text. Since many of the topics to be later developed have been touched on, subsequent instructors can assign review reading and not have to repeat the background. A brief oral review and the pursuit of the major point(s) becomes the thrust of the class session. The remainder of the background helps students see where meat is being placed on the bones. Experienced engineering instructors may wish to review these ideas again as a senior elective after most of the engineering courses have been completed. In this context the text becomes the springboard for more specific discussion rich in technical engineering detail.

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A lot of today's frustration is
caused by a surplus of simple
answers coupled with an acute
shortage of simple problems.

CHAPTER 1

WHAT IS AN ENGINEER?

1.1 PREFACE TO THE STUDENT

Times change. People change. Some things change, others do not. Training for the professions takes longer simply because the body of knowledge on which they are based grows larger. Engineering students choose their careers in large measure because of a desire to create. Scientists explain what *is*; engineers create what *never was*. The enthusiastic freshman seems ready (in attitude) to innovate but the engineering college says, "Not now, for first you must have a foundation in physics; chemistry; mathematics; expository English; and in the language of vision, graphics." Not sure that this is really so, the freshmen apply themselves to their studies, which appear at best tangential to their objectives. What has Rolle's theorem to do with heat exchangers? What have energy surfaces to do with power plants? What have crystal structures to do with turbomachinery rotor design? What have themes on the vanishing American home to do with design of pop-top cans?

As a sophomore the student again asks, "Now?" and the college responds, "Not now, for we must now particularize your new knowledge in the areas of mechanics of solids (statics, dynamics, strength of materials), mechanics of fluids, and structure of materials as well as continue teaching you calculus and differential equations." About half the starting group reaches the junior year and the inquiry, "Now?" is a little more feeble, a little more tired. The answer however is consistent. "You must now study thermodynamics, electrical circuit theory, fluid flow and heat transfer, ac and dc machinery, electronics, manufacturing processes, kinematics, theories of failure, and theory of machines. You must not neglect a sequence in social studies and a sequence in the humanities."

When seniors encounter their first design course, is it any surprise that in response to the project assignment they inquire of the instructor, "What do you want me to do?" The structure of the engineering educational experience has subdued or even suppressed the creative desires that led to the selection of engineering in the first place. Perhaps, with the two-thirds of the students that are no longer with us at the senior level has gone some of the creative instinct and desire. They have simply gone to another place where an outlet is provided earlier.

This is not to say that engineering is not creative nor that opportunities for engineers to be creative do not abound. But it is necessary that students be intellectually convinced that the delays they encounter in exercising their creative bent will in the long run enhance their ability to design. Students can be introduced to the designer's dilemma early in their academic career; they can be convinced that tools are necessary for innovation in the engineering framework. This early conviction can keep the inner lights burning so that the response to their initial design problem is more like "Which of these alternative solutions will you permit me time to develop?"

When you enter your engineering classroom building, do you ever consider that you *bet your life* the engineer who designed the building structure knew what he was doing--fifty years ago? How could he design the building framework this well when the knowledge of materials and theories of failure were much more meager than now? Part of this success was due to a philosophical viewpoint and a methodology that incorporated it. Do you believe that this is worth investigating? Now?

The material in this course and those to follow are part of your essential preparation to do *what has not been done before*. The essential purposes of engineering are not necessarily to design bridges, highways, railroads, lathes, automobiles, electric motors, and turboalternators. This we know how to do. Engineers in selected industries are already custodians of these arts. Much of their design is close to routine, slipping away from the mainstream of engineering and entering the field of technology. You will be called on to conceive of processes, systems, and components that will make food out of what is now nonfood, make resource material out of what presently is not, make water out of that which is not usable water, make a resource out of what is now garbage, make clean air out of what now is not, make a mass transportation system out of what is now chaos. In short, you will be called on to create what never was, under pressure of time and shortage of money and brain power and with insufficient information. You will convince the politicians, the public, and the vested interests that the alternatives leading to human survival (with any quality of living) are few in number. You will do it because your "pinky" is in the pencil sharpener too.

The resources available for engineering education are always limited. The delay of design considerations until all background work is completed is an economical approach to the engineering education problem. Thus engineering methods come late in the curriculum. Despite your enthusiasm you are not ready to discuss creative design, much less participate in it. To convince you of this we are going to embark on an overview of engineering, not from a helicopter but through the window of mathematical modeling. You will see that you have much to learn, but in your journey you will learn many things that will ease that journey, help you learn to learn.

The place to begin in understanding the nature of engineering and its contribution to the human experience is to ponder an orthographic projection of the planet earth. These views do not show fine surface detail; nevertheless, a number of inferences can be drawn that form some of the bases for engineering.

First, the planet is finite in extent and therefore encompasses a finite amount of matter. Second, humans can live in the lower part of the air ocean and even move through it, provided they take all they need with them and expend a great deal of energy to maintain flight. Humans can live in the water ocean for just a matter of moments. They can move on the interface between the air and water oceans, if they take all they need with them and expend energy to sustain movement. They can live in the land ocean if they take all they need with them. At the interface between the air ocean and the land ocean they can live and sustain themselves on some parts of the land surface. The available area of habitation is finite.

Third, humans need food, water, clothing, and shelter. The air ocean serves them for respiration only in its lower 20,000 ft. The air ocean is finite and vital. Water is essential to humans and to the food chains in which they participate. The water resources of the planet are finite.

Humans as predatory nomads were so successful that their numbers grew, and the limiting processes controlling population were modified by the discovery of agricultural foodstuffs. This anchored them to the land and they were required to defend it; and to make the transportation problems tractable and sustain their numbers, they utilized the land that was arable near rivers and the sea so that distribution of food and goods was possible on a large scale. This commitment to the land for sustenance and to the waterways for transportation lead to the emergence of nations and defense of their domains against others.

Engineering is concerned with assessing the present human condition, and offering humanity some alternatives to the natural course of events. The alternatives have to be conceived (invented, created) in the human mind, be compatible with the universe of matter and humanity, be viable in the existing human condition, be more good than bad, and be embraced as preferable to other alternatives by human groups affected.

Therefore, those who would practice the engineering art must be knowledgable as to the present and imminent human condition; be able to envision what needs to be done; and, understanding matter and people, be able to conceive viable alternatives to the natural course of events.

1.2 RATIONAL DECISION MAKING

Having conceived an alternative, it has to be sufficiently delineated (specified) so that it can be tested for *suitability* (will it accomplish its purpose), *feasibility* (can it be carried out with present resources of knowledge and the three m's: materials, men, and money) and *acceptability* (are the probable results worth the estimated cost). Then those in charge of the enterprise must be convinced the decision to implement the alternative can be made. The follow-up problems of production, distribution, maintenance, and retirement are also part of the engineering picture, as well as cognate problems of organization of the work force, materials, and facilities (human and other resources).

People are not rational. They are emotional beings and creatures of habit. They have learned that in certain areas of endeavor a rational approach pays dividends. They understand that most decisions are subjective, no matter how complete the window dressing of objectivity. The tests for suitability, feasibility, and acceptability are rational tests and when applied objectively are very useful in avoiding undesirable consequences. Yet their effectiveness in application is reduced by emotion, subjectivity, misinformation, and ignorance.

The tin can in many ways was a blessing to society for it enabled food products to be preserved and distributed over a long time period with small cost. The annoyance of the requirement for a can opener nagged at consumer and designer alike until ideas and technical materials problems were blended to produce the pop-top can. Now let us apply the three tests. Is the pop-top can suitable? It is a container that can do everything expected of an ordinary tin can. It also allows opening without any tool other than a finger. It is a suitable solution to the problem. Is the pop-top can feasible? The design can be executed in a mass production situation and be economically competitive. Is the pop-top can acceptable? Are the probable results worth the estimated cost? The answer is no, yet the product was marketed successfully. The pop-top can has led to a rain of cans along our highways, in our parks, and on isolated private property. The state of Michigan has tried collecting these and found the cost of collection to be about 30 cents per can (just for collection, not for disposal). The cost of recovery of the refuse exceeded the cost of the can and its contents when new and full. Why was it marketed? The corporation making the suitability-feasibility-acceptability tests did not have to consider the cost of collection. They may have been unaware of the current American behavior concerning litter. They may not have been able to foresee all the consequences of their action of offering the alternative to the marketplace. They may have chosen to ignore conclusions they may have reached. Because they visited ugliness and cost burdens on society after using the suitability-feasibility-acceptability test does not indicate that the test is inherently inadequate. It does indicate that its use does not ensure good decisions, and the decisions are no better than the information and values that go into them. The tests are as valid as the user makes them. Engineers must be familiar and skilled with them to obtain the maximum benefit from them.

We have the carcasses of 40 million automobiles in automobile graveyards. We are adding 8.5 million more each year. The birthrate of automobiles is consistently increasing and the death rate is also increasing (the average car is junked six years after birth). The economics of salvage have changed so that it costs money to recirculate the carcass in the materials cycle. Who should bear the cost? Who should design, operate, and maintain the "car eaters" that will be necessary to recycle the metal and prevent our inundation by this ugly solid refuse? When suitability-feasibility-acceptability questions are asked by car-producing corporations of themselves, the matter of the vast expense visited on the public by road construction and maintenance, the matter of 50,000 deaths (and a million hospitalizations) per year, and the matter of half the police effort in the United States being concerned with automotive problems are lost. When the love affairs of individuals for their cars are exploited to the extent that public transportation systems are in trouble and must be subsidized to exist, the matter of the greater good is lost. Is the suitability-feasibility-acceptability test defective? No, just skills of the persons that use it.

The secretary of health, education and welfare stated in 1969 that the average human body has 12 parts of DDT for every million parts of fatty tissue. By the government's own regulations, cattle, sheep, and hogs are unmarketable when their DDT content exceeds 7 parts per million. DDT was a solution to a problem and was adapted to the solution of many other problems. Did the users, promoters, and producers foresee the spread of DDT to all living things on the earth, including fish under the ice cap? Did the acceptability test fail because it was defective or because the persons using it were ignorant, or blind, or possibly dishonest? (Of course we may have struck a blow against cannibalism, since the average American is no longer fit to eat.)

The scalpel is a menace in the hands of a child; is not much more than a knife in the hands of an adult; and often is a source of life in the hands of a surgeon. The tools of any profession or trade are nothing of themselves but are the means to accomplishment in the hands of the skilled. Do not expect more of the tools of the engineer or architect than those of the stonemason. Do expect to study them, practice with them, and eventually apply them to professional work.

The reader should understand the following ideas as a result of reading and studying this section.

--Suitability test: Will this action, if adopted, indeed accomplish the intended purpose?
--Feasibility test: Can the contemplated action be carried out with resources

of knowledge, men, money, and materials or can the necessary resources be assembled in time?

--Acceptability test: Are the probable results of the contemplated action worth the anticipated costs?

--The steps in applying the suitability-feasibility-acceptability test are:

1. State the precise purpose(s) of the contemplated action.
2. Test for suitability.
3. Test for feasibility.
4. Test for acceptability.
5. If the action is not suitable, feasible, and acceptable, discard. If the action barely failed one test, flag for future reference if the situation should change, and set aside. If the action is suitable, feasible, and acceptable, retain for assessment of relative merit among other alternatives.

The suitability-feasibility-acceptability test is used to eliminate possible alternatives from further consideration. When used with skill, it is a fine filter to eliminate dubious solutions. When used without skill, consequences undesirable and unexpected plague the designer.

You will learn other skills here and in other courses. Give them your diligent attention and effort. Try to master them. The difference between a brand-new truck and a worn-out one is only a few pounds of weight. The difference between a skilled engineer and a technician is not detectable on any scale, for engineers' tools are hardly discernible unless you observe engineers in practice or view their works.

1.3 ENGINEERING

The first civilization not based on slavery is the one that resulted from the industrial revolution. Machines were substituted for the muscles of workers and animals. The food for these machines is *energy*. Humankind's appetite for energy seems insatiable. An index to this appetite is the extent of the generation of electrical power, which has doubled every recent decade (i.e., increased exponentially). Energy available where needed, when needed, under control, and in the right form is bedrock of industrial civilization. The energy chain from resource form (fossil fuel, solar radiation, hydraulic potential, tidal flows, etc.) through conversion to transportable form (electric power) to site consumption (electric, hydraulic, pneumatic, and mechanical motors and devices) and the systems that use them are among the concerns of engineers.

In the process of "creating what never was," engineers have to some extent compartmented their activities. Those who design vehicles that operate in fluid or vacuum environment are sometimes called aerospace engineers. Those who design agricultural equipment and systems (machinery and structures) are often identified as agricultural engineers. Those who apply engineering instrumentation and analysis to biological phenomena and are moving toward the design of systems and devices to meet biological and/or medical needs are sometimes categorized as biomedical engineers. Those who are involved in the design of products that are formed from natural and synthetic minerals rendered durable by a process of heat treatment at high temperatures (nonmetallic, inorganic substances, such as glass, porcelain enamels, abrasives, cements, refractories, etc.) are called ceramic engineers. Those who design processes and equipment associated with changes in the chemical state of matter are designated as chemical engineers. Those who are involved with the design, construction, maintenance, and operation of public and private facilities, such as transportation, structures, water supply, waste disposal, irrigation and drainage, and river and harbor facilities are called civil engineers. Those involved in the design, planning, inauguration, and management of systems involving interaction of money, labor, and machines are called industrial engineers. Those who design systems and component machines for processing of energy, processing of material, vehicles of transport, and automating of production techniques are called mechanical engineers. Those involved with the design and specification of metallic materials used by engineers to meet some need are called metallurgical engineers.

The preceding brief categorization represents a coarse description. The words are more likely to be used by educators, professional societies, and licensing boards than by the engineers themselves. In looking over engineers' shoulders you might be in error in any attempt to guess their formal preparation for their careers or the company titles for their positions. An engineer designing an electric motor is more likely to be a mechanical engineer by education than an electrical engineer, with the job title "design engineer, small ac motor division."

Nevertheless, these distinctions are helpful at this point. In them and their amplification is the word *design*. This is one of the things all engineers have in common.

It is useful to the engineering student to draw a distinction between *things* with which engineers are inevitably associated and *disciplines* in which they study and to which they contribute. These distinctions can be made in any field of engineering. The things tend to be different but the disciplines are in large measure shared among engineers. Our example will involve mechanical engineering. Table 1.1 recognizes objects that are associated with mechanical engineering solutions. In their preparation to become mechanical engineers and in their maintenance and improvement of knowledge they do not study these objects specifically. Their attention at school and thereafter is categorized into disciplines that involve the objects as examples. Table 1.1 also indicates the disciplines of interest to mechanical engineers, who share interest in these with many other kinds of engineers.

The reader should understand the following ideas from this section.

- --Engineering offers society suitable, feasible, and acceptable, i.e., satisfactory, alternatives to the natural course of events.
- --Engineers create what never was.
- --As presently constructed, our civilization is in a large measure dependent on abundant food and energy.
- --Engineers are categorized for educational and associative purposes by discipline, but employment categories are usually functional.

1.4 DESIGN AND THE DESIGN PROCESS

What is design? It is the central purpose of engineering. It begins with the recognition of a need and the definition of the problem and continues through the conception of an idea to meet this need. It proceeds with a program of analysis and directed research and development and leads to the construction and evaluation of pilots or prototypes. It concludes with effective multiplication and distribution of a product or system so that the original need may be met wherever it exists.

The usual product of an engineering effort is a *service*, embodied in a *template* (plans and specifications) for building an object or for replicating objects that meet a specified need. Mass-produced objects, such as millions

Table 1.1. Objects and Disciplines of Mechanical Engineering

		Objects
Mechanical Engineering	Machine elements	Structures, fasteners
		Shafts, bearings, seals
		Gears, brakes, clutches
		Springs, linkages, cams
	Machines	Turbomachinery
		Fans, blowers, pumps, compressors, turbines
		Reciprocating machinery
		Engines, pumps, compressors, hydraulic motors
		Other combinations of machine elements
	Machine systems	Stationary power stations
		Vehicular power plants
		Vehicles
		Production facilities
	Worker-machine systems	Biomedical apparatus
		Machine-operator complexes
		Environmental controllers
		Human-and-computer controllers
		Disciplines
Mechanical Engineering	Design of machines	Synthesis, analysis theory
		Kinematics, dynamics
		Strength, reliability
		Energetics
		Liability, safety
		Simulation, analog
		Computer-aided design
	Testing of machines	Instrumentation, measurement
		Inference statistics
		Test codes, standards
	Manufacture of machines	Materials science
		Manufacturing methods
		Quality control
	Control of machines	Automatic feedback control
		Vibration
		Information theory
	Maintenance of machines	Reliability
		Servicing, scheduling

of barrels of detergent or gasoline; thousands of locomotives, planes, tractors, radios; millions of yards of cloth or carpet; or billions of kilowatt-hours of electricity are examples of products replicated from the engineering template.

What skills and knowledge do engineers need to function as designers?

1. Engineers must be able to recognize needs. This awareness has to be tuned to sharpen their perceptions.