Approaches to Improve Engineering Design

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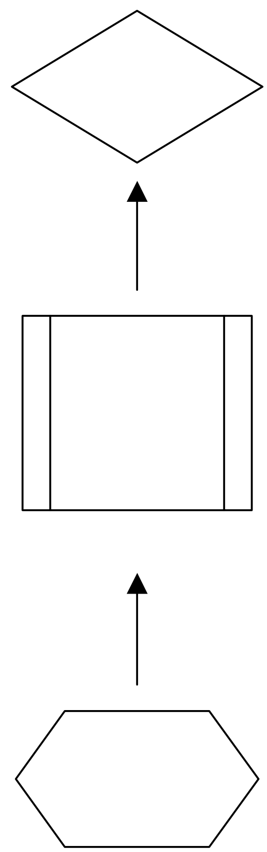
APPROACHES TO IMPROVE ENGINEERING DESIGN



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PREFACE

Design is a process by which human intellect, creativity, and passion are translated into useful artifacts. The practice of engineering design involves not only pure and applied sciences, behavioral and social sciences, and economics but also many aspects of business and law. A designer must work effectively with a team composed of members of different disciplines and make tens or even hundreds of decisions for simple products and thousands of decisions for complex products. Tools to aid designers extend from design guides and rules of thumb that capture experience to synthetic environments that allow the designer to fly through virtual models.

Both engineering design and the ability to teach it have been the subject of many meetings, publications, and organizations as well as any number of spirited discussions. Without doubt, the various aspects of this issue can admirably engage both sides of our brains. The authors of this report set out to examine the theories and techniques for decision making under conditions of risk, uncertainty, and conflicting human values. This report attempts not only to analyze existing tools but also to identify opportunities to establish a more rigorous fundamental basis for decision making in engineering design.

Decision-making tools can be useful design aids when appropriately applied. However, because the knowledge embodied in a designer or design team to synthesize and create is uniquely human, design cannot ever be totally automated. Decision tools and many other methods can aid the design process by organizing knowledge and providing systematic frameworks to enable the designer to generate new options and make intelligent choices to realize a product. The design community can make progress only when engineering design decisions are understood from the perspective of stakeholders in manufacturing enterprises and society. Time, effort, and resources must be invested in understanding engineering design as it is practiced, in creating a taxonomy to facilitate communication among the stakeholders and participants, and finally in identifying what needs to be done to move forward.

The authors reviewed previous studies about decision making in engineering design and consulted with a cross section of engineering design leaders in industry and academia. In conducting the data gathering and analysis and in formulating findings and recommendations, the authors brought wide-ranging expertise in economics, decision theory, academic research, and industrial practice. This diversity was valuable in deliberations and instructive in the difficulties of communicating across disciplinary areas, especially in the study of decision analysis for engineering design.

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This report has been reviewed by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's (NRC's) Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the authors and the NRC in making the published report as sound as possible and to ensure that the report meets the institutional standards for objectivity, evidence, and responsiveness to the study charge. The content of the review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their participation in the review of this report: Ernest R. Blood, Caterpillar Inc.; Clive L. Dym, Harvey Mudd College; Jay Lee, University of Wisconsin at Milwaukee; Steven C. Lu, University of Southern California; Farrok Mistree, Georgia Institute of Technology; and David J. Vander Veen, General Motors.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of the report was overseen by George Dieter, University of Maryland, appointed by the Division on Engineering and Physical Sciences, who was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authors and the institution.

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OVERVIEW

A scientist studies what is, whereas an engineer creates what never was.
—*Theodore von Karman*

Design is the process by which human intellect, creativity, and passion are translated into useful artifacts. Engineering design is a subset of this broad design process in which performance and quality objectives and the underlying science are particularly important. Engineering design is a loosely structured, open-ended activity that includes problem definition, learning processes, representation, and decision making.

Engineering designers attempt to create solutions to satisfy particular specifications while complying with all constraints. When a satisfactory solution cannot be discerned, the designer must create new options. The traditional design approach has been one of deterministic problem solving, typically involving efforts to meet functional requirements subject to various technical and economic constraints.

In seeking a logical and rigorous structure to aid in developing a satisfactory design, or one that is acceptable to the customer or user of the product, a number of approaches have been proposed to organize, guide, and facilitate the design process. Examples include Taguchi's theory of robust design, Deming's principles of quality control, Quality Function Deployment, design for manufacture, and concurrent engineering. In some cases these approaches can lead to different and conflicting answers. It is important, therefore, that they be assessed individually and collectively to determine both their strengths and limitations for particular applications. A selection of these techniques is summarized in Chapter 4 and some of their limitations and advantages are noted.

PRIOR STUDIES

The National Research Council study *Improving Engineering Design* (NRC, 1991) reported that the best engineering design practices were not widely used in U.S. industry and that the key role of engineering designers in the product realization process was often not well understood by management. To reverse this trend the report recommended a complete rejuvenation of engineering design practice, education, and research, involving intense cooperation among industrial firms, universities, and government. The authors found that few of the recommendations have been implemented.

The 1991 study was authored at a time when the United States was losing market leadership to the "Asian tigers." It reflected pessimism about the ability of the United States to compete in world markets and attributed some of the nation's problems to poor design practices. A short decade later, the U.S. economy is leading the world, based in part on continuing annual productivity increases. Many observers credit this dominance largely to the leading position of the United States in the information age that has displaced the industrial age. Information technologies clearly have had, and will continue to have, a large impact on engineering design.

It is logical to ask whether proficiency in engineering design matters in this new economy. The authors' answer is a resounding yes! The globalization of the economy and the associated competitive pressures to introduce new, better products faster and at lower cost make engineering design even more important.

Recently, the importance of engineering design was re-emphasized by Wm A. Wulf, president of the National Academy of Engineering (Wulf, 1998), and by the Accreditation Board for Engineering and Technology in its standards (see Appendix A), which require an increased emphasis on design in engineering curricula.

The National Science Foundation (NSF) has been actively working to address various issues in the engineering design area. In 1996, it sponsored a workshop entitled "Research Opportunities in Engineering Design" to determine research priorities in engineering design by examining industry and education needs and to formulate recommendations for the NSF's Engineering Design Program (NSF, 1996). The NSF funds an on-line decision-based design open workshop to engage design theory researchers in a dialogue to establish a common foundation for research and educational endeavors (<http://dbd.eng.buffalo.edu/>). The NSF also sponsored Gordon Research Conferences in 1998 and 2000 on theoretical foundations for product design and manufacturing (GRC, 1998, 2000).

THE CHANGING NATURE OF ENGINEERING DESIGN

In the past it was too often sufficient to design, produce, and market designs based mostly on lore, empiricisms, and extrapolations. Many industrial processes and products remained essentially unchanged as long as the companies were profitable and the industries were unchallenged.

In today's economy the globalization of business and markets, the changing nature of world trade regulations and business operations, and the impacts of information technology on business have fundamentally changed the economy and are having a profound effect on engineering practice. To be competitive in today's global marketplace, incremental changes and empirical methods are inadequate. Products must be developed and introduced to markets faster, with unprecedented demands for high performance and low cost.

Strategic changes in existing industries are required to counter the salary differences between the workers in this country who produce exports and those across the globe who produce imports. Furthermore, new and unprecedented demands on the performance and operation of new and emerging technologies and the major innovations required for industries to be competitive on a global scale have surpassed the existing general knowledge from which such designs can be made. There is little or no experience on which to base such technological advances. Thus, there exists a chasm between existing empirically developed systems and possible innovations.

Engineers today do have extraordinary tools and resources including computers, remarkable materials, and advanced engineering environments at their disposal. Much deeper understanding of the industrial processes is required, however, before those resources can be put to good use. The result, a new and essential tool for engineering practice also known as Research for Design (R4D), can be used to develop knowledge bases that enable innovative, reliable, cost-effective, and efficient designs. Design is a complex process involving aspects ranging from product quality to life-cycle analysis, but first and foremost, the physicochemical phenomena or behavior of the system elements, must be understood to make the innovations required and to assure functional performance of the design.

The research in R4D is focused and directed to provide the designers the specific information they require in real time. It differs from the R in R&D, which usually means basic scientific research. R4D focuses on the people-made world to expand the knowledge base from which advances in design and production can be made. It is often multi-disciplinary and addresses the functional characteristics of large systems that consist of intricate components. Every company must have an ever increasing, relevant engineering knowledge base and the technologies and the people for translating that base into products rapidly and efficiently.

R4D requires researchers to be in continual contact with designers and systems engineers in order to identify, define, and obtain the precise information required for the development of cutting-edge technologies. Recent technological advances in distributed networking, telecommunications, multi-user computer applications, and interactive virtual reality (called "advanced engineering environments" [NRC, 1999]) not only enable disparate communities to interact in real time but also allow seamless integration of research, development, and application cycles to bring about efficient interactions and rapid progress.

Major advances in engineering design are based on increased computational power and communication (information technology). High-fidelity models of complex systems and advanced visualization techniques, as reported in *Advanced Engineering Environments: Achieving the Vision, Phase 1* (NRC, 1999), provide powerful new tools to today's designers. But stunning graphics and improved models are not sufficient to design increasingly complex systems; methodologies to make sound design decisions are required.

2

DECISION MAKING IN ENGINEERING DESIGN

The role of decision making in an engineering design context can be defined in several ways. As shown in Figure 2-1, the decision process is influenced by sets of conditions or contexts.

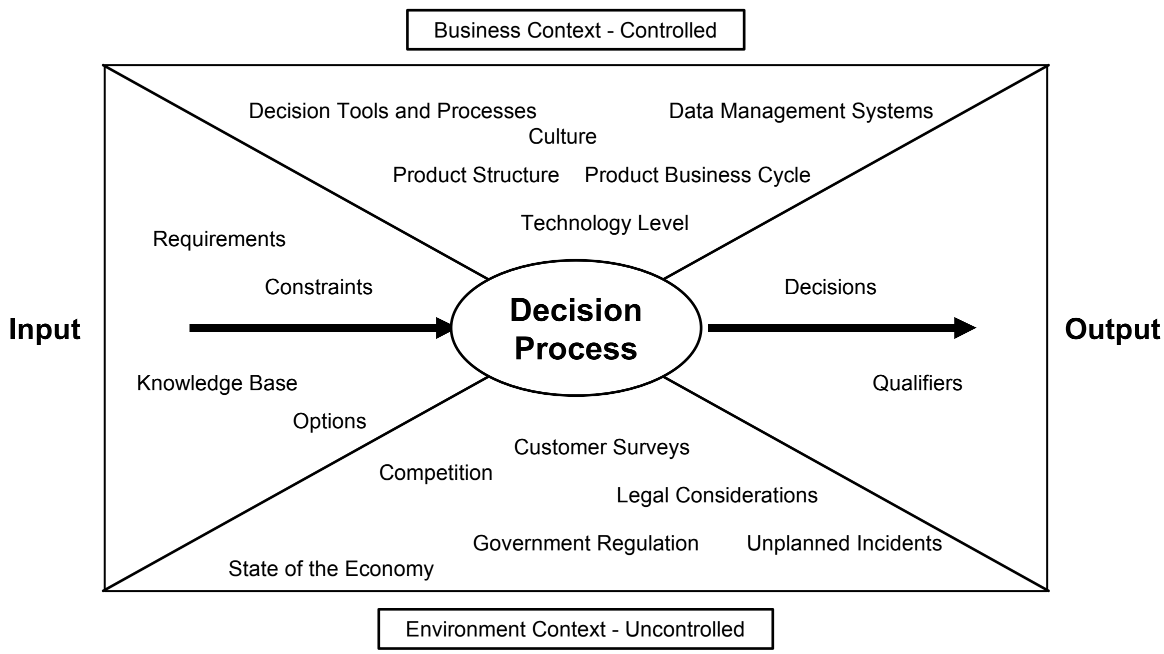

Figure 2-1 Decision process in the context of business and environment.

The business context represents the long-term view of the engineering company and is largely in the control of the company. The environmental context, such as the state of the economy, is not controlled by the company and must be considered a variable. The input context, such as the completeness of and variation in requirements and constraints, is established by the customers as is the output context, such as state of readiness to implement decisions, risks, and qualifiers.

Closing with the customer is an iterative process reconciling the customer's needs with the developer's design capabilities and requiring collaboration and experience with the product. In the real world, decisions made by the experts can be delayed and overturned by higher-level management based on poorly defined or unstated environmental issues.

In today's engineering environment routine decisions can involve geographically dispersed teams working under challenging cost and timing constraints. Under these conditions, the quality of most decisions can be improved through the application of computer-based tools. These tools can be put in the following categories: knowledge-based engineering, workflow, and collaboration.

Knowledge-based engineering tools provide computational representations of engineering design rules, allowing engineers to execute modeling, analysis, and optimization far more quickly while staying within design practice constraints. This frees the engineer from the routine portions of analysis and allows more time to trade design options, thereby improving design decisions.

Work process management tools can help manage the execution and coordination of tasks via the Internet by routing and tracking work throughout the design process. These tools manage both schedule execution and process compliance (such as configuration control) globally.

Collaboration tools, including Internet-based conferencing and graphics sharing, help the day-to-day working relationship between engineers at distributed locations. This ongoing real-time collaboration results in timely and coordinated design decisions.

Figure 2-2 shows the character of decisions affected by two elements of the business context. On one axis is the duration of the decision and on the other is the criticality of that duration for the product. A decision in this context is a choice made by the design engineer for a particular solution for the problem at hand. Decisions with long-term impact often are irreversible after implementation; therefore the decision maker must seriously analyze the decision. A large number of short-term incremental decisions can, however, be made relatively risk free. All decisions can be plotted on the context chart and fall into one of the relevant subgroups. Increasing investment of scarce time and other resources in the decision process is appropriate for the decisions that are critical or irreversible.

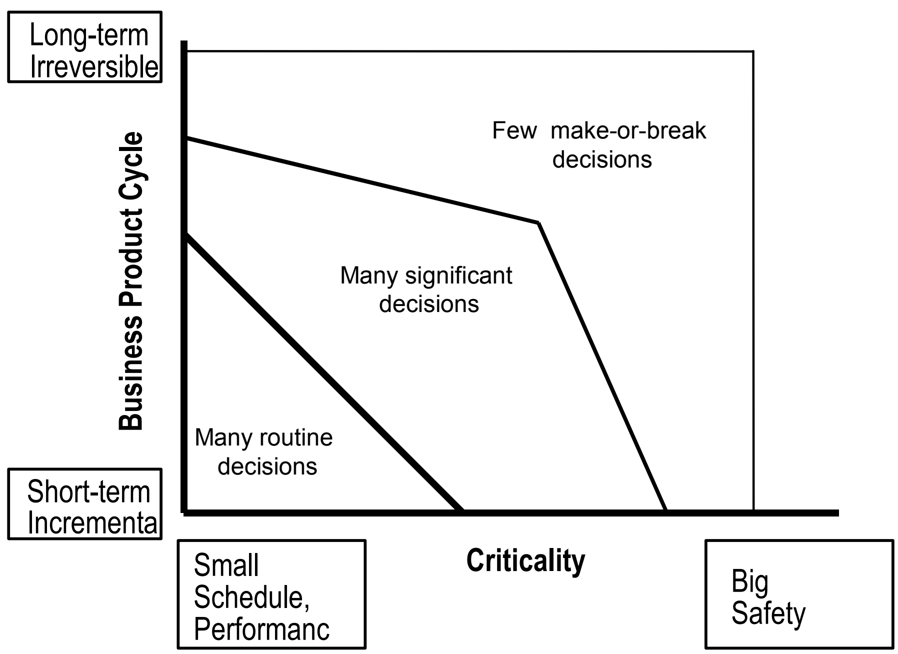

Figure 2-2 Decisions framed in relevant context.

Correctly assessing the context for making a decision is important because it dictates the level of effort and type of tools applied to the decision process. The most critical decisions often employ multiple tools, preferably logically sound and internally consistent in all circumstances. Framing addresses how to pose the decisions, and is described more fully in Chapter 3.

Table 2-1 Framing a Decision in the Relevant Context

	Routine Decision	**Make-or-Break Decision**
Context	• Small impact • Reversible • Short term • Data available • Standard decision process	• High impact • Irreversible • Long term • Safety or product liability critical • No well-defined decision process
Decision Processes and Tools	• Use standard or automated decision process • Supporting data available • Use simple decision tools • Small team or individual • Low-level reviews	• Use a variety of decision processes • Generate supporting data • All functions involved • Large team including management

Decisions that make or break the business (Table 2-1) are often laden with trade-offs, which are usually complex in nature. Further, preferences for these attributes typically differ across stakeholders, such as customers, operators, and manufacturers. Framing and resolving these trade-offs are time pressured with much potentially relevant information to be considered. These trade-offs are also subject to many uncertainties regarding customer buying preferences, user abilities and preferences, technology maturity and availability, and competitive advantages of possible functions and features. These trade-offs usually cut across disciplinary boundaries in terms of balancing weight, power, speed, cost, and economy of use. In some cases these trade-offs are resolved by fixing design requirements, which makes design more tractable but increases the chances of noncompetitive solutions because of a restricted ability to trade off design options. Most contemporary design methodologies avoid premature freezing of requirements.

The complexities just portrayed result in multi-disciplinary teams for most design efforts. The notion of such teams once implied multiple disciplines, such as mechanical and electrical engineers, working together. More recently, however, multi-disciplinary has come to mean engineers, industrial designers, marketing and sales professionals, and finance experts working together. This enables richer, more comprehensive trade-offs across form, functions, features, and price. This challenges many design decision tools because of the bias and limitations of individual disciplines. Richness in this context refers to the wealth of relevant information and the many players in the decision making process. Because conceptual and mathematical representations of different disciplines do not easily mesh, it is difficult to reach common analytical solutions. Either each discipline tends to sub-optimize their piece of the problem or, more likely, decisions are made more subjectively through negotiation rather than calculation.

Economic attributes ranging from financial metrics to consumer utility models cut across all disciplines, especially when supported by the methods and models of probability and statistics. These models and methods allow exploration of the intersections of market-driven preference spaces and technology-driven physical spaces.

Economic attributes drive actual design decision making, regardless of the extent to which the methods and tools include such attributes. Similarly, uncertainty and risks are pervasive and must be addressed. These overarching issues must be considered regardless of the decision making tools used. These cross-cutting approaches provide the context for design engineers to synthesize and analyze ways of providing desired functions and features within economic constraints, as well as quality, reliability, and maintainability considerations. Analyses of signal flow, stress characteristics, and control stability are in this way integrated into the overall design context.

Traditional design engineering is still pursued, but it is less and less isolated by trade-offs and optimization within a discipline-limited set of purely physical variables. This is nowhere more evident than in the linkages of design variables to economic considerations. Representations of interactions of product and process variables on costs have become central to product realization in many domains. Multi-attribute, multi-stakeholder design contexts, laced with uncertainties and rich in information, are the norm. The framing of critical design decisions across contributing disciplines is central to success in such contexts.

3

BASIC TOOLS FOR APPLIED DECISION THEORY

Decision analysis, or applied decision theory, was developed about 35 years ago to bring together two technical fields that had developed separately. One field was the theoretical development of how to help a person make simple decisions in the face of uncertainty. This field was begun in the 18th century with the work of Bernoulli, then Bayes, and finally Laplace. It was improved and refined to a high state of development in the years following World War II.

At that time the control and systems engineering development during World War II was available to make practical the application of fundamental ideas about decision making under uncertainty to the actual problems faced by decision makers. The new field of decision analysis provided both a formal, systematic way to analyze decisions and an important communication medium for achieving mutual understanding between decision makers and those who advise them.

Many important creative activities—from engineering design through medical treatment to business strategy—have unique features in their technological basis and their possible consequences, among many other elements; however, they all share the characteristic of being fundamental decisions. They differ in their alternatives, forms of uncertainty, and preferences for consequences, but they share the features of all decisions: the need to distinguish the quality of the decision from the desirability of the consequence, the need to incorporate uncertainty and to value experiments, tests, surveys, and other forms of information gathering that might reduce uncertainty at a cost, and the need to establish preferences for outcomes, including outcomes achieved with different probabilities. This is true whether we are designing a planetary probe or managing a portfolio of chemical entities for a pharmaceutical company. Recognizing the similarities of all decision processes allows us to use important general insights in applying them; this is particularly true for engineering design.

The purpose of decision analysis is to provide decision makers with clarity of action in an uncertain decision situation. The metaphor for decision analysis can be conceptualized as a high-quality conversation about a decision. Sometimes the conversation can be very brief and carried on by oneself. More difficult and puzzling decision problems may require the assistance of several analysts and extensive computer modeling. This spectrum is the domain of decision analysis.

Perhaps the single most important distinction of decision analysis is that between making a good decision and achieving a good outcome. The quality of the decision can be evaluated only in light of the situation when the decision was made and not with any reference to its results.

A good decision is one that is best for me given the alternatives I have, the information I possess, and the preferences I assess. For example, if someone offers to sell me for $10 one of 100 lottery tickets for a prize of $10,000, I would readily buy the ticket. Of course, if I am sure of the validity of the offer, as I am assuming, I would like to buy all 100 tickets, but he offers me only one. I know the good outcome is winning the $10,000 and the bad outcome would be losing the $10. However, I am making a good decision to buy the ticket, even though there is a 99 percent chance of the bad outcome. I always want to choose the alternative that gives me the best combination of probabilities and outcomes for my given risk preferences. The fact that I am not likely to enjoy a good outcome, as in this case, is no indication I have made an improper decision.

There is a common but fallacious belief that experiencing a bad outcome implies a bad decision was made. Such opinions are commonly voiced in sports. The football team tried to make a two-point conversion and failed: The coach made a bad decision. That the operation was a success but the patient died may simply be an example of a bad outcome following a good decision. One necessary test of a good decision is whether you would make the same decision again in the same situation if you had not yet learned its consequences.

THE DECISION BASIS

What is a good decision? A good decision is one that is systematically correct given a decision situation properly framed by a committed decision maker. The specific description of this situation is the decision basis. The three elements of the decision basis can be thought of as the legs of a three-legged stool, as shown in Figure 3-1. The quality of a decision rests on having framed the decision correctly, that is, answering the right question, understanding the issues (knowledge), what can be done (options), and what you want (desired outcomes). Tools for applying logic help the decision-making group or individual to reach a conclusion and direct action.

One element is what the decision maker can do in the face of the alternatives to be considered, which may call for an immediate decision or allow for postponing it to the future after some of the uncertainties are resolved. These sequential decisions allow us to represent options and to calculate their value.

The second element of the decision basis is information (i.e., what links the alternatives to what will ultimately happen), which can be in the form of models describing the field of concern in the decision. Some decisions, like the launching of a satellite, have the advantage of extensive physical models to guide the decision. Other decisions (say, those related to the spread of wildfires or the progress of a disease) will involve considerably more uncertainty. Still more uncertain will be the behavior of a jury or of consumers responding to advertising.

Regardless of the extent of modeling available, the decision maker will ultimately face some uncertainty in any significant decision problem. The decision maker represents these uncertainties in the form of probabilities or probability distributions. These distributions will be informed by any available experimental data, but in many cases, particularly in applications of new devices or systems, the experienced judgment of

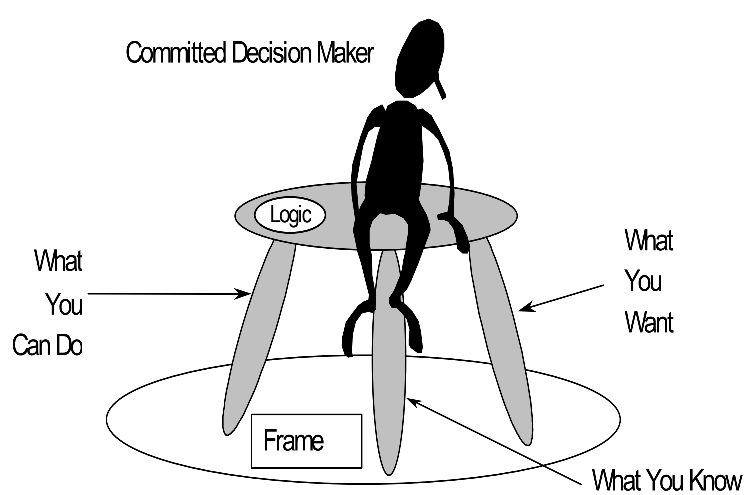

Figure 3-1 The quality of a decision.

experts may be the only available resource.

The third element of the decision basis is preference, or what the decision maker wants. Preference has three identifiable dimensions in most cases. The first is valuation, or the trade-off among different attributes of the consequences of the decisions. This is summarized by a value function specifying how much more valuable one set of attributes is than another. The second dimension of preference is time: how much values in the future will be worth relative to values today. This dimension is essential in purely financial decisions, but it also has application in, for example, medical decisions, where the patient's quality of life must be balanced against the duration of life, and in any other decisions where the attributes of the future must be balanced against the attributes of the near term. The third dimension of preference is risk preference. Risk preference is the dimension of preference stating which probability distributions over attributes of each outcome are preferable to others. This can be as simple as whether the decision maker prefers to receive a sure million dollars or to toss a coin for a payoff that will be either $3 million or nothing.

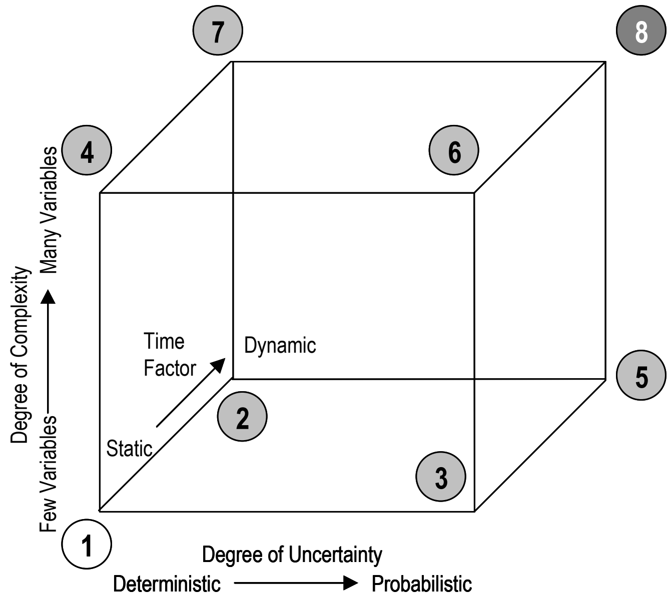

Figure 3-2 The problem space for characterization and decision making.

When all three elements of the decision basis are formally specified, the best decision can be determined by employing rules (axioms) to extend the exercise of choice to the case where the uncertainties facing a decision maker are explicitly recognized. In fact, all alternatives will be ranked and evaluated by this decision process.

The importance of models in engineering design leads us to discuss them in more detail by means of the problem space in Figure 3-2. This diagram illustrates the three dimensions of difficulty a problem may have: uncertainty, complexity, and dynamic or time effects. The corners with fewer degrees of difficulty tend to be those explored early in human history and are studied early in the engineering curriculum. As we move from problems with few of these factors to more of them, our ability to model decreases, until at the corner numbered 8 we have very few mathematical representations, if any, where all three dimensions can be treated in a general way. This means there will be a need for judgment in deciding which factors must be carefully considered and which can be treated approximately. As stated in the Executive Summary, design is not an endeavor that can be totally automated.

Returning to the stool, the seat is the logic acting on the decision basis to produce a course of action. The person seated on the stool is the decision maker who has stated the decision to be made. The ground on which the stool is placed is the frame developed for the decision situation.

FRAMING

Framing concerns how we choose the decision problem to which we will apply this structure. For example, suppose a manufacturer of buggy whips in the early 1900s noted profits were falling and decided to call in a consultant to see how manufacturing could be done more efficiently. The decision would be framed as one of improving the buggy whip manufacturing process. Observing the growing automobile revolution, however, the framing would more appropriately address how to change the product line to serve the new demands of automobile owners while phasing out buggy whip production. *Framing is the most critical part of the process of decision making*, because making the right decision in the wrong decision frame can be a serious error.

Proper framing is the key to working on the right problem. Improving the efficiency of buggy whip production would be the correct solution to the wrong problem. In principle the methods of decision analysis could be used in selecting a frame; this use would be a meta-application. The choice of a frame can usually be accomplished by a guided conversation. An aid in framing is the decision hierarchy shown in Figure 3-3. The frame selected for the decision separates it from other decisions made previously or taken as given, shown above, and those to be made later, shown below.

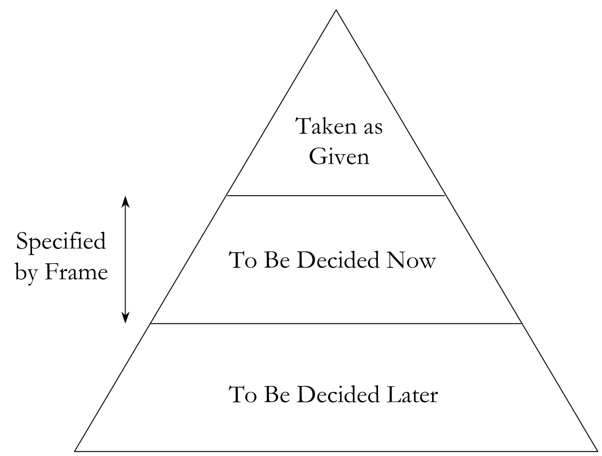

Figure 3-3 The decision hierarchy.

SENSITIVITY ANALYSIS

Because all aspects of the problem are explicitly considered, a sensitivity analysis can be performed on every input. Sensitivity to changes in alternatives, changes in information, and changes in preference can be determined. Because the formal decision model links every input to the ultimate value measure, sensitivity analysis is a simple computational task. Judgment is required to choose the extent of multi-variable sensitivity analysis.

Of particular importance, and unique to decision analysis, is the ability to place a value on the resolution of any uncertainty, provided a value measure is one of the attributes of the decision problem. The decision maker can thus determine what it would be worth to resolve any or all of the uncertainty. If opportunities for information-gathering exist such as surveys, experiments, pilot plants, prototypes, or market trials, the decision maker must determine whether their value exceeds their cost. The same logic guides design of the most beneficial experiments and the application of their results to present and future decisions.

Most important is the notion of framing to ensure that the problem being addressed is the fundamental problem facing the decision maker. Often the successful practice of decision analysis requires a complete reframing of the originally contemplated decision. Professional decision analysts also ensure that the decision maker is actively involved in the decision-making process, to gain their commitment both to the process and to any resulting decisions.

The practice of decision analysis is based not only on the pioneering contributions from probability, decision theory, and systems engineering, but also on the insights provided in the last few decades by cognitive psychologists. These professionals have sensitized us to the types of mistakes people make in thinking about decisions, which can be as subtle as making decisions based on percentages rather than absolute amounts. The cognitive biases to which we are all subjected must be recognized both in providing the inputs to a decision analysis and in appreciating the necessity for formal analysis in complex decision situations.

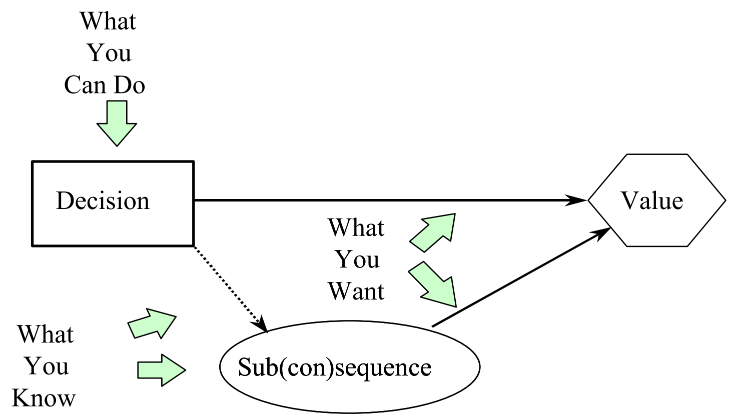

Figure 3-4 The decision process.

The analysis of the decision can be carried out using any of several tools, such as those shown in Figure 3-4. Examples are shown later in the report. Only a few are illustrated here. The decision analysis cycle depicts the overall iterative nature of the formulating, analyzing, and learning process.

Figure 3-5 shows a simple influence or decision diagram for a simple decision. A rectangular box represents a decision node, an action under the control of the decision maker. Ovals represent uncertainties or, in some cases, calculations. Finally, hexagons represent the value node, with

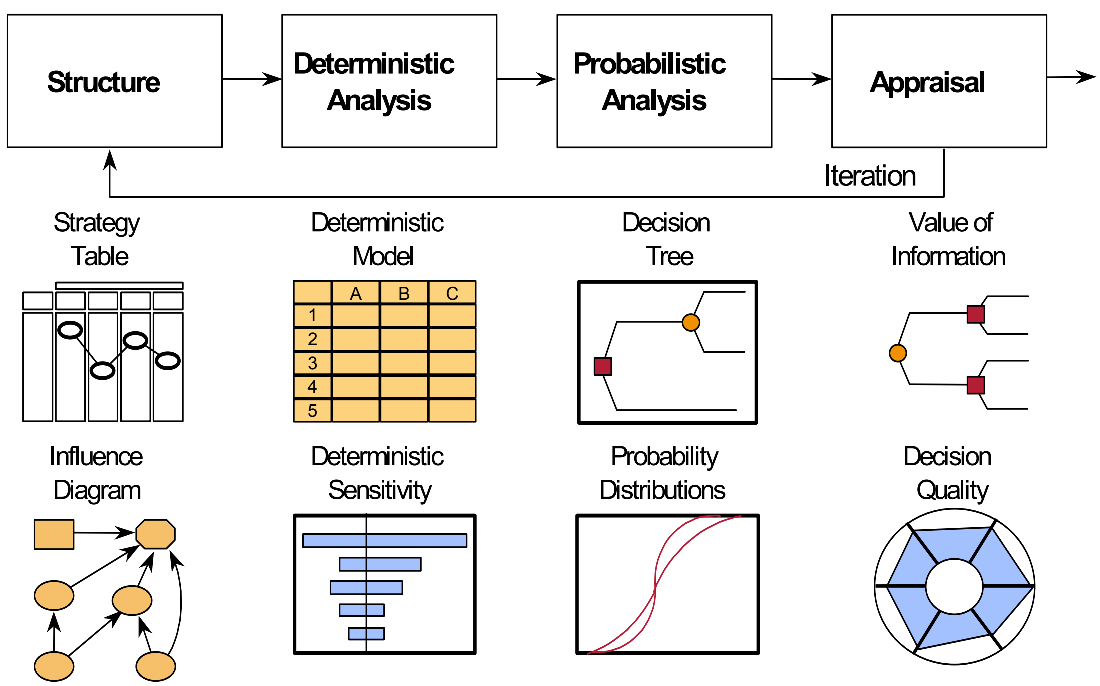

Figure 3-5 Decision diagram.

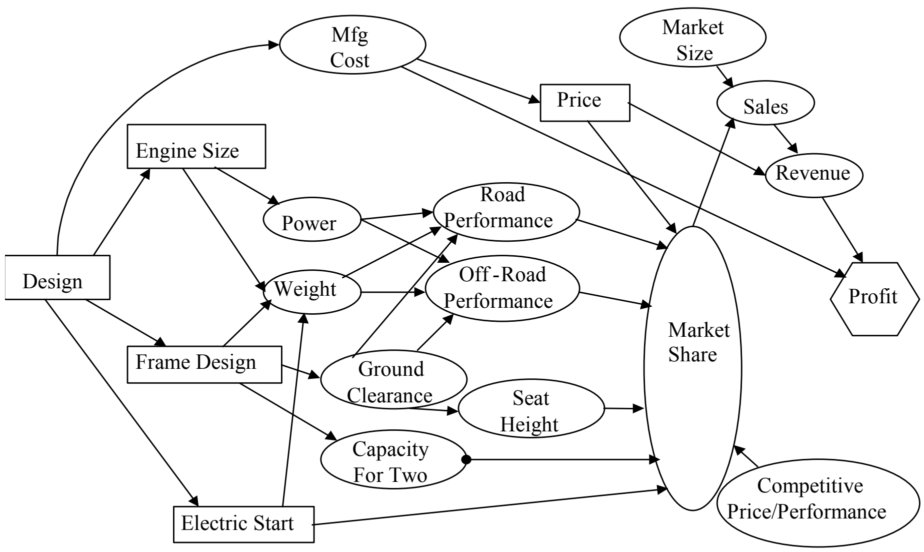

Figure 3-6 Decision diagram for design of a dual-sport motorcycle.

inputs showing what the decision maker values. Arrows into any node show what its value depends on, either functionally or in the sense of conditioned probability. Arrows into decision nodes show what is known when the decision is made.

In the sample decision diagram in Figure 3-6, note that the manufacturing cost will be known only when the price decision has been made. Such diagrams have important properties. First, at the level of relation, they reveal the logical structure of the problem in a way that allows nontechnical people to understand and contribute. Every relevant thought should have a representation in the diagram. However, decision diagrams are more than useful graphics. When

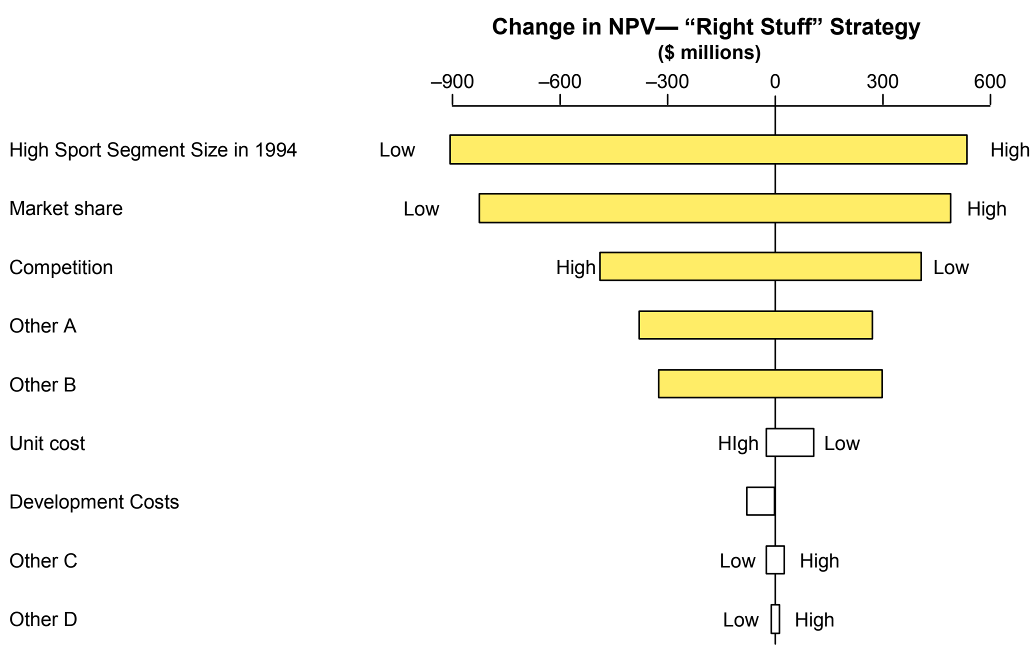

Figure 3-7 Tornado diagram

each decision in the diagram is properly specified, the decisions can be processed directly by a computer to yield the best overall decision. This method can calculate the value of information regarding any uncertainty and can also illustrate many of the sensitivities for a preferred course of action. Decision diagrams also serve as an important communication link among those involved in the decision.

Another valuable idea is a form of sensitivity analysis known as the tornado diagram because of its shape. Figure 3-7 illustrates for a particular strategy how the net present value of the final decision implementation changes as each uncertainty ranges from a low to a high value. A low value is defined as one with a very high probability of being exceeded, a high value as one with very low probability of being exceeded. The effect on net present value for each factor is ordered in decreasing range of impact to produce the tornado shape. This diagram quickly demonstrates the effect of each uncertainty for a given alternative. A series of tornado diagrams would show engineers at all levels of the design process the economic implications of their decisions.

A useful guide in assessing decision quality is the spider diagram shown in Figure 3-8. Here the state of quality in each of the six elements can be plotted as a percentage and then connected to form a web. In this diagram "100 percent" does not represent perfection but rather a situation in which further improvement would not be economical. The result of such an assessment is knowledge of where, if anywhere, to direct additional analysis effort.

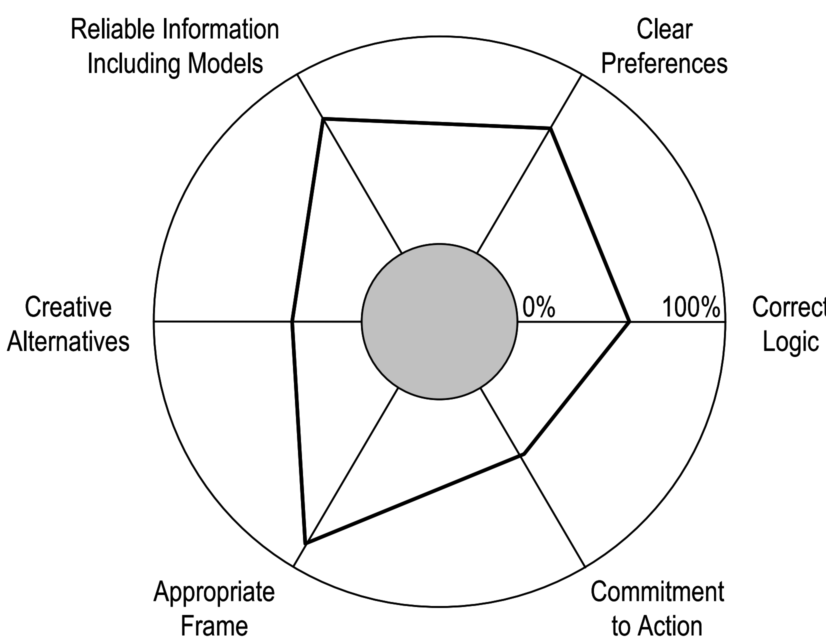

Figure 3-8 The decision quality spider. 100 percent means further improvement is not economical.

4

METHODS, THEORIES, AND TOOLS

Various tools are commonly used to aid designers, and several additional theories offer more analytically rigorous support to engineering designers. Concurrent engineering may be the most practical method to improve the design process, and other common tools are used to obtain input from stakeholders in the design process (the Pugh Method, Quality Function Deployment, Decision Matrix techniques, and the Analytical Hierarchy Process). These tools incorporate relatively high levels of subjective judgment. An additional set of tools address variability, quality, and uncertainty in the design process (Projected Latent Structure, the Taguchi method, and Six Sigma). These tools are more analytical and are typically coupled to the processes used to produce products. Still other tools are used to generate alternatives for designers (artificial intelligence and TRIZ). Design theories also exist (Dym's, Suh's Axiomatic, Yoshikawa's, and a Mathematical Framework) that are less widely used but offer more rigorous analytical bases. Finally, certain other tools are used primarily in the fields of management science and economics, and are being explored in current research for applicability to decision making in engineering design.

This review is illustrative rather than exhaustive given the voluminous existing literature about each tool and theory. Series of individuals and groups are devoted to research and application for each separate tool or theory mentioned here. Subjective comments on the applicability or limitations of the tools and theories are of course based only on the authors' knowledge of the tools and of the relevant literature.

CONCURRENT ENGINEERING

Concurrent engineering is defined as "a systematic approach to the integrated, simultaneous design of products and their related processes, including manufacture and support. This approach is intended to cause the developers, from the outset, to consider all elements of the product life cycle from conception through disposal, including quality, cost, schedule, and user requirements" (Winner et al., 1988). According to Dean and Unal (1992) concurrent engineering consists of getting the right people together at the right time to identify and resolve design problems. Concurrent engineering includes designing for assembly, availability, cost, customer satisfaction, maintainability, manageability, manufacturability, operability, performance, quality, risk, safety, schedule, social acceptability, and all other attributes of the product. Table 4-1 highlights the contrast between concurrent engineering and conventional engineering design.

The concurrent engineering environment has the following characteristics:

- Reduced cycle time
- Overlapping of functional activities
- Collaboration in functional decisions

Table 4-1 Comparison Between Concurrent Versus Linear (Serial) Engineering

Concurrent Engineering	**Linear (Serial) Engineering**
Parallel design of products and processes	Sequential design
Multifunctional team	Independent designer
Concurrent consideration of product life cycle	Sequential consideration of product life cycle
Total quality management tools	Conventional engineering tools
All stakeholder inputs	Customer and supplier not involved

- Concurrent evolution of system and component decisions
- Critical sequencing

Concurrent engineering strives to meet the need for continually shorter product development cycles and the need to represent the inputs of all stakeholders. Decision-making tools and processes continue to evolve to support making the best decisions in this environment. In the concurrent environment functional activities such as engineering and manufacturing are done simultaneously. This is contrasted with a traditional serial process in which the design team finishes its work before the drafting department prepares and releases the drawings, at which time manufacturing starts. Because of the overlapping of functional activities, cycle times may be greatly reduced and decisions become highly interdependent. This environment causes many decisions to be made without complete information, which has led to the development of methods to share product requirements, to assess risks effectively, and to develop abatement plans. System and component trades must be made concurrently, which requires effective methods for flow-down and tracking of requirements, as well as flow up and tracking of status. The tight schedules resulting from reduced cycle times require disciplined scheduling and monitoring of key decisions as well as management of the required sequencing and the downstream impact of design decisions. Cross-functional decision making requires integrated, highly reliable, and readily accessible databases.

The tools and methods being developed to support this environment, most of which are computer based, can be categorized as follows:

- **LAN- and Web-based management tools.** Often an individual decision (say, material selection for a component) is dependent on a higher level system requirement (say, operation in a corrosive environment). Without good management tools the individual decision maker may be unaware of the requirement. These management tools usually include a function for informing the individual decision maker of multi-level critical decision dates and status. An informative interconnected data management system is essential.
- **Tools and processes for assessing risks and developing risk abatement plans.** Because of compressed cycles and overlapping functional activities, decisions must be made with incomplete information or data. For example, manufacturing of components may begin before the final product drawing is complete and issued. There is inherent risk in starting manufacturing prior to drawing release as a change in definition may result in rework or scrap. Tools need to be

developed to aid the decision maker to assess the risks and develop suitable abatement plans. Work with design structure matrices is a good start in this area. When these situations are routine occurrences, as with the above example, standard abatement plans may be developed.

- **Automated analysis tools for rapid evaluation of alternatives.** The accuracy of decisions and reduction of risk can be greatly improved by the quantification of alternatives. Many tools exist or are under development to automate or codify analysis to improve cycle time and efficiency. Parametric Modeling, Design of Experiments, and Automatic Finite Element Meshing are examples.
- **Data-sharing tools.** In a cross-functional concurrent decision making environment with compressed cycle times, data must be readily available to all decision makers. Data must be accurate, timely, complete, easily accessed, and in many cases, configuration controlled. The data must be informative, not merely numerous. An excellent example of a shared database is the use of three-dimensional solid models for distributing geometric information for drawing, tooling, manufacturing, and customer appraisal analysis.

As decisions are made in the concurrent environment, the impact of each decision on the product is evaluated. This makes the concurrent engineering environment not only contextual but also a fundamental part of the decision process. As a process rather than a decision tool, it requires a wide variety of supporting tools as described above and in the following sections. Through continual feedback, the concurrent environment decision process facilitates evaluation and modification of decisions whenever undesirable or unexpected consequences result.

TOOLS TO OBTAIN STAKEHOLDER INPUT

THE PUGH METHOD

Stuart Pugh, University of Strathclyde, is the author of two books discussing the problems of engineering design (Pugh, 1990, 1996). The second book (Pugh, 1996) is largely a compendium of his many papers.

Pugh (1990) developed the product development process and a set of discipline-independent methodologies to carry out the process, such as customer surveys, the product design specification document, and the method of controlled convergence. In the Pugh method a decision matrix is prepared with columns to identify design concepts (variant) and the rows to represent criteria. A design team chooses both concepts and criteria. One of the column concepts is chosen as a datum against which all others are to be judged. In the matrix cells for each row criteria a plus (+), zero (0), or minus (–) sign is then used to indicate whether the concept is better, equivalent, or less than that of the datum. For each concept the number of plus and minus signs is noted and the best concept is selected. Omitted concepts with unique plus cells are especially studied to provide insight. New concepts (variants or designs) are now formed, criteria modified and added, a new datum selected, and the process repeated. The process requires continuous elaboration until the datum column becomes uniquely best. This variant initiates the final detailed design process.

Pugh argues against ranking or weighting of either concepts or criteria beyond the simple plus (+), zero (0), and minus (–). In defense of his matrix approach to engineering design Pugh states, "The matrix does not make the decisions: it is simply a procedure for controlled convergence onto the best possible concept and is not composed for absolutes in the mathematical sense; the decisions remain with the user" (Pugh, 1990). The authors agree with the method's creator that his method should not be used to make decisions.

QUALITY FUNCTION DEPLOYMENT

Quality Function Deployment (QFD) has its origins in Japan in the late 1960s, during an era when Japanese industries broke from their post-World War II mode of product development through imitation and moved on to product development based on originality (Akao, 1997). It provides a synthesis of the concepts and tools required to translate customer aspirations into the final technical and manufacturing activities needed to produce a quality product. QFD is a matrix management tool meant to translate the factor termed the "voice of the customer" into items that can be measured, assessed, and improved. It is particularly useful in finding gaps in a developing program and offering opportunities for new ideas to enter a design activity.

Don Clausing of the Massachusetts Institute of Technology is largely responsible for the introduction of QFD methodology to U.S. industry in the early 1980s. The blending of the ideas of QFD with those of Pugh's Total Design theory is often called EQFD (Enhanced QFD) (Clausing and Pugh, 1991).

Quality Function Deployment is used to identify critical customer attributes and to create a specific link between customer attributes and design parameters. Matrices are used to organize information to help marketers and design engineers visualize and answer three primary questions:

- What attributes are critical to our customers?
- What design parameters are important in meeting those customer attributes?
- What should the design parameter targets be for the new design?

QFD constructs, in a fashion similar to Pugh, an evaluation matrix at each stage of product development both to display relevant states of knowledge and to provide a mechanism for decisions. This matrix correlates the identified customer needs called "the whats" (rows) to the engineering specifications called "the hows" (columns). Ideally, a cross-functional team made up of members from the core functions in product development should develop the matrix. The matrix rows are usually descriptive verbalizations of the customer's wants. The matrix columns are more likely to be quantitative measures of engineering requirements. The engineering measures are frequently correlated, or represent incompatible desiderata, and an additional triangular array is often placed atop the matrix displaying these associations. The schema, often called the "House of Quality," is illustrated in Figure 4-1.

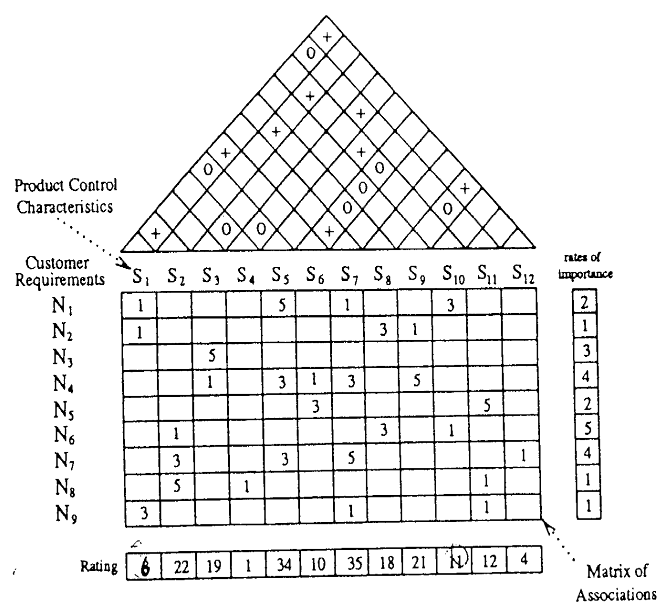

Figure 4-1 The House of Quality. Source: Carriere and Finster (1989).

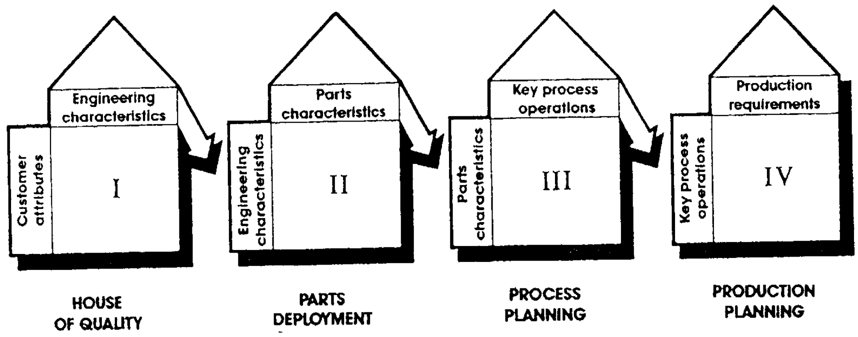

Figure 4-2 A cascade of evaluation matrices. Procedure adapted from Hauser and Clausing (1988).

The first step in building a House of Quality is to construct an evaluation matrix indicating how each engineering specification affects each customer need. Many cells of the matrix may be empty (blank), while others will contain a score testifying to the importance of the row-column association. Information on technical difficulties and cost can also be displayed. An additional step is to construct the "roof" for the house, a triangular matrix displaying relationships among engineering specifications. For instance, specifications for take-off weight for a commercial aircraft will strongly affect the required take-off distance. The roof of the House of Quality also provides a good indicator of design trade-offs to consider in the future. Additional information matrices may be attached to the "house." For example, information on customer perceptions of competing products and competitive benchmark data can provide "wings" and "cellars."

The essential motivation for constructing a House of Quality schema is to provide a viewer, new or old to the design problem, a quick and thorough appraisal of its scope. It is an aid to the decision-making process.

The House of Quality can be used as a stand-alone tool to generate answers to a particular development problem. Alternatively, it can be applied in a more complex system in which a series of decision tools are used. The procedure is illustrated in Figure 4-2.

The use of evaluation matrices is only a part of a larger philosophy implied by QFD. QFD also emphasizes the importance of teamwork by diverse experts. Moreover, customers are not viewed solely as those who will use the final product but also as those at the receiving end of each stage of the creation of the final product.

DECISION MATRIX TECHNIQUES

Decision matrix techniques are used to define attributes, weight them, and appropriately sum the weighted attributes to give a relative ranking among designs. An example of the framework for such a process is shown in Figure 4-3.

The advantages of this method are as follows:

- The method encourages team interaction (causes the design team to consider attributes of a variety of potential solutions and their relative importance and thus a good way to help calibrate the team).
- Analysis can be performed relatively quickly.
- The method can identify non-viable design variant options and remove them from further consideration.

Disadvantages of this method are the following:

- Criteria may have interdependencies.
- Risk must be overtly addressed as an additional criterion.
- Subjective weighting often reflects the design team's opinion rather than the customer's view.
- It is not a stand-alone decision tool.
- Sometimes it is used merely to rationalize decisions.

The decision matrix is prepared using technical or economic criteria (or both). When all row criteria are not be considered equally important they are weighted individually. For every column concept (variant) each criterion is assigned a value, typically on a scale of 1 to 10. The final weighted value for all matrix cells is found by multiplying the criteria weights by their corresponding design variant value. The sums of both the values and the weighted values are then found for each concept variant.

The "Weighted Sum of Attributes" decision matrix shown in Figure 4-4 is an example typical of frequently encountered design decisions in which a variety of concepts are viable but vary considerably in their ability to meet conflicting requirements. In the example, for instance, all the concepts will provide attachment, but only one has loose parts. To help reach a decision, as only one concept will be used, the decision matrix shown in Figure 4-4 was prepared. As is often the case with this tool, (1) the weighted sums are not highly differentiated; (2) the weighting changes the decision relative to the unweighted sums, thus demonstrating the need for careful selection of the weights; and (3) the values often have to be normalized to prevent the dominance of one key requirement due to its high values. In the current example, if the parts count were in the hundreds of parts, its value would dwarf other considerations, unless of course, it was assigned a very low weight.

This example does not indicate a clear winner, merely that one choice (Quick-Nuts) can be eliminated, provided the weightings and assigned values are reasonable. The matrix evaluation nevertheless can still be a useful tool. Further consideration of the weightings and playing "what if" will at least allow the decision maker to understand which requirements have been emphasized in the selection of a concept and which requirements may need careful attention in detail design.

		Concept Variants					
		Concept 1		**Concept 2**		**Concept 3**	
Criteria	**Weights**	**Value**	**WV**	**Value**	**WV**	**Value**	**WV**
Criterion 1							
Criterion 2							
Criterion 3							
Criterion 4							
…							
Sum:							
Weighted Sum:							

Figure 4-3 General format of the decision matrix.

		Concept Variants					
Key Requirements		Cam-Lock		Screws		Quick-Nuts	
Weighting Factors		Value	Weighted Value	Value	Weighted Value	Value	Weighted Value
2	Part count #	5	10	12	24	12	24
10	Loose parts #	0	0	12	120	12	120
8	Weight in lbs	10	80	1	8	2	16
10	Reliability MBTF	10	100	1	10	10	100
7	Assembly time, min	5	35	10	70	7	49
	Sum	30		36		43	
	Weighted Sum		225		232		309
	Recommendation					Eliminate option	

Note: Lower scores indicate superior choices. MTBF is mean time between failures.

Figure 4-4 Decision matrix for access door attachment.

As part of playing "what if," sensitivity studies can also be conducted by perturbing the values with varying ranges or probability distribution functions. The "Weighted Sum of Attributes" decision matrix is an important decision tool, but its limitations need to be well understood by the decision maker.

ANALYTIC HIERARCHY PROCESS

The Analytic Hierarchy Process (AHP) is a methodology for multi-criteria analysis and decision making developed by Thomas L. Saaty (1980, 1987). It can help decision makers to:

- examine a complex problem with a number of possible solutions,
- evaluate and prioritize alternatives, and
- organize the information and judgments used in decision making.

The analytic hierarchy process allows the relative independent judgments made by people to be used in a more formalized decision making process. The basic idea assumes it is much easier for a person to say a car is much bigger than a motorcycle than it is to say how many times it is larger, or even exactly what is meant by "larger." It is similar in approach to the Pugh method of employing plus (+), zero (0), and minus (–) judgments. The word "hierarchy" in the name reflects the notion that these judgments may be made at several levels and then combined to provide an overall evaluation. While proponents of the process claim it has many uses even beyond decision making, the focus of this discussion is on its use as a decision aid.

At each level of the hierarchy the process proceeds by having the user establish rough pair-wise comparisons between attributes by using such comparatives as "more important" and "much more important." These pair-wise comparisons, often redundant, are used to produce a relative weighting of the various attributes. This process is repeated at the next level in a manner demonstrated by example to provide an overall evaluation.

A general form of a hierarchical model of a decision problem is a pyramid with a broad overall objective at the highest level. Lower levels list the criteria and respective subcriteria used to choose among alternatives. At the lowest level are the alternatives to be evaluated.

Consider the example of selecting an automobile to purchase. Presume the attributes of interest are comfort, performance, and safety. At the highest level of the hierarchy the user would be asked to judge, for example, whether comfort is more important than performance, equivalent to performance, or less important than performance. Then a similar set of comparisons would be made between performance and safety, and finally, another set of comparisons between comfort and safety. These would be manipulated to provide the relative weights, usually in the form of percentages, to be assigned to comfort, performance, and safety in purchasing the car.

The next step is to address which car best meets the criteria. Suppose three cars are under consideration: A, B, and C. The user would be asked to compare car A with car B with respect to comfort; then A to C with respect to comfort; and finally B to C with respect to comfort. After the averaging process, these comparisons would result in the relative percentage weightings of the three cars with respect to comfort. The same judgments would then be made with respect to performance. Is A much better than B with respect to performance, equivalent to B in performance, etc. Then A would be compared to C, and B would be compared to C with respect to the same performance attribute. After the averaging process, the relative weights of the three cars would be obtained with respect to performance. Finally, the same procedure would be carried out for safety. Now it can be said for car A what percentage of the values for comfort, performance, and safety it should receive; and the same computation can be done for cars B and C. For each car, multiplying the car's percentage of each value attribute by the percentage the value represents with respect to a desirable car and summing overall attributes will provide for each car the percentage of overall value attributable to it. In one case, car A could have 55 percent of total value, car B could have 30 percent of total value, and car C could have 15 percent of total value. Proponents of the process would say this is an argument for purchasing car A.

The procedure, as can be seen, is very easy to perform because it uses only simple judgments. The problem is determining the strength of the recommendation of car A because it is highest on this scale. Additional difficulties occur when a large number of alternatives require paired comparisons, because k alternatives require $k(k-1)/2$ pairs. Moreover, care should be taken to ensure that some of the paired comparisons do not contradict each other.

The axiomatic structure of this process does not guarantee the alternative with the highest rating will be the most preferred alternative. Unfortunately, it can be shown that the addition of a new alternative may change the ranking of existing alternatives, a property seen as undesirable in a decision process. The analytic hierarchy process has difficulty with uncertainty, which it can handle only in an approximate way. The process therefore provides no basis for valuing the elimination or reduction of uncertainty.

The main advantage of the analytic hierarchy process is ease of understanding and application. It may have real value in making decisions with robust influence factors, where there is no possibility of a major loss and where the complete set of alternatives is known a priori.

The difficulty with the analytic hierarchy process, in addition to the theoretical features mentioned above, is that it cannot answer the questions necessary to build confidence in the selection of an alternative. The very simplicity of the process limits its ability to answer hard questions.

METHODS AND TOOLS TO ADDRESS VARIABILITY, QUALITY, AND UNCERTAINTY

Once the decisions have been made and product design concept finalized, the next steps are to translate the concept to reality. This section deals with decision-making tools, which are methods to address the quality of the design process, to address the variability in the process, and to convert the concept to final product. The general process of making decisions is greatly affected by the context (see Figure 2-1) in which the decisions are made. Design decision making in the context of variation can be conceptualized as shown in Figure 4-5.

The context of variation in Figure 4-5, similarly to Figure 2-1, has been segmented by the categories of input, output, controllable design parameters, and uncontrollable (noise) parameters. In Figure 4-5, the context is related to variation; therefore, the above four categories provide a context for decisions in which the variation needs to be considered in decision making.

While there may be variation in the input requirements, the primary variation to be considered is in the design, environmental, and manufacturing parameters. An example of variation in a design parameter is the seal clearance in a shaft. Examples of variation in environmental and manufacturing parameters are ranges in the line voltage a product will see in use or differences in the ability of machines to meld tolerances. As a result of such variations, the performance of individual product units will vary with respect to the design target. If the output variation is too great or the mean is not appropriately centered near the design target, then some of the units will not perform acceptably. The decision process must adequately consider variation in design, manufacturing, and environmental parameters to ensure products delivered to the user will perform within specified limits of design intent.

The consideration given to variation in the design process differs depending on whether the variation is in a design-controlled parameter or in manufacturing- and environmental-uncontrolled parameters. In the context of design decision making for products, the design parameters in Figure 4-5 are controllable whereas the environmental and manufacturing parameters are for the most part uncontrollable or at least contain an element of random variation (noise). The strategy in the design decision process for controllable design parameters is to use analysis, including statistical tools such as "Design of Experiments," to select values (settings) for these parameters such that the product performance is within acceptable limits. The noise variation of environmental and manufacturing parameters cannot be changed or controlled by selection of parameter values as can be done with design parameters. The variation in environmental and manufacturing parameters either is known or can be measured and included in sensitivity analysis of design parameters. Experience has shown that inclusion of environmental and manufacturing noise variation in design decisions is crucial for products to consistently meet the design intent.

In summary, design decision making in the context of variation can significantly contribute to the success of a product from the standpoint of customer satisfaction (market share) and economic viability (profit to business). Employing "Design of Experiments" or similar methods enables one to rapidly quantify product performance and economic viability across a broad design space. Including variability or noise parameters in the design and decision process, as illustrated in Figure 4-5, enables the designer to quantify the sensitivity of the product to variation and determine the probability of success for achieving objectives relative to design limits. Additionally, for those controllable noise variables, product performance and cost trade-offs can be quantified in terms of design intent and probability of success. In total then, the process conceptualized in Figure 4-5 enables design decision making based not only on deterministic assessment but also on the inherent, real-world characteristics of product design.

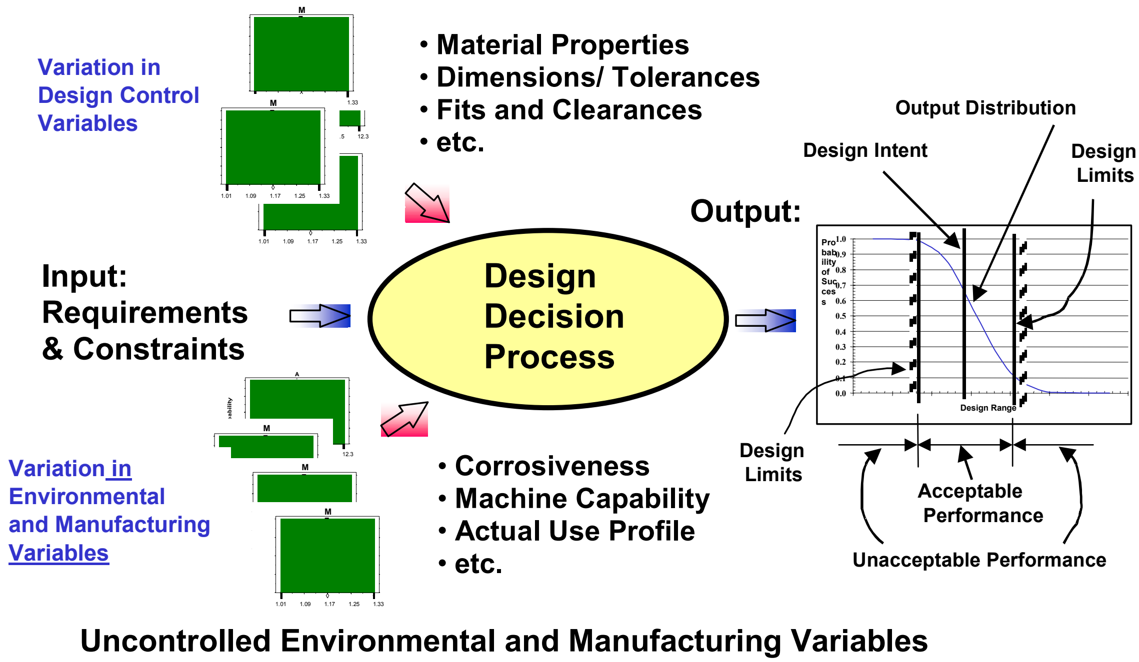

Figure 4-5 Decision making in the context of variation.

PROJECTED LATENT STRUCTURE

Also called Partial Least Squares or PLS, Projected Latent Structure is a method for constructing predictive models when controllable variables are many and highly redundant. The emphasis is on predicting the responses and not necessarily on trying to understand the underlying relationships among the variables. PLS is not usually appropriate for screening out factors with a negligible effect on the response. However, when prediction is the goal ant ehre is no practical need to limit the number of measured factors, PLS can be a useful tool (Tobias, 1995). The original mathematics of PLS is the work of Herman Wold (Wold, 1985). Svante Wold and B. Kowalski (Wold, 1978; Beebe and Kowalski, 1987) are given credit for establishing the field of "chemometrics," based largely upon PLS methodology. In chemometrics the X factors (controllable variables) may include the many spectroscopic measures taken on samples drawn from a chemical process, along with associated measures of temperatures, pressures, concentrations, and flow rates. The Y responses (the behavior of other variables) in turn may represent the mass, volume, viscosity, density, flow rates, and other quality measures on intermediates and final products, once again gathered across many samples. The objective of PLS is to analyze the data sets X and Y in the hope of discovering one or more signs of structure (low dimensional linear relations) while recognizing X and Y may both have structural aspects unrelated to one another. The idea of PLS is to extract latent factors, accounting for as much variation as possible while modeling the response well. PLS has been successfully applied in the chemical process industries. The opportunity to explore applications of PLS to the design and assembly of hardware appears unexploited to date.

TAGUCHI METHOD

In Japan in the early 1960s, Genichi Taguchi began an introduction of statistical patterns of experiments (the fractional factorial, orthogonal arrays, and response surface "experimental design") as aides in the design and manufacture of products (Taguchi, 1988). Several concepts were involved.

- Quality should be measured by the deviation from a specified target value, rather than by conformance to preset tolerance limits.
- A defined loss function should be established to provide a financial measure of customer dissatisfaction with a product's performance as it deviates from a target value.
- Process parameters are not constants and their intrinsic variability will be reflected in the variability of the product.
- The product user's environment adds further variability challenges to quality performance.
- Engineering design must provide a robust product that is on target and simultaneously insensitive to variability arising from both the process and the environment.

Taguchi argues for the application of statistical methods throughout the entire engineering design process, from product concept to customer usage. He was among the first to emphasize the importance of statistical planning and analysis of experiments to identify and measure sources of variability and sensitivity to assist in resolving the problems of design engineering. Of particular note is Taguchi's development of parameter design wherein non-linearity in response is used to decrease the sensitivity of that design to a given level of noise variability in manufacturing and use. Taguchi's great contribution to the practice of engineering design is his emphasis on the need to study the sensitivity of product responses to variability in both manufacturing and environmental factors (Ross, 1996).

SIX SIGMA

In statistics the Greek letter sigma is used to identify the standard deviation, as a measure of the variability of measurements. When measurements are reasonably approximated by a normal distribution located on target, then the interval of target plus or minus two sigma will contain approximately 95 percent of all the measurements. If this interval also defines product specifications, then 5 percent of the product will be defective. When the specification limits are set at target plus or minus six sigma, this results in only 3.4 defects per million outputs. However, the terminology "six sigma" has come to mean far more than a simple counting of defects. It now identifies an entire quality culture of strategies, statistics, and tools for improving a company's bottom line (Pyzdek, 2001).

The Six Sigma concept was introduced by Mikel Harry at Motorola in the 1980s. Many other corporate giants, including Texas Instruments and General Electric, have adopted it since then. The tools utilized in Six Sigma include problem statement development, brainstorming, histograms, fish-bone diagrams, process mapping, measurement-systems analysis, graphical analysis, capability analysis, hypothesis testing, regression analysis, analysis of variance, supplychain management, design of experiments, statistical process control, and failure-mode-effects analysis.

METHODS AND TOOLS FOR GENERATING ALTERNATIVES

Generating alternatives to meet the requirements of a product is an inherent part of the design process. In the simplest form a single designer can consult design guides for past practices and select a reasonable option. More creative designers could examine other fields to adopt new ideas or imagine a novel solution to the problem.

Group practice, in its simplest form, includes brainstorming to generate design alternatives. Newer tools draw on a range of computational capability to enhance the generation of options. Generally, the techniques can identify alternatives by employing a very large set of data using several methods or tools, possibly including artificial intelligence. A few of these techniques are summarized here.

DESIGN INFORMATION SYSTEMS, SUPPORT SYSTEMS, AND ENVIRONMENTS

Design decision making involves more than methods and tools for addressing decision events. Decisions usually occur in information-rich environments involving a range of stakeholders and disciplines. A wide variety of efforts have been developed aimed at supporting designers to make decisions in such rich contexts.

These efforts usually are pursued under the rubric of decision support, often involving many of the methods and tools discussed elsewhere in this report, but also frequently involving various levels of artificial intelligence. Gero and Sudweeks (1996, 1998), in two recent proceedings of the biennial International Conference on Artificial Intelligence in Design, provide a broad view of the many efforts in this area, which include design processes (decision-driven process models, cognitive theories of design decision making), knowledge management (representation, acquisition, sharing), decision support (reasoning, structure generation, form generation, component selection, optimization), and design support (interactive tools, collaboration support).

Figure 4-6 indicates the scope of this field, gleaned from an analysis of the papers included in these volumes. Traditionally, the focus has been on detailed design and automated decision making. However, current research is moving toward conceptual design and problem formulation, with necessary emphasis on decision support and, consequently, provision of information and knowledge needed for making design decisions. Gero and Sudweeks assert, "Computer-aided decision making will produce better designs."

Numerous efforts have been undertaken to integrate much of the above into design environments. The long series of studies by Cody, Rouse, and Boff (1995) is a good example of work in this area. Analyses of the results of studying hundreds of designers yielded the requirements for the architecture of an interactive design environment, supported by an artificially intelligent Designer's Associate.

Evaluation of a series of prototypes led to an important insight. Specifically, the cost of developing and maintaining the knowledge bases associated with what the Designer's Associates envisioned would be prohibitive. Simply, there would be too much data and information to compile and maintain. This led to the recommendation to develop more focused support systems where the embedded knowledge required would be far less comprehensive.

One direct result of this conclusion is the Product Planning Advisor (<http://www.ess-advisors.com/Products/Software/software.htm>), which supports design teams in formulating and evaluating alternative functions/features of product concepts relative to market models, as well as both current and likely competitive offerings. This much more focused design support tool combines intelligent support with multi-stakeholder, multi-attribute market models and quality function deployment representations of relationships among product functions/features and stakeholders' attributes. The Product Planning Advisor has been employed in hundreds of product planning efforts, many involving top high-technology companies.

Artificial intelligence (AI) developers have, at various stages in its history, promised comprehensive automated decision making. AI as a category includes such approaches as neural networks, expert systems, genetic algorithms, intelligent agents, and fuzzy logic. More realistically, however, for all but routine design decisions, AI can best provide powerful knowledge-based support of design decision making, rather than automated decision making. It does this in part by building on an understanding of human decision making in design contexts and tailoring support to enhance human abilities (e.g., pattern recognition) and overcome human limitations (e.g., errors). Thus, AI is not used to automate human decision making; rather the theory determines how AI can best assist decision making. Some recent attempts to exploit AI for the purpose of generating new design alternatives show promise.

TRIZ

TRIZ, a Russian acronym that translates to Theory of Inventive Problem Solving, describes a process to encourage creativity. The theory is based on the presumption that a conflict between two objectives creates a need for creativity. For example, the design has to be light and strong. The developer of the process reviewed hundreds of thousands of patents to see what ideas were used to reconcile these conflicting objectives. He developed a matrix that showed, for the intersection of conflicting objectives, alternatives used in existing patents. Some of the intersections are relatively sparse; others have several suggestions. The intent is that one of the suggestions might spark the creativity of the person facing the design problem. TRIZ was created by Genrich S. Altshuller in Russia (Altshuller, 1988). He and his coworkers analyzed about 1.5 million patents and worked out a methodology to resolve the technological problems.

The salient TRIZ principles are as follows:

- All engineering systems have uniform evolution in the direction of increased ideality. Many others (such as economic and educational systems) have the same evolutionary trends.
- Any innovative problem represents a conflict between new requirements and an old system.

TRIZ is composed of various systematic techniques including inventive principles; psychological inertia overpass system; physical, chemical, and geometric effects; substrate-field

Support/Focus	Detailed Design	Conceptual Design	Problem Formulation
Information/Knowledge			
Decision Support			
Decision Making			

Figure 4-6 Scope of artificial intelligence in design.

and functional analysis; technological ideality concept; and technology forecasting. It helps find a quasi-ideal solution to innovative problems through the resolution of hidden conflict based on inferred knowledge of system evolution.

TRIZ is more than a methodology. It represents a unique way to enhance creativity by getting individuals to think far beyond their own experience, to reach across other disciplines, and to resolve problems using knowledge extracted from other areas of business, science, or technology.

FORMAL METHODS FOR REPRESENTING DESIGN PROBLEMS

This section covers some limited formal methods and theories for representing design problems. They are selected as representatives from different schools of thought in approaching design problems: traditional engineering, decision theory, and artificial intelligence.

ENGINEERING DESIGN: A SYNTHESIS OF VIEWS

Dym (1994) attempts to articulate what is meant by engineering design, how it can be discussed both for designed artifacts and for the process of design, and what areas are amenable to, and perhaps most require, formal research approaches. The central thesis elevates representation as the key element in design. In addition, recent research in AI aimed at rendering design computable is purported to provide new techniques for design representation to enable improved understanding of design concepts and processes.

Design activities encompass a spectrum from routine design of familiar parts and devices, through variant design requiring some modification in form or function, to truly creative design of new artifacts. The spectrum of design concerns includes some processes susceptible to thoughtful analysis—in other words, cognitive processes. One principal consequence of this recognition is the need to focus on the languages of engineering design. On the other hand, creative designs are almost certainly not susceptible to encapsulation with current representation technologies and, therefore, cannot be modeled.

For the last half of the twentieth century mathematics was the language of engineering, owing in part to the central role of mathematics in physical sciences modeling. Engineers understand that much of what they really know cannot be expressed in mathematics alone. Engineers use graphics and pictures, as well as words, although often in a very structured way (e.g., in specifications and codes, in heuristics or rules of thumb). Designers and modelers of cognitive design processes understand that many languages of design have been devised and used.

Design knowledge includes information about such features as design procedures and shortcuts, as well as about designed artifacts and objects and their attributes. Designers think about design processes when they begin to create sketches and drawings to represent the objects they are designing. A complete representation of designed objects and their attributes requires a complete representation of design concepts that may be less easy to describe or represent than physical objects (e.g., design intentions, plans, behavior).

The languages or representations used in design include:

- verbal or textual statements to articulate design projects, describe objects, describe constraints or limits, communicate between different members of design and manufacturing teams, and document completed designs;
- graphical representations to provide pictorial descriptions of designed artifacts such as sketches, renderings, and engineering drawings;

- mathematical or analytical models to express some aspect of an artifact's function or behavior, which is in turn often derived from some physical principle(s) that can be expressed mathematically;
- numbers to represent discrete-valued design information (e.g., part dimensions); and
- continuously varied parameters in design calculations or within algorithms representing a mathematical model.

Different languages are used to represent engineering and design knowledge at different times, and the same knowledge is often cast in different languages in order to serve different purposes. For example, fundamental structural-mechanics knowledge can be expressed analytically, as in formulas for the vibration frequencies of structural columns; numerically, as in discrete minimum values of structural dimensions or in finite element meshing algorithms for calculating stresses and displacements; and in terms of heuristics or rules of thumb, as in the knowledge that the first-order earthquake response of a tall, slender building can be modeled as a cantilever beam whose foundation is excited. Therefore, designers must realize that what they need to know is not just a set of formulas; they must know how to apply knowledge in different forms to serve different purposes. This means designers must master the languages of engineering design.

SUH'S AXIOMATIC DESIGN

This theory (Suh, 1990) describes design as a mapping between what designers want to achieve and how they achieve it. The framework of axiomatic design views design as a collection of mappings between four domains: the customer domain, the functional domain, the physical domain, and the process domain. In each domain the design is specified using different elements: customer attributes (CAs), functional requirements (FRs), design parameters (DPs), and process variables (PVs). In addition there are constraints (Cs). The design process starts with the identification of customer needs and attributes, and formulates them as FRs and constraints. These FRs are then mapped onto the physical domain by conceiving a design embodiment and identifying the DPs. There may be more than one solution to this mapping. Each DP is then mapped onto a set of PVs to define it. Each DP typically introduces new FRs, DPs, and PVs, and so the mapping process iterates by zigzagging between domains, until the design can be implemented without further composition. In principle this approach takes a broad view of design, but the axioms and methods are almost entirely about mapping from the functional to the physical domain, so they do not address all aspects of design. The principles of this theory potentially apply to a variety of design problems, including mechanisms, software, and organizations.

Based on Nam Suh's experience and observations about existing designs and his assessment of successful and unsuccessful designs, he proposes two axioms:

- **Axiom 1, the Independence Axiom**: Maintain the independence of functional requirements. This means that when two or more functional requirements exist, the design solution must be such that each one of the FRs can be satisfied without affecting the other FRs. That in turn means a designer must create a design (or design parameters) able to satisfy each FR independently of the other FRs. Thus, this first axiom establishes a requirement about the design to guide the creative process and any decisions among alternatives.
- **Axiom 2, the Information Axiom**: Minimize the information content. Suh defines information as the logarithm of inverse probability of meeting the

> functional requirement. Among designs satisfying Axiom 1, Suh's axiomatic design approach states that the best design is the one with the minimum information or maximum probability of meeting the functional requirements, considering tolerances and nominal requirements.

In addition to these two axioms (and numerous associated theories and corollaries), Suh through case studies and examples essentially outlines a design methodology consistent with his axioms. The methodology involves techniques for zigzagging between functional requirements and design parameters and the use of matrix algebra to assess independence. The theoretical framework has some appeal to experienced designers who recognize that achieving conflicting functional requirements with one design parameter (independence axiom violation) is the source of some badly compromised designs and that the information content embedded in the functional requirements might be a valid assessment of such complexity. Suh's axiomatic approach represents a substantial and potentially useful addition to design methods, but the technique has not shown significant practical application, as is discussed below. Moreover, the theoretical basis has some apparent limitations. It is not clear that Suh's assertion is correct that an ideal design always has an equal number of functional requirements and design parameters.

On the one hand, although we can agree that independence is desirable, design constraints such as manufacturability, low cost, and ease of use may at times conflict with independence or for objective reasons override independence. The best design, therefore, may have more functional requirements than design parameters. On the other hand, there are cases where decreased sensitivity to variations in use or manufacturing may be particularly important and can be improved by having more design parameters than functional requirements. Thus the independence axiom can result in a useful assessment tool but is not a requirement for all good designs. Further development of the information definition may also be needed to best meet customer needs rather than simply meeting the given tolerances.

In summary, the axioms while useful do not appear to constitute a complete and optimal design method. This could be why the best practical applications to date use axiomatic design in combination with other design methods. One can use the independence axiom in combination with robust Taguchi methods to examine which design parameters to use in achieving a robust design. One could also use axiomatic principles to assess concepts created by TRIZ methodology (Mann, 1999).

YOSHIKAWA'S GENERAL DESIGN THEORY

Yoshikawa and his associates began in the late 1970s to publish papers on a general theory of design. This work attempts to address design in a rather complete fashion by defining design as "creating artificial things [that] have not existed in the real world previously." Some of these papers have focused on how the approach might be applied to extending computer-aided design (CAD) systems to include engineering and simulation information. Although a formal mathematical basis is sketched, this approach remains largely philosophical with some interesting general observations about the nature of design. This approach has resulted in no new design methods or engineering design tools, nor (as yet) has it seemed to directly add new tools to the intelligent CAD area.

A MATHEMATICAL FRAMEWORK FOR ENGINEERING DESIGN

The decision-based design view of engineering design states that much of design consists of decision-making activities, and that decision support methods used in engineering design should reliably produce good advice. This is a non-trivial condition that demands that design methods adhere to the mathematics of decision theory. Only in this way can paradoxical results, in which a design method might recommend even the worst design alternative, be prevented. Rigorous decision theory has developed over the last 300 years and has its roots in the work of many mathematicians and economists, including Daniel Bernoulli, Charles Lutwidge Dodgson (Lewis Carroll), John von Neumann, Oskar Morgenstern, and Kenneth Arrow. Hazelrigg (1998, 1999) uses the results of these mathematicians and economists to lay out a decision theory-based framework for engineering design, thereby extending the earlier work of such people as Myron Tribus (1969), Richard de Neufville (1990), and Andrew Sage (1977).

The purpose of Hazelrigg's framework is to provide a self-consistent method for rank ordering alternatives in the context of engineering design. The framework recognizes some key aspects of design, in the context of decision theory, that other methods fail to consider: (1) that all design decisions are made under conditions of significant uncertainty and risk; (2) that the preferences of key importance in a decision are those of the decision maker (not those of the customers or stakeholders); and (3) that alternatives must be ranked on a valid and validated real scalar measure. Thus, Hazelrigg uses the preference of the company CEO or other decision authority as the basis for a valid scalar measure (typically net present value of cash flow generated by a design), together with von Neumann-Morgenstern utility theory to assure validity of the measure under uncertainty and risk.

Hazelrigg adds two axioms to those of von Neumann and Morgenstern, although the first can be derived from the von Neumann-Morgenstern axioms and is presented only for convenience. The two additional axioms are as follows:

- **Axiom 1, the Axiom of Deterministic Decision Making:** Given a defined set of alternatives from which to choose, each with a known and deterministic outcome, the decision maker's preferred choice is the alternative whose outcome is most preferred.
- **Axiom 8, the Axiom of Reality in Engineering Design:** All engineering designs are selected from among the set of explicitly considered potential designs.

The von Neumann-Morgenstern axioms provide a basis for comparison of known alternatives. They do not provide a basis for comparison of a known alternative with an unknown alternative, and some engineers thus argued that Hazelrigg's framework is not valid. The addition of Axiom 8, which states that any chosen engineering design is a known option included in the set of options under consideration for selection (this should be intuitively obvious, as we do not produce products we never imagined), assures that the von Neumann-Morgenstern results apply to engineering design.

The von Neumann-Morgenstern axioms provide two results of consequence:

- **The Expected Utility Theorem.** Given a pair of alternatives, each with a range of possible outcomes and associated probabilities of occurrence, the preferred choice is the alternative with the highest expected utility.
- **The Substitution Theorem.** A decision maker is indifferent between a lottery and a certainty outcome whose utility is equal to the expected utility of the lottery, and for purposes of analysis, the two may be substituted one for the other.

Early applications of these ideas to engineering design include Greenberg and Hazelrigg (1974). Recent applications of utility theory exist, for example, Thurston et al. (1994); and many other recent papers apply decision theory to engineering design, but they largely fail to consider uncertainty and the decision maker's attitudes toward risk. Marston and Mistree (1997) use the von Neumann and Morgenstern axioms, but advocate additional areas (such as subjectivity in options and in designer preferences) to be included in design theory. A recent paper by Thurston (2001) assesses the appropriateness and usefulness of decision-based design. Of course, the desirability of a design to customers, as expressed in willingness to pay, is an important consideration in formulating an objective function—usually profits for the designer's company.

The Nobel laureate Kenneth Arrow in 1951 provided results of extreme importance to engineering design. Arrow states six conditions that should be satisfied by a selection method, such as the following: If, under all conditions and by every measure, alternative A is preferred to alternative B, then the selection method should not choose B over A. He goes on to prove that, in the case of three or more alternatives and three or more selection criteria (voters, for example), no selection method can be assured of giving a valid result. Arrow's Impossibility Theorem points to the dangers of naive multi-criteria decision methods that comprise many engineering design selection methods. Based on Arrow's result, Haunsperger and Saari (1991) have provided numerous paradoxical examples illustrating how naive decision support methods fail.

An early application of these ideas to engineering design can be found in Dyer and Miles (1976). Recent work by Allen (2001) points out, in the context of the von Neumann and Morgenstern setting for decision making under uncertainty, that a weakening of Arrow's axioms permits a possibility result for group decisions with risk aversion. Scott and Antonsson (1999) argue that despite the common participation of many individuals in the design process, engineering design is closer to multiple criteria decision making than to social choice theory, so Arrow's theorem need not apply.

DECISION MAKING IN MANAGEMENT SCIENCE AND ECONOMIC FIELDS

The fields of management science, game theory, and economics commonly use decision-making techniques, and some of these may have application to engineering design. In fact, many opportunities exist for cross-application of decision-making tools among unrelated fields. Operations research has developed numerical methods useful in computational economics and game theory. Constrained optimization packages for linear programming, integer programming, and non-linear programming are well known. Fixed-point algorithms can be used to find equilibria in economies and games.

DECISION MAKING IN ECONOMICS

The academic discipline of economics lies behind the business side of engineering design and technology management. Using economics terminology, engineering design consists of product selection and technology choice. Economists use techniques from constrained optimization, decision theory, game theory, and microeconomics (the study of resource allocation) in general to solve such problems. The methodology used in economics also typically differs somewhat from that used in engineering.

Economics tends to focus on the development of an overriding general framework for analysis of a wide variety of applied problems and policy issues. Such a framework involves the elucidation of a fully consistent general model from fundamental principles, starting with constrained optimization. A goal is to rigorously examine the implications of appropriate assumptions. Numerical work should be preceded by a precise statement of the equilibrium concept or constrained optimization problem (i.e., the objective function and feasible set) and by a careful examination of the conditions under which the model has a solution. Note the term "model" refers to the general and rigorous framework. The model includes the abstract exogenous information, assumptions, and definitions.

The basic product selection problem can be cast as a constrained optimization problem along the following lines. Once a firm has made its product selection decision, the firm's profits (revenues minus costs, where revenues depend on demand) depend on its costs, the price at which the product is sold, and the number of units of the product produced and sold. Of course, profits also depend on the selection of products manufactured and sold by all other firms and their respective prices. Given the products of all other firms and their prices, one could construct the profit function for each feasible product choice and find its maximum value, subject to price and quantity being consistent with market demand. Then one could pick the product for which maximum profits are greatest. (This assumes other firms do not strategically alter their decisions in response to the product choice of the firm in question.) This extension can be analyzed with game theory. Engineering considerations enter through the feasibility constraints faced by firms and through their cost functions (which depend on the production technology, the quantity manufactured, and input prices) for each possible product. The basic question reduces to a (highly non-trivial) constrained optimization problem. (The case of a multi-product firm is more difficult to analyze, but the same principles can be applied.)

Decision making in economics, whether for consumers or firms, is based on constrained optimization; however, the objective functions and constraints faced by consumers are different from those for firms.

The consumer's decision problem starts from preferences—essentially, data in the form of a yes or no answer to the question of whether some combination of items to be consumed is at least as good as some other combination of items. Standard rationality assumptions on preferences are well known and give rise to utilities. The following axioms are typically used to study individual choice behavior in economics:

- Symmetry: X is at least as good as X.
- Consistency (transitivity): If X is at least as good as Y and Y is at least as good as Z, then X is at least as good as Z.
- Decisiveness (completeness): Either X is at least as good as Y or Y is at least as good as X (or both).
- No drastic changes (continuity): If X is strictly better than Y, then X^1 is strictly preferred to Y^1 whether X^1 is sufficiently close to X and Y^1 is sufficiently close to Y.
- More is better (monotoricity): If X is greater than Y, then X is as least as good as Y.

Frequently an additional axiom stating that variety is strictly desirable (strict convexity) is added in order to guarantee that optimal choices are unique. Utility functions summarize the preference relation such that the utility associated with one combination exceeds the utility of another combination if and only if the first combination is strictly better according to the consumer's preference. The consumer's constraints reflect affordability (given all prices and income) and survivability (minimum quantities of food, shelter, and the like may be required).

If uncertainty is involved, preferences over lotteries (randomizations over combinations of items to be consumed) are the appropriate fundamental concept. Rationality axioms lead to cardinal utility representation (see von Neumann and Morgenstern, 1980). Cardinal utilities reflect attitudes toward risk and are unique (given the preferences over lotteries) up to multiplication by a positive constant and addition of a constant.

For firms, profits are the appropriate objective functions in simple cases. A sole entrepreneur should maximize expected utility of profits when uncertainty is present. In intertemporal settings, the firm should maximize the present discounted value of profits or the expected utility of profits. If shares of the firm are traded, the basic goal is to maximize the firm's market value, although complications (such as shareholder purchase of significant amounts of the firm's output) can cause the objective to change. The firm's constraints are derived from its available production technology, which when combined with all input prices, determines costs and from that aggregate, demand for its products.

The interactions and interdependencies among individuals, firms, and products can be captured by market equilibrium. When strategic aspects of individual and firm behavior matter, game theory provides a rigorous analytical tool.

GAME THEORY

Game theory is the study of formal models of strategic behavior in which the payoff or utility received by a player (individual or firm) can depend not only on the player's own decisions but possibly also on the decisions of all other players. Game theoretic models are classified into cooperative and non-cooperative games.

A non-cooperative game is specified by a set of players, a strategy set for each player, and a payoff function (or utility depending on the strategies chosen by all the players) for each player. A Nash equilibrium is defined by the principle that each player chooses a strategy to optimize his or her own payoff given the decisions of all other players. Well-known conditions guarantee that a game has a Nash equilibrium, which may require randomized strategies. When there are multiple Nash equilibria, refinement concepts can narrow the equilibrium set. Non-cooperative games were introduced into the engineering design literature by Vincent (1983) for the study of collaboration within teams.

In a cooperative game, players can communicate and make binding agreements within coalitions (non-empty subsets of players), but cooperative games do not analyze the formation of coalitions. Many solution concepts are available, some of which are defined axiomatically.

SUMMARY OF METHODS, THEORIES, AND TOOLS

Table 4-2 provides a cursory rating of several tools with respect to potential values in current use, concept creation, concept development, selection among alternative concepts, and ease of use. Some decision analysis and applied decision theories are also included in this comparison. Concurrent engineering is included here as a tool, but it is more of an operating philosophy. It has its primary basis in the economics of product and process development, whereas the other approaches with a primary basis in economics build on theories of preferences (e.g., von Neumann-Morgenstern axioms).

The "ease of use" criterion is used in two ways to describe the tools and methods, encompassing both conceptual difficulty and execution difficulty. For example, QFD is overwhelming to execute if pursued fully, not because it is conceptually difficult but because filling in the huge number of cells in the matrices becomes daunting. Suh, however, is conceptually difficult. Mathematically rigorous approaches can often be conceptually difficult to employ (e.g., in terms of understanding and justifying assumptions and perhaps overly narrow problem definition). On the other hand, broadly applicable methods, including Concurrent Engineering and QFD, face difficulty in some applications because of the very breadth they address.

Table 4-2 Summary of Tools and Applications Examined

		Primary Basis						Ratings[a] - Potential Value for:				
		Knowledge Engineering	Logic/Set Theory	Matrix Algebra	Probability	Statistics	Economics	Current Utilization	Concept Creation	Concept Development	Selection Among Alternative Concepts	Ease of Use
Practical	Concurrent Engineering						X	4	2	4	4	1
Qualitative	Decision Matrix			X			X	4	1	2	4	5
	Pugh Method			X				3	4	5	1	2
	QFD			X				2	2	4	2	1
	AHP			X				3	1	2	4	
	Product Plan Advisor	X		X	X			3	2	3	4	3
Statistical	PLS				X	X		1	3	3	2	1
	Taguchi Method				X	X		4	1	4	4	2
	Six Sigma				X	X		3	3	3	3	2
Creative	AI Support	X						2	4	2	2	2
	TRIZ	X						3	3	1	1	3
Axiomatic	Suh's Theory		X	X				2	2	3	5	1
	Yoshikawa Theory		X					1	1	1	1	1
	Math Framework		X		X	X	X	1	1	1	5	3
Validating	Game Theory				X		X	1	1	1	3	2
	Decision Analysis		X		X		X	3	1	4	5	3

[a]Rating by several authors: 1= low; 5= high.

The "selection among alternative concepts" criterion has multiple interpretations. The multi-attribute matrix-oriented techniques are often used to select among overall product concepts, while the statistical methods are more typically used to select among process alternatives and among more detailed design differences. This criterion demonstrates the main strength for some of the more mathematically rigorous approaches. Not surprisingly, such approaches have little basis for generating alternatives. In contrast, knowledge-based approaches such as AI and TRIZ are much better for generating alternatives than for choosing among them. Approaches such as QFD and Pugh attempt to aid in both.

Cooper et al. (2000) state, "The choice of tool may not be that critical; indeed, the best performers use an average of 2.4 tools each—no one tool can do it all!" One could use Table 4-2 and the discussion in this chapter as a guide to choosing approaches for design application. For example, effective choices include:

- Concurrent engineering as an overall framework for decreasing costs and time to market;
- TRIZ for generating alternatives;
- Some form of Decision Matrix Technique for initial screening of ideas;
- Six Sigma for process design and evaluation with emphasis on quality control;
- Decision Analysis for making major investment decisions and for selection among viable concepts; and
- Taguchi and axiomatic methods for reliable, robust design development.

Design is an intellectual activity of the human brain and is therefore difficult to understand or even to describe using mathematical theories. Because all human intellectual activity includes decision making, decision making is an integral and inherent part of any design process. A variety of tools, methods, and theories have been developed over time to help describe and facilitate decision making processes, and some of these have been applied to various aspects of design, but none approach a general and useful theory fundamental to all areas of design.

In current practice each of these formal approaches to representing design processes is valuable yet individualistic. Specific theories do not currently acknowledge or make reference to others, making it difficult to determine the compatibility or contradictions among them. This lack of coordination impedes the teaching and general reduction to practice of potentially useful tools. Although some work is being conducted to understand the connections among these theories (Jin and Lu, 1998), much more is needed.

The validation of individual theories is anecdotal and difficult to justify across the wide range of design processes. Each of the tools described here must take into account the uncertainty of the data input. This data may come from actual measurements, from analysis of historical data, from solicited expert opinions, or from moderated opinions of potential users. Much of this input data depends on the ability of humans to judge attributes, and on how their judgment is affected when the number of attributes becomes large or complex. This variable makes validation of designs and design tools difficult.

Each methodology can clearly be an intellectual activity of value provided its potential applicability and limitations are well understood. However, comparison and contrast of the results of each tool can provide additional insight to the designer, and tools used in tandem may result in incalculable synergies. While the value of a single tool with applicability across every design query might be desirable, today's designers must use what is available.

In summary, as in all human activities, the tools and methods used in design are the ones that have the most utility given the constraints imposed by time and other resources available. Box (1979) has stated that "all models are wrong, some are useful," to which the committee adds the codicil, "all tools are useful, some are appropriate."

5

IMPLICATIONS FOR ENGINEERING DESIGN EDUCATION AND RESEARCH

Rapid changes in computer-based design tools and the increasingly rapid introduction of new products into a global economy put unprecedented demands on designers and those who educate them. The demands on practicing engineers include completing designs in shorter times and operating with a limited knowledge of functional performance. Engineers must often serve as members of teams whose members are physically dispersed, teams composed of engineers of various disciplines, or teams that may include such professionals as lawyers, psychologists, or artists. Finally, the legal liability associated with designed products requires not only that the product perform as intended but also that their designs and associated design decisions be documented and traceable.

It follows that tools to facilitate and enhance the productivity of designers and to document the basis for design decisions must advance. Several of the available tools are useful for these ends but have severe limitations. Quality Function Deployment, for example, can be very subjective, and the Analytical Hierarchy process can be applied only in simple decisions. Although they are far from perfect, these tools are widely used because they provide cost-effective solutions for designers.

Several theories of design are not widely used because they are either difficult to apply (Suh, 1990) or restricted in applicability to a narrow set of circumstances (Hazelrigg, 1999). Research to enhance existing theories or develop new ones that could be broadly applied is highly desirable, and the theories must be applicable in the real world, where design time and cost are as critical as product features.

This increasing demand and limited supply of adequate tools warrants research to improve the process of making design decisions. Decision analysis is a particular area for further investigation in engineering design because it has already established applicability in other fields. Further developments in engineering theory established on a credible axiomatic base are desirable as well.

A pervasive need exists for more rigorous design tools that can be easily used and that apply to a wide range of design processes. Progress in this area has been limited. The inability of the engineering design community to constructively critique current theories and to work together to formulate more general tools with wider application is striking.

> **Recommendation**. Constructive dialogue should be encouraged to allow the best aspects of each method and theory for decision making in engineering design to be incorporated into common practice. Sponsored academic research could be used as a mechanism to assist integration of existing theories and development of new ones. Workshops or other cooperative ventures should be held in which experts establish

engineering design tools that could evolve into common practice. The ease of use and practicality of these solutions should be paramount.

Much of the research in decision analysis per se has come from such fields as business and economics, where the multiplicity of variables renders intuitive reasoning impractical. Currently, formal decision analysis and decision theory are being confidently applied in such areas as medicine and business, where they are used to facilitate decisions with significant impact. This type of state-of-the-art decision making that takes uncertainty and the cognitive response of decision makers into account could be a valuable part of engineering design, but no design process tool widely used today in engineering design is mathematically rigorous and universally applicable.

Far greater productivity of design engineers will result from additional advances in computing capability to model, simulate, and visualize products; from the understanding of physical, chemical, and biological systems; and from robust decision analysis tools. The ability to quantitatively describe the attributes of a successful design through modeling will continue to improve design methodologies.

A common framework and knowledge base must be established to use more universally those design or decision-making tools designed for one set of conditions. If simple and attainable input data can be described, and this data readily used by each tool, the formal decision-making tools used successfully in other fields and in other design applications will no doubt increasingly be applied to improving engineering design and the design tools.

Recommendation. More research should be focused on enhancing design tools and methods applicable to all engineering disciplines. The increasing complexity of physical systems, as well as software and biological and medical systems, begs for increasingly quantitative and transparent tools for making and justifying design decisions. Research for designers to develop appropriate knowledge bases is required. The many gaps isolating related tools and theories must be bridged and a taxonomy to facilitate comparisons between approaches must be created.

Underlying any improvement to engineering design processes must be a sound foundation in statistics, probability, and mathematics on the part of the practicing engineer. A brief survey of engineering curricula revealed the first two were given cursory and, in the committee's view, insufficient treatment. The committee estimates less than a third of newly graduated engineers have even one formal course in statistics! For engineers to make informed decisions, they must have a sound understanding of statistics, mathematics, and probability.

Under current Accreditation Board for Engineering and Technology (ABET) guidelines, mathematics, such as differential-integral calculus and differential equations, is required. Statistics, along with linear algebra, numerical methods, and advanced calculus, is "encouraged." Only industrial engineering undergraduates have a formal statistics requirement. Just one-fifth of the specialized program requirements give further emphasis to the importance of statistics, but none require statistics.

The mathematics of uncertainty is properly identified as "probability," and the application of uncertainty, its management, and engineering, is "statistics." Statistics is the methodology employed when one searches for structure (information) in collections of data possessing error-prone and noise-like variability. Statistics provides for the construction of surveys and experimental plans needed for the production of information-laden data. Gleaning information from data and succinctly expressing that information verbally, graphically, and quantitatively should be a part of every engineer's education.

> **Recommendation**. Statistics and probability should be required and incorporated into the undergraduate engineering curriculum to emphasize their relevance to engineering design and decision making, process control, and product testing.

Engineering design begins with the development of understanding in the form of a conceptual model of a desired object. Many models may be proposed, each encompassing extrinsic information coupled to the experience and knowledge of the decision maker or team. Uncertainties will certainly abound, and decisions among alternatives will be forced upon the decision team. The theory and practice of making decisions under uncertainty is clearly appropriate to any study of engineering design.

Once a design and its targets have been defined, the design team begins the task of moving from general considerations to specific requirements. In this evolutionary process, decisions are made repeatedly, balancing costs, sensitivity to manufacturing and environmental variability, product reliability, and customer acceptability. Many tools assist in providing support for these decisions. Tactile physical models may be used or computers may construct three-dimensional visualizations. Decision trees and time path sequences are employed. Matrix displays of weighted attributes that contrast factors versus responses are almost always used. Patterns of experiments (statistical designs) may be employed to estimate sensitivities, make comparisons, and elucidate operable regions. Failure mode and effects analyses are common. These tools provide the basis of knowledge, the frame upon which decisions are made. The art of engineering design couples the use of tools to the ability to make the best decision in the face of uncertainty.

> **Recommendation**. Decision-making tools and decision theory should be included in a required undergraduate design course. Interdisciplinary capstone courses that include legal, social, and economic issues, as well as team building skills, can be particularly useful teaching tools and should be included in this undertaking.

Although the authors tried to reach a consensus—and all did generally support most of the recommendations—some held dissenting views that they expressed as follows:

> It is not wise to invest more money in developing theoretical foundations for decision making in design, firstly, because, as the report indicates, the developments to date are fragmented and not in any way unified. They are applicable only as adjuncts to the entire complex design process. Secondly, the new challenges facing industry (a.k.a. the changing nature of engineering design) require fundamental changes to the design process, because most of these new products will require "creative" designs (Dym's terminology) for new, unique, or vastly improved products. Such designs are not amenable to formal methods but require the development of knowledge bases concurrently with the designs.

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APPENDIX A

ACCREDITATION BOARD FOR ENGINEERING AND TECHNOLOGY ABET 2000

The following material is reprinted from *Criteria for Accrediting Engineering Programs*, effective for evaluations during the 2000-2001 accreditation cycle, revised March 18, 2000. (Engineering Accreditation Commission of the Accreditation Board for Engineering and Technology, 111 Market Place, Suite 1050, Baltimore MD 21202, pages 4-6.)

I.C.3.d. While ABET favors a flexible approach to the design of curricular content, it also recognizes the need for specific coverage in each curricular area. These are:

I.C.3.d.(1) Mathematics and Basic Sciences

I.C.3.d.(1)(a) Studies in mathematics must be beyond trigonometry and must emphasize mathematical concepts and principles rather than computation. These studies must include differential and integral calculus and differential equations. Additional work is encouraged in one or more of the subjects of probability and statistics, linear algebra, numerical analysis, and advanced calculus.

I.C.3.d.(1)(b) The objective of the studies in basic sciences is to acquire fundamental knowledge about nature and its phenomena, including quantitative expression. These studies must include both general chemistry and calculus-based general physics at appropriate levels, with at least a two-semester (or equivalent) sequence of study in either area. Also, additional work in life sciences, earth sciences, and/or advanced chemistry or physics may be utilized to satisfy the basic sciences requirement, as appropriate for various engineering disciplines.

I.C.3.d.(1)(c) Course work devoted to developing skills in the use of computers or computer programming may not be used to satisfy the mathematics/basic sciences requirement.

I.C.3.d.(2) Humanities and Social Sciences

I.C.3.d.(2)(a) Studies in the humanities and social sciences serve not only to meet the objectives of a broad education but also to meet the objectives of the engineering profession. Therefore, studies in the humanities and social sciences must be planned to reflect a rationale or fulfill an objective appropriate to the engineering profession and the institution's educational objectives. In the interests of making engineers fully aware of their social responsibilities and better able to consider related factors in the decision making process, institutions must require course work in the humanities and social sciences as an integral part of the engineering program. This philosophy cannot be overemphasized. To satisfy this requirement, the courses selected must provide both breadth and depth and not be limited to a selection of unrelated introductory courses.

I.C.3.d.(2)(b) Such course work must meet the generally accepted definitions that humanities are the branches of knowledge concerned with man and his culture, while social sciences are the studies of individual relationships in and to society. Examples of traditional subjects in these areas are philosophy, religions, history, literature, fine arts, sociology, psychology, political science, anthropology, economics, and foreign languages other than English or a student's native language. Nontraditional subjects are exemplified by courses such as technology and human affairs, history of technology, and professional ethics and social responsibility. Courses that instill cultural values are acceptable, while routine exercises of personal craft are not. Consequently, courses that involve performance must be accompanied by theory or history of the subject.

I.C.3.d.(2)(c) Subjects such as accounting, industrial management, finance, personnel administration, engineering economy, and military training may be appropriately included either as required or elective courses in engineering curricula to satisfy desired program objectives of the institution. However, such courses usually do not fulfill the objectives desired of the humanities and social sciences content.

I.C.3.d.(3) Engineering Topics

I.C.3.d.(3)(a) Engineering topics include subjects in the engineering sciences and engineering design.

I.C.3.d.(3)(b) The engineering sciences have their roots in mathematics and basic sciences but carry knowledge further toward creative application. These studies provide a bridge between mathematics and basic sciences on the one hand and engineering practice on the other. Such subjects include mechanics, thermodynamics, electrical and electronic circuits, materials science, transport phenomena, and computer science (other than computer programming skills), along with other subjects depending upon the discipline. While it is recognized some subject areas may be taught from the standpoint of either the basic sciences or engineering sciences, the ultimate determination of the engineering science content is based upon the extent to which there is extension of knowledge toward creative application. In order to promote breadth, the curriculum must include at least one engineering course outside the major disciplinary area.

I.C.3.d.(3)(c) Engineering design is the process of devising a system, component, or process to meet desired needs. It is a decision making process (often iterative), in which the basic sciences and mathematics and engineering sciences are applied to convert resources optimally to meet a stated objective. Among the fundamental elements of the design process are the establishment of objectives and criteria, synthesis, analysis, construction, testing, and evaluation. The engineering design component of a curriculum must include most of the following features: development of student creativity, use of open-ended problems, development and use of modern design theory and methodology, formulation of design problem statements and specifications, consideration of alternative solutions, feasibility considerations, production processes, concurrent engineering design, and detailed system descriptions. Further, it is essential to include a variety of realistic constraints, such as economic factors, safety, reliability, aesthetics, ethics, and social impact.

I.C.3.d.(3)(d) Each educational program must include a meaningful, major engineering design experience that builds upon the fundamental concepts of mathematics, basic sciences, the humanities and social sciences, engineering topics, and communication skills. The scope of the design experience within a program should match the requirements of practice within that discipline. The major design experience should be taught in section sizes that are small enough to allow interaction between teacher and student. This does not imply that all design work must be done in isolation by individual students; team efforts are encouraged where appropriate. Design cannot be taught in one course; it is an experience that must grow with the student's development. A meaningful, major design experience means that, at some point when the student's academic development is nearly complete, there should be a design experience that both focuses the student's attention on professional practice and is drawn from past course work. Inevitably, this means a course, or a project, or a thesis that focuses upon design. "Meaningful" implies that the design experience is significant within the student's major and that it draws upon previous course work, but not necessarily upon every course taken by the student.

I.C.3.d.(3)(e) The public, from catalog statements and other advising documents, and ABET, from the self-study questionnaire, should be able to discern the goals of a program and the logic of the selection of the engineering topics in the program. In particular, the institution must describe how the design experience is developed and integrated throughout the curriculum, show that it is consistent with the objectives of the program as required by section I.C.2. above, and identify the major, meaningful design experiences in the curriculum.

I.C.3.d.(3)(f) Course work devoted to developing drafting skills may not be used to satisfy the engineering design requirement.

I.C.3.e. Other courses, which are not predominantly mathematics, basic sciences, the humanities and social sciences, or engineering topics, may be considered by the institution as essential to some engineering programs. Portions of such courses may include subject matter that can be properly classified in one of the essential curricular areas, but this must be demonstrated in each case.

I.C.3.f. Appropriate laboratory experience which serves to combine elements of theory and practice must be an integral component of every engineering program. Every student in the program must develop a competence to conduct experimental work such as that expected of engineers in the discipline represented by the program. It is also necessary that each student have "hands-on" laboratory experience, particularly at the upper levels of the program. Instruction in safety procedures must be an integral component of students' laboratory experiences. ABET expects some course work in the basic sciences to include or be complemented with laboratory work.

I.C.3.g. Appropriate computer-based experience must be included in the program of each student. Students must demonstrate knowledge of the application and use of digital computation techniques for specific engineering problems. The program should include, for example, the use of computers for technical calculations, problem solving, data acquisition and processing, process control, computer-assisted design, computer graphics, and other functions and applications appropriate to the engineering discipline. Access to computational facilities must be sufficient to permit students and faculty to integrate computer work into course work whenever appropriate throughout the academic program.

I.C.3.h. Students must demonstrate knowledge of the application of probability and statistics to engineering problems.

I.C.3.i. Competence in written communication in the English language is essential for the engineering graduate. Although specific course work requirements serve as a foundation for such competence, the development and enhancement of writing skills must be demonstrated through student work in engineering work and other courses. Oral communication skills in the English language must also be demonstrated within the curriculum by each engineering student.

I.C.3.j. An understanding of the ethical, social, economic, and safety considerations in engineering practice is essential for a successful engineering career. Course work may be provided for this purpose, but as a minimum it should be the responsibility of the engineering faculty to infuse professional concepts into all engineering course work.

APPENDIX B

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APPENDIX C

WORD USAGE

Analysis A discrete answer derived from a set of equations. The validity of the answer depends critically on whether the equations properly represent phenomena of concern and their conditioning. Computers are helpful tools for making complex calculations; however, if the results are not validated (usually by experiments), they may be erroneous due to discretization or numerical process problems, which cannot be anticipated.

Decision A choice made by the design engineer regarding a particular solution for the problem at hand.

Decision theory A conceptual, complete view of decision making that can apply to virtually any decision.

Design (noun) The process by which human intellect, creativity, and passion are translated into useful artifacts. The plans or specifications for a product or service in the form of drawings, layouts, detail specifications, patterns, outlines, and processes that provide details of shape, materials, structure, layout, process steps, and configuration.

Design (verb) To methodically apply science and engineering principles so as to convert ideas into useful products. The stages of design range from developing requirements, through synthesizing, analyzing, and testing, to defining and creating a final product design definition in the form of drawings, for instance.

Design ability Mastery of scientific, engineering, and mathematical fundamentals, including analysis and experimental techniques in the presence of uncertainty. This encompasses such skills as conceiving, inventing, planning, and integrating, as they are applied to useful products in real environments.

Design engineer (1) A person trained or professionally engaged in the application of science, mathematics, and design methods to create useful and economical products and services.

Design engineer (2) A person or team responsible for assuring the functionality of devices or systems (i.e., that the performance and operations meet desired objectives reliably and efficiently); the people who do the "how" part of design.

Designer Anyone who intentionally influences the function or form of an evolving artifact, including, especially in complex system, managers, specialists, and others.

Engineering design Application of lore, empiricisms, intuition, and technical knowledge bases together with the use of scientific methods to the creation of useful and economical products.

Frame	The relevant environmental elements and factors that may influence a decision, judgment, or conclusion.
Key characteristics	The small number of factors and tolerances considered crucial to the performance or assembly of a product.
Knowledge bases	The accumulated intuition, past experience, empirical data, and/or data extrapolations on which engineering designs are primarily based. Almost all industrial processes were developed by these means. In general, traditional knowledge bases are inadequate, given the additional societal, political, environmental, economic, and resource constraints confronting today's designers.
Model	A structure or equations containing all the appropriate physics, chemistry, and system characteristics.
Physical programming	A numerical constrained optimization technique for engineering design that emphasizes the physical attributes of the product and the physical constraints applied.
Risk	The possibility of loss or a bad outcome; the degree of probability of such an outcome.
Risk assessment	Estimate of the probability of a bad outcome.
Risk evaluation	Establishing the importance of the risk.
Risk management	Decision making to balance risk and risk mitigation.
Robustness	The ability to provide required performance independent of the variability encountered in manufacturing and use.
Uncertainty	An estimate of the amount by which a calculated value may differ from the true value. This is the result of the limited knowledge about a phenomenon, and is described by the designer or design team assigning a probability or probability distribution based on their level of knowledge.
Validation of a result	The proving of some result conclusively according to principles of logic and usually with the use of mathematics. This requires that the result and any associated assumptions or definitions be stated precisely.
Validation of a model	Testing the reasonableness of a model empirically by statistical hypothesis testing for lack of fit, ability to forecast, and parsimony or the attempt to judge whether the model coincides qualitatively and quantitatively with reality based on one or more case studies.