

PROJECT ADMINISTRATION DATA SHEET

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Project Director: Dr. John W. Hooper School XXX OIP/Microelectronics

Sponsor: Lockheed Georgia Company Research Center

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Title: CMOS VLSI DESIGN TECHNOLOGY RESEARCH

ADMINISTRATIVE DATA

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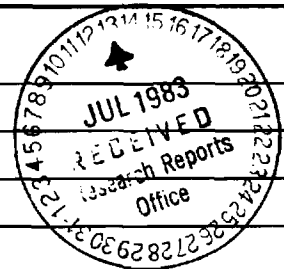
RESTRICTIONS

See Attached _____ Supplemental Information Sheet for Additional Requirements.

Travel: Foreign travel must have prior approval - Contact OCA in each case. Domestic travel requires sponsor approval where total will exceed greater of \$500 or 125% of approved proposal budget category.

Equipment: Title vests with N/A; none proposed.

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SPONSORED PROJECT TERMINATION/CLOSEOUT SHEET

SP 222

Date March 5, 1986

Project No. B-10-6²2

School/~~EES~~ OIP

Includes Subproject No.(s) E-21-612/John Hooper

Project Director(s) Dr. John W. Hooper GTRC
~~XXXXXXXXXX~~

Sponsor Lockheed Georgia Company

Project Title CMOS VLSI Design Technology Research

Effective Completion Date: 12/31/84 (Performance) _____ (Reports)

NOTE: Sponsor verified that they have received all required reports. Project Director is asked to send 2 copies of final report to PPC/SSD if you have not already done so.

Contract Closeout Actions Remaining:

- None
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CHAPTER 18 TECHNOLOGY EVALUATION

ABSTRACT: Having forecast and analyzed the likely impacts of technological changes, one needs to evaluate these and derive recommendations for technology management. Technology evaluation methods provide alternative approaches, depending on issues, data, and decision needs. The chapter offers both quantitative evaluation aids and participative approaches.

OBJECTIVES:

This chapter provides a framework to conduct various sorts of evaluations. It offers an array of evaluation methods, from the simple to the sophisticated.

18.1 E-VALU-ATION

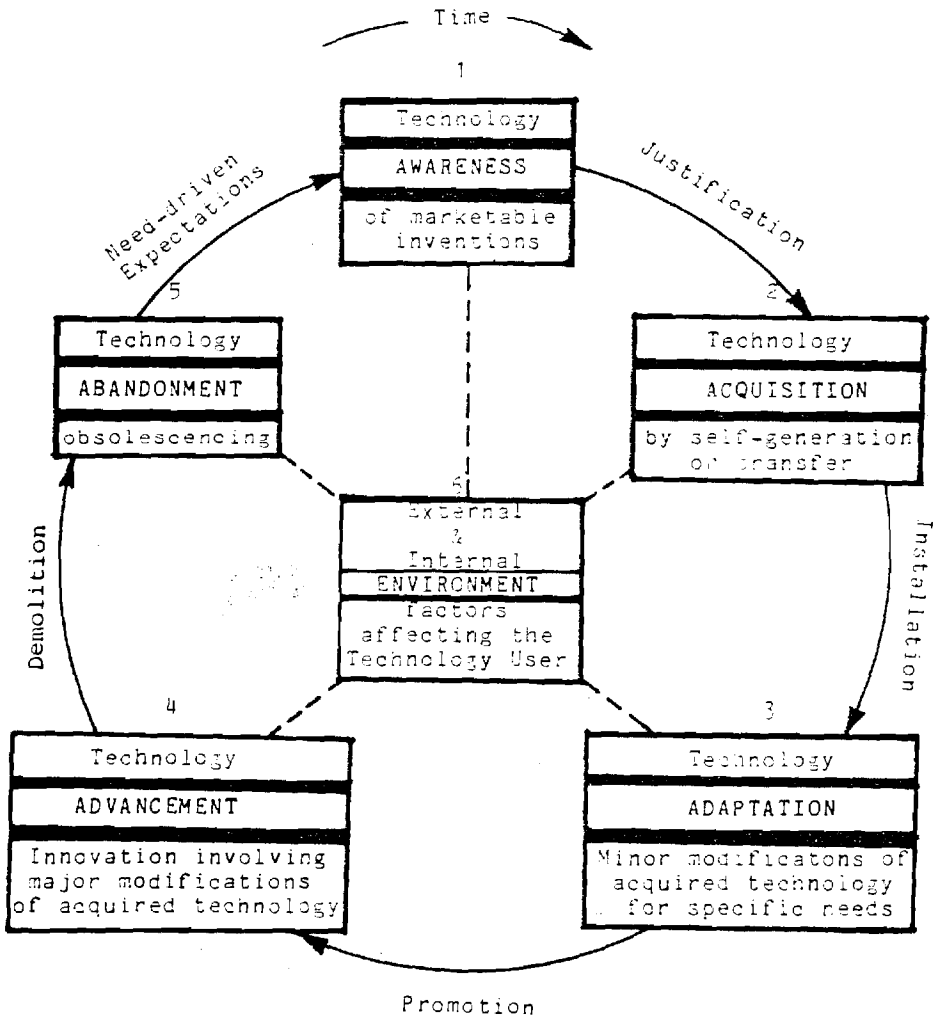
Figure 18.1 (Sumanth, 1989b) suggests six "A's" of the technology life-cycle. These pose a variety of possible evaluation demands, including:

- * Justification of the acquisition of a new technology -- i.e., evaluating the costs, risks, implementation requirements, and business advantages (e.g., an engineer wants a more powerful computer)
- * Selection of a new technology over alternatives -- i.e., "comparison technology assessment" (e.g., whether to design a new printed circuit board to employ surface mount technology or tape-automated bonding)
- * Impact assessment (e.g., whether plans to construct a new fusion facility need to be modified)
- * Sustainable development -- i.e., whether a technology over the course of its full life cycle poses unacceptable threats to the environment)¹ (e.g., approval of a new plastic for use in automobiles considers costs of its disposal years later, dispersed in millions of vehicles).

¹Bregha (1989) notes the commitment of the Canadian Government to take action on the "Brundtland Commission" (World Commission on Environment and Development) 1987 recommendation to emphasize "sustainable development." He indicates the implications of integrating impact assessment to cover full life-cycle issues. In particular, tiering of assessments (and evaluations) is needed. For instance, a program environmental impact statement (EIS) addresses certain general issues that then need not be assessed again in subordinate, project EISs.

Fig. 18.1

Fig. 1. The "Technology Cycle" (TC), showing the 5 Basic Elements of Technology Management at any level (Product, Service, Function, Work Center, Plant/Division, Corporation, Industry, National, or International), applicable to deal with an existing or new technology. The dashed lines represent 'Analysis'.



This chapter completes the logical sequence of impact identification--analysis--evaluation; it also presents evaluation tools useful in justifying and selecting technologies.

The title of this section emphasizes that evaluation is the process of assigning value. Evaluation requires criteria (and measures for these). Criteria reflect the values held by the evaluators or the parties whose judgment they are trying to address. (Measures reflect the degree to which the criteria are met.)

It is sometimes important to elucidate the values of parties at interest. This may help to establish criteria for the evaluation. It may also serve to clarify potential conflicts concerning the decision(s) involved. Kenneth Hammond and his colleagues have tried to separate conflict due to misunderstanding of a situation ("cognitive conflict") from that due to incompatible criteria ("motivational conflict"). The technique of policy capture (c.f., Hammond and Adelman, 1976) provides one way to identify and characterize value judgments of various stakeholders. Clarifying value differences can help each side understand the judgments of the others. This can lead toward "win/win" positions in which diverse stakeholders work out mutually acceptable tradeoffs. See Example 18.1.

Another technique to clarify values is value tree analysis (Peters, 1986). First, one identifies representatives of the concerned interests. Second, one interviews them to get them to express their pertinent values. Third, each interest group's values are arrayed as a tree, with "general" values located near the stem and more "specific" values as more remote branches. Fourth, each interest group is asked if they agree to the depiction of their own value tree. Fifth, the analyst tries to consolidate the various trees into a common structure that accentuates the shared, basic values, yet also clarifies the differing specific values. This tree can then be used to establish evaluation criteria relevant and acceptable to the parties at interest.

Example 18.1 Policy Capture

The County landfill is almost full. Several sites for a new landfill; incineration; and a recycling proposal each generate heated debate. Suppose the two dominant considerations are costs (C) and environmental protection (E). A number of specific scenarios are devised that implicitly cover the full range of possible levels for C and for E. Stakeholders are asked to participate in a policy capture exercise in which they give preference scores for each scenario (e.g., on a 1 to 100 scale). This process yields data on each stakeholder's preference regarding each scenario, for instance:

<u>Scenario</u>	<u>C</u>	<u>E</u>	<u>Stakeholder A Preference</u>	<u>Stakeholder B Preference</u>
1	30	51	99	10
2	94	72	5	40
3	78	87	40	90
4	60	75	35	60
5	12	23	70	20

[This could be extended over additional scenarios, stakeholders, or considerations.]

A multiple regression program then calculates the weightings the stakeholders have implicitly given C and E (by statistically associating the C and E values with the preference values over the set of scenarios). This information can capture the extent to which each party values C and E, for instance:

$$\text{A's Preference Function} = 77.5 - 1.5 C + 0.9 E$$

$$\text{B's Preference Function} = -23.7 - .2 C + 1.3 E$$

In words, A prefers low cost alternatives that, secondarily, offer high environmental protection. B emphasizes environmental protection and, only slightly, considers low cost.

Two-dimensional plotting of the scenarios against the C and E axes can further clarify choices. For instance, some of the options may dominate others -- Scenario 3 offers better E at lower C than Scenario 2. This could simplify choices by showing that the only reason for favoring a dominated choice would be personal interests, especially "NIMBY" -- not in my backyard!

Mitchell et al. (1985) and Crews and Johnson (1975) show pitfalls in applying policy capture, including: failure to include all pertinent factors, sensitivity to presentation, time demanded of participants, representative sampling concerns, and non-linearities.

Values underlie the criteria for technology evaluation. Example 18.1 presumes that the parties at interest can trade off along the two key considerations. The parties try to maximize their utility -- the state or quality of being useful. Implicitly, their working together suggests a utilitarian approach -- seeking the "greatest good for the greatest number." The approaches to follow do not assume that different stakeholders' values can always be traded off commensurably. A naive evaluator might try, for instance, to find a common measure (typically dollars) for all objectives. That is an untenable posture -- Arrow's theorem demonstrates the logical impossibility of a social utility function -- there is no rationally defensible basis for aggregating individual preferences (Arrow, 1963).

Instead of seeking to maximize some universal utility, evaluators must cope with multiple objectives. In particular, Gastil (1977) has differentiated three basic values in addition to utility.

- 1) Utility -- the greatest net social good
- 2) Equity -- the evenness with which those social goods are distributed. For example, comparison of cost-benefit ratios may show Technology A superior to Technology B; however, distributional justice demands to know who gets the benefits and who pays the costs -- Technology B may be preferred if it distributes fewer goods more equitably.
- 3) Transcendence -- non-material (spiritual) values that people hold dear. For instance, the ancient Greeks devoted a great part of their available resources to learning, architecture, and the arts; medieval Europe, to monasteries; modern America, to space exploration. These higher (transcendent) human attainments come at the expense of utility -- the "man on the street" would be materially better off if the U.S. had never invested in the space program. However, that "one great leap for mankind" in going to the moon has enormous transcendent value.
- 4) Reverence -- another non-material value maintains the sacredness of certain considerations. Reverence may oppose eliminating an endangered species, thereby denying the material utility in exploiting a natural forest. Or similarly, lower the utility of a straight highway in favor of respecting an Indian burial ground.

Evaluation begins with the question -- how are things to be valued? Other "pre-evaluation" factors also influence outcomes.

"Bounding" will influence what factors are included or excluded in any calculations to follow. Nuclear power may look good until one includes the eventual costs of disposing of the nuclear wastes generated -- then again, it may turn positive as "greenhouse" concerns raise the costs associated with fossil fuel plants. Implications may differ if one breaks them out for each affected party, rather than treating them as a whole. On the other hand, some impacts attain more significance when integrated with other situational considerations (e.g., air pollution from a refinery is evaluated differently if it is to be located in the stressed Los Angeles atmosphere). The following section presents a framework to deal with multiple evaluation objectives.

18.2 AN EVALUATION FRAMEWORK

Rational evaluation entails determination of five factors:

- 1) Criteria
- 2) Alternatives to be considered
- 3) Types of Measures to be used
- 4) Measurement Inputs
- 5) Ways to Combine those measures.

18.2.1 Criteria

Selection of criteria critically influences any evaluation -- any answer depends upon the question. Some few evaluations hinge upon a single criterion. Choice of technology for a low-cost component of a complex military system might be based unidimensionally on relative reliability, for instance. More typically, one faces multiple criteria. These may relate to a common objective, providing a reasonable "social utility" target. A company designing a new computer faces tough choices as it strives to keep costs down and performance up, but these should be largely free of the "motivational conflicts" noted earlier. Many technology evaluations entail multiple criteria that reach beyond utilitarian formulas to address differing motives with respect to the distribution of goods and regarding non-material aspects (transcendence and reverence). In such cases one should aim for a multi-dimensional portrayal of how well the alternatives stack up against the various criteria, rather than an optimal solution. In those cases, formal evaluation methods can facilitate the participative (political) processes (Section 18.5) that act as the main decision aids.

Requirements analysis is often recognized as a distinct project step, demanding resources in its own right. Requirements serve as criteria, though not necessarily as the complete set of criteria. For instance, an Air Force project seeks to design a "Pilot's Associate" to help fighter pilots fly better. A logical

starting point is to ask pilots what they do now, what activities are most troublesome, and what they might like from such an "Associate." Such inputs must be integrated with a preliminary sense of what a Pilot's Associate could be capable of within the design time frame. A good follow-up would be to mock up one or more prototypes to get pilots' reactions to something more concrete. Finally, the requirements analysis should provide explicit performance criteria for the technology under development. Additional criteria (e.g., low cost) will round out the evaluation profile for technology choices to be made.

Impact assessment often generates a large set of potential concerns. Impact evaluation may need to focus on a reduced set as key decision criteria. Lough and White (1988) exemplify this in evaluating two alternative strategies for decommissioning nuclear power plants. They had identified some 19 significant impacts relevant to decommissioning. To facilitate formal evaluation, they narrowed to 4 key impacts (cost, occupational radiation exposure, institutional impacts, and public attitude), setting aside the other impacts (e.g., noise, public exposure to radiation, employment impacts) to streamline the evaluation process.

18.2.2 Alternatives

Conflicting interests may disagree over the alternatives to be considered, as well as the criteria for evaluation. Evaluations involving multiple parties are inherently more delicate, as are multi-step evaluations. Determining the set of alternatives to be considered is a political decision. Groundrules can help avoid a too fat set of alternatives that unduly increases the evaluation workload and can serve to confuse the issue. The following are suggestive:

- * Exclude clearly inferior alternatives
- * Eliminate alternatives that are technically or economically infeasible
- * Establish certain a priori minimal standards for alternatives to be considered
- * Seek to configure alternatives to be comparable in scale
- * Try to have roughly comparable levels of information available on all alternatives

Peter Nijkamp (1986) distinguishes several relevant characteristics of alternatives that affect the course of evaluation:

- * Discrete vs. continuous alternatives
[determining what price to set on a new technology would be an example of continuous alternatives]
- * Concurrent vs. sequential alternatives
[deferred choices pose different alternative considerations -- time value of payoffs, risks involved, etc.]
- * Mutually exclusive vs. non-exclusive alternatives
[non-exclusive choices complicate evaluation].
- * Static vs. dynamic alternatives
[evaluations under dynamic conditions where alternatives evolve over time raise considerations about process (on-going) and criteria (retained flexibility)]

Lawrence Susskind (1983) points out further complexities: how far into the process to allow additional options to be added? how diverse a set of options to consider in one evaluation process? how to package hybrid options?

18.2.3 Types of Measures

Types of measures vary on a few critical dimensions. At one extreme, all of the criteria would be measured on the same metric (e.g., dollars). If different metrics are required, in some cases these will all be "interval" scaled (i.e., quantitative measures for which the intervals are meaningful, such as dollars, percentages, bits per second). In other cases, some or all of the measures will be more or less subjective (qualitative). These can be handled in several ways.

Two important "ordinal" scales are rating and ranking. Ratings compare against some standard(s), whereas rankings give relative indications among the set of alternatives. A sample technology rating scale is (McConnell and Khalil, 1988):

- 5 - excellent technology for this attribute
- 3 - average
- 1 - poor
- 0 - technology does not possess this attribute.

Mason (1986) used another scale in matching community strengths with corporate needs:

- +5 - abundance of the feature
- 0 - moderate availability
- 5 - poor availability.

[Specification of intermediate value meanings may enhance inter-rater comparability].

Scales range in precision from binomial (0 or 1; yes or no) to as fine a gradation as one wants (e.g., from 1 to 1000). An interesting non-linear variation may better capture human judgment (Cetron and Bartocha, 1973):

- 8 - major
- 4 - significant
- 2 - minor
- 1 - minimal.

Scales with an odd number of values (e.g., 5-point scales) allow raters to opt for a neutral, middle position. An even number of values forces raters to express a leaning.

An interesting rating scale results from creating an interval scaling that may be based on subjective, component judgments. The "Futures Foregone" (FF) index (Freeman et al., 1982) was used to compare alternatives for 106 discrete land regimes in the U.S. (Potential Natural Vegetation Communities -- PNCs). For each of 10 activity categories (e.g., wood harvest, tree life forms), for each PNC, this was calculated as

$$FF = \frac{[\text{Base Year Total} - \text{Projected Year Total}]}{\text{Projected Year Total}}$$

Projected year totals could derive either from quantitative trend projections or from subjective expert estimates.

Ranking can likewise be done with various scales. Very simply, rankers may be asked to judge one alternative higher or lower than another (with or without an option to say "the same"). Refinements can take many forms. Sharif and Sundararajan (1984) use a more precise scaling that offers a good model for comparing technological alternatives (Table 18.1).

Sometimes it is important to measure stochastic (probabilistic) information separately. The Futures Group (1975) devised an "Impact Likelihood vs. desirability matrix" (Figure 18.2). This 2-dimensional array of information allows participants in the evaluation to sort out reasons for relative enthusiasm for an alternative. For instance, #13's lack of enthusiasm for the alternative mapped is based on preference, while #12's misgivings relate to likelihood.

Table 18.1 Relative Importance Scale

<u>Importance</u>	<u>Definition</u>	<u>Explanation</u>
1	Equal Importance	Alternatives contribute identically to the objective
3	Weak Dominance	Experience or judgment favor one alternative over the other
5	Strong Dominance	Experience or judgment strongly favor one alternative over the other
7	Demonstrated Dominance	One alternative's dominance over the other is demonstrated in practice
9	Absolute Dominance	Evidence favoring one alternative over the other is affirmed to the highest possible order

[2,4,6,8 = intermediate values]

Fig. 18.2

	Very desirable	Desirable	Neutral	Undesirable	Very undesirable	No opinion	Participant codes
Almost certain				3			1. Private industry 2. Private industry 3. Government – administrative
Very likely		7 8	16	9	13		4. Environment and research 5. Public utility 6. Government – administrative 7. Government – legislative 8. Environment and research 9. Public utility 10. Government – legislative
As probable as not		12	10		4		11. Public utility 12. Private industry 13. Environment and research
Very unlikely		1 2 12					14. Private industry 15. Private industry 16. Government – administrative
Almost impossible						6	
No opinion							

FIGURE 14.2. Impact likelihood vs desirability matrix: individual responses (by participant code) to the notion of creation of tax shelters for investment in geothermal development. [Comments (by participant code): (1) tax shelter not the way to go; (3) big companies don't use them much (it means more regulations and might encourage smaller companies—encourage drilling, not necessarily discovery, since indiscriminate activity might result); (6) subsidies are generally given to "wrong" people—they are not really productive; (10) in normal times this would be a natural development—but now public attitudes are against it; (12) tax incentives are needed for development.]
Source: The Futures Group (1975: 369).

It is often helpful to "normalize" measures across criteria. If all measures are "dimensionless" and on similar scales, nothing need be done. However, where measures differ, one would like to make them comparable. "Standardization" may prove suitable:

$$\text{Standard Score} = \frac{[\text{Raw Score} - \text{Sample Mean}]}{\text{Sample Standard Deviation}}$$

Another useful strategy is to sum the scores, say, for all of the alternatives on a given criterion; then divide each score by this sum. This results in decimal values that sum to 1. (Converting these to percentages by multiplying by 100 may yield an informative measure of relative performance.)

As a final note on measures, sometimes judgments will be categorical without any viable ordering. Such "nominal" measures can be presented as is, but they should not be subjected to statistical manipulations (e.g., computing correlations). If such statistical manipulations are desired, one can convert a nominal measure into a set of binomial measures. Suppose one were concerned about employment and thought that religion might relate. The nominal variable, religion:

Religion: 1 = Catholic; 2 = Protestant; 3 = Other

could be transformed into two binomial variables:

Catholic: 0 = No; 1 = Yes
Protestant: 0 = No; 1 = Yes

Note that a third binomial variable for Other is not appropriate; such information would be completely redundant for individuals who were "No" on both the Catholic and Protestant variables.

18.2.4 Measurement Inputs

Measures of the extent to which alternatives fulfill criteria can be obtained directly or indirectly. Indirect possibilities include analysis of priorities established in previous decisions, analysis of official position statements, and surmised positions (evaluators construct consistent positions based on perceived stakeholder preferences).

Direct inputs entail asking stakeholders, or their representatives, to provide the inputs. This could involve various expert opinion methods (Chapter), such as survey, interviews, group meetings, or Delphi.

Rankings of large sets of alternatives can be problematic. A

well-established approach to obtain valid judgments is pairwise comparison. A given alternative is compared with one other (using whatever ranking scale), then with a second alternative, and so forth. This simplifies the judgments required, but is very demanding [(n-1)! judgments for a set of n alternatives, for each criterion considered]. A matrix of pairwise comparisons can be consolidated to an ordering of the factors under study by standard matrix calculations of eigen vectors and eigenvalues (c.f., Sharif and Sundararajan, 1984).

Interpretive structural modeling (ISM) is an approach to simplify the generation of pairwise comparisons and convey the results graphically. ISM computer programs can facilitate judgments by assuming transitive relationships (i.e., if you prefer A to B and you prefer B to C, the program will assume you prefer A to C, and save you making that judgment). Relationships can also be portrayed using directed graphs produced by the program (c.f., Watson, 1978).

"All together" rankings of a group of 15 alternative technologies correlated highly with pairwise comparison rankings for a set of 10 criteria, in one study (Sharif and Sundararajan, 1984). This suggests that direct ranking may not sacrifice judgment quality to pairwise comparison, and it is much quicker for the participants.

18.2.5 Ways to Combine Measures

Nijkamp (1986) forcefully points out that evaluation for policy making is not primarily aimed at identifying the optimal solution. Rather, the purpose is to rationalize the decision process by explicating and presenting information on criteria, alternatives, interest conflicts, and so forth. For instance, one might rank order the alternatives separately for each of the criteria to help people perceive the tradeoffs involved. Dominance among alternatives across criteria can be noted.

Having duly disclaimed the goal of deriving an optimal solution, it is nevertheless often of interest to consolidate measures across criteria to compare alternatives. Suppose a design team has narrowed a choice for a given function down to three technologies as alternatives (A, B, and C). Suppose that the selection criteria boil down to three (D - dollars; F - performance on the target function; and R - reliability). Imagine that Table 18.2 reflects the design team's consensus as to:

- * The relative weights that should be assigned to each criterion
- * The measure of how well each technology fulfills each

criterion.

The calculations with Table 18.2 give the linear additive weighting model. Virtually identical calculations masquerade under labels such as "weighted scoring model," "decision matrix," "relevance trees," and "attribute trees." Simpler ways to combine criteria and alternatives are possible (e.g., equally weighting all criteria; binary scoring in which an alternative does or does not meet minimal requirements for each criterion) (Carrasco and Kengskool, 1988) -- but these seem to use the available information less fully at no great computational savings. The "Analytic Hierarchy Process" (Saaty, 1980) is based on pairwise comparisons to generate criteria weights and comparison of alternatives -- as presented in this chapter -- it allows extension to additional hierarchical levels.

The linear additive weighting model readily allows sensitivity analysis. For instance, a stakeholder could check to see that changing the weights for reliability to ".3" and functionality to ".4" results in Alternative B being favored.

The following section introduces approaches that go beyond the linear additive weighting model.

Table 18.2 Weighted Decision Matrix

Weight	Criteria	Alternatives		
		A	B	C
0.3	D (Dollars)	.2	.5	.3
0.6	F (Functionality)	.6	.2	.2
0.1	R (Reliability)	.1	.4	.5

Linear additive calculations yield total scores for each alternative of:

$$A = .3(.2) + .6(.6) + .1(.1) = .43$$

$$B = .3(.5) + .6(.2) + .1(.4) = .31$$

$$C = .3(.3) + .6(.2) + .1(.5) = .26$$

$$\underline{1.00}$$

NOTE: Relative weights assigned to the criteria should sum to 1.0. In this example the performance of all the alternatives on each criterion sum to 1.0; this is one way -- not the only way -- to assure that criteria are not being subtly weighted by differing scoring patterns on each.

A decision aid is a tool which can be used to help evaluate alternative actions or policies and to assist in the selection of a most preferred alternative or set of alternatives. The impetus for research on normative decision making and the development of decision aids has derived mainly from the need to solve complex resource allocation problems, as viewed from an organizational or managerial level. Typical application areas have included problems in water resources development, health services delivery, production scheduling, inventory control, civilian and military procurement, and portfolio selection for capital investment.

Perhaps the primary distinguishing feature of contemporary work on decision-aiding is the recognition that the solutions to complex problems must explicitly embrace a range of competing concerns. Such concerns give rise to multiple, conflicting, and noncommensurate criteria against which alternatives must be evaluated before eventual selection. For example, consider the evaluation of different designs for an automobile (White *et al.*, 1986; White and White, 1988). This problem is faced by consumers before making a purchase, by manufacturers before deciding to which models to produce, and by government regulatory agencies before issuing standards.

All of the different automobile designs under consideration comprise the set of alternatives to be evaluated or decided among. Each design is characterized with respect to a range of different attributes, such as size, weight, structural configuration, fuel economy, styling, performance, and various safety features. These attributes determine the value or score of the car with respect to any set of criteria.

Among the many criteria for a good design, we might focus on just two objectives, say, safety and cost. These criteria are conflicting, because improvements in safety generally lead to designs which are more expensive to build and operate. These criteria are also noncommensurate, because there exists no universally acceptable transformation between safety, as measured in terms of human injuries and fatalities prevented, and cost, as measured in terms of dollars.

The recognition that decisions must balance competing goods has given rise to a body of theory and practice called multiple objective decision analysis (Keeny and Raiffa, 1976; Hwang and Masud, 1979; Goicoechea, *et al.*, 1982; Chankong and Haimes, 1983; French *et al.*, 1983; Hansen, 1983). Two related problems are addressed. These are problems arising in multiple objective optimization theory, or MOOT, and problems in arising multiattribute utility theory, or MAUT.

As a methodology, MOOT concerns the solution of vector optimization problems--mathematical programming problems with vector-valued objective functions. Since the maximum or minimum of a vector-valued function is not apparent without explicit definition (usually requiring a value judgement), the solution to a vector optimization problem consists of a set of alternatives, rather than a single answer. This set is variously referred to as the set of nondominated, noninferior, efficient, or Pareto-optimal solutions. MOOT deals with the extension of scalar optimization problems to the vector case. The properties of and solution procedures for scalar problems are well understood. MOOT seeks to identify conditions under which solutions to appropriate scalar optimization problems qualify as nondominated solutions to the vector optimization problem.

MAUT concerns the formal representation of the preference structure of the decision maker. In other words, MAUT deals with the existence and specification of a decision maker's overall (scalar) objective function. MAUT addresses tradeoffs among conflicting and noncommensurate criteria in order to identify the most preferred solution from among the set of nondominated solutions to a vector optimization problem. From a methodological standpoint, MAUT concerns the formal definition of preference structures, the techniques for elicitation of these preference structures, the conditions for the existence and uniqueness of a real-valued "value" or "utility" function which faithfully represents the preference structure of a given individual, and the decomposition and assessment of value and utility functions from preference data.

As an example, suppose that we are to evaluate the six alternative automobile designs listed in Table 1 on the basis of safety and cost alone. The safety value of each design is measured on a scale of 1 to 10, with 1 representing a design that is best able mitigate occupant injuries and fatalities in the event of an accident. A safety value of 10 represents the the least safe car. The annualized cost of each design, including average annual operating and maintenance costs and amortization of purchase price, is measured in dollars. Our objective is to determine the best automobile, that is, the car with the best combination of safety and cost.

The safety values and costs of the six designs are cross plotted in the solution space in Figure 1. Designs closest to the origin have lesser costs and greater safety. In the solution space we can see that the *Battlebus* is preferred to the *Fashionable* in terms of lower social cost, but that *Fashionable* is preferred to *Battlebus* terms of lower cost. Thus it is impossible to choose between *Battlebus* and *Fashionable* at this stage in the analysis, unless we are willing to state a preference for the tradeoff between safety and cost.

Automobile design	Safety value [dimensionless]	Annualized cost [\$]
Aggressor	4	5000
Battlebus	3	4700
Commuter	5	3500
Durable	8	2400
Fashionable	7	4200
Exciter	9	3100

Table 4. Data for the automobile example problem.
 18.3

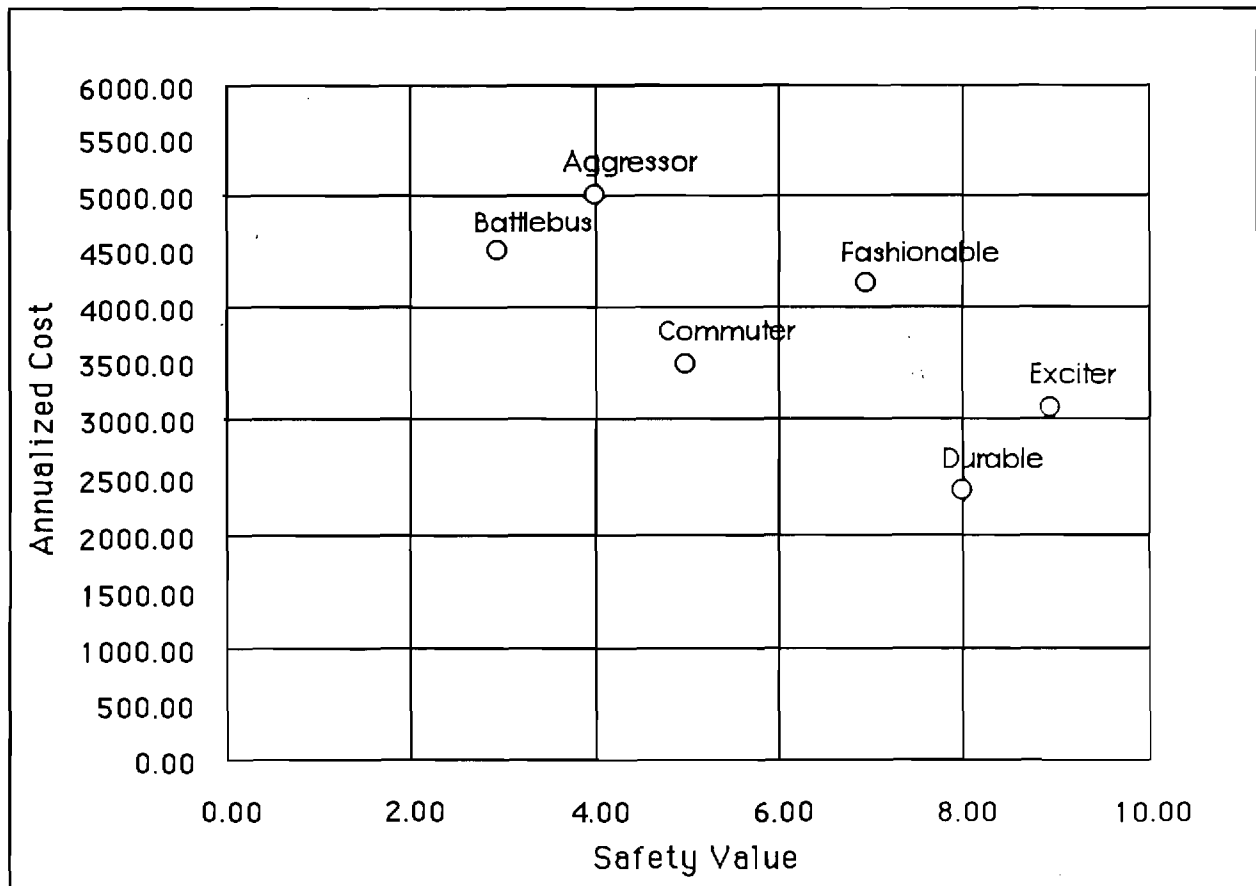


Figure 4. Alternatives in the solution space for the automobile design problem.
 18.3

Incontrast, the *Commuter* is preferred to the *Fashionable* in terms of both of the objectives. If only one alternative is to be chosen, then it clearly is not *Fashionable*. *Commuter* is said to dominate *Fashionable* and for this reason *Fashionable* can be eliminated from further consideration. Similarly, *Battlebus* dominates *Aggressor* and *Durable* dominates *Exciter*. The design alternatives represented by *Battlebus*, *Commuter*, and *Durable* are said to be nondominated, in the sense that no other alternative is superior (or at least as good) with respect to both of the objectives.

The set of all feasible nondominated alternatives can be thought of as discrete points along a curve in the solution space called the Pareto optimal curve (or transformation curve, or efficient frontier). Further ordering of the alternatives on the Pareto optimal curve can not be achieved without the introduction of value judgements concerning the relative preference between safety and economic objectives. The Pareto optimal curve for the example problem is shown in Figure 2.

This where MAUT must be applied. If we could develop exact preference information using MAUT, then a family of isopreference curves could be superimposed over the Pareto optimal curve, as illustrated in Figure 2. Isopreference curves have the property that any two points in the solution space that lie along the same curve are equally valued. The most preferred alternative is that which has the greatest value or utility. This alternative is located in the solution space at the point of tangency of the Pareto optimal curve and the highest isopreference curve (the point representing *Commuter* in Figure 2).

Whether or not we can actually compute explicit isopreference curves, the concept illustrates the importance of determining the decision maker for a specific problem. Different decision makers may well have the same preference orders with respect each individual objective, but different decision makers are quite likely to have different isopreference curves. Different consumers, different manufacturers, and the different regulatory agencies all are likely prefer safer and less expensive automobiles. Nevertheless, they each may disagree as to which nondominated design is the best, because they disagree regarding the appropriate tradeoffs between safety and cost.

Table 2 provides a taxonomy of the large number and great variety of techniques which have been developed for multiple objective decision-aiding (Deason, 1983). As an example of one approach to solving a multiple-objective optimization problem, we will illustrate the application of a generating technique to a formal multiple-objective problem. Specifically, we will illustrate a generating technique called the constraint method.

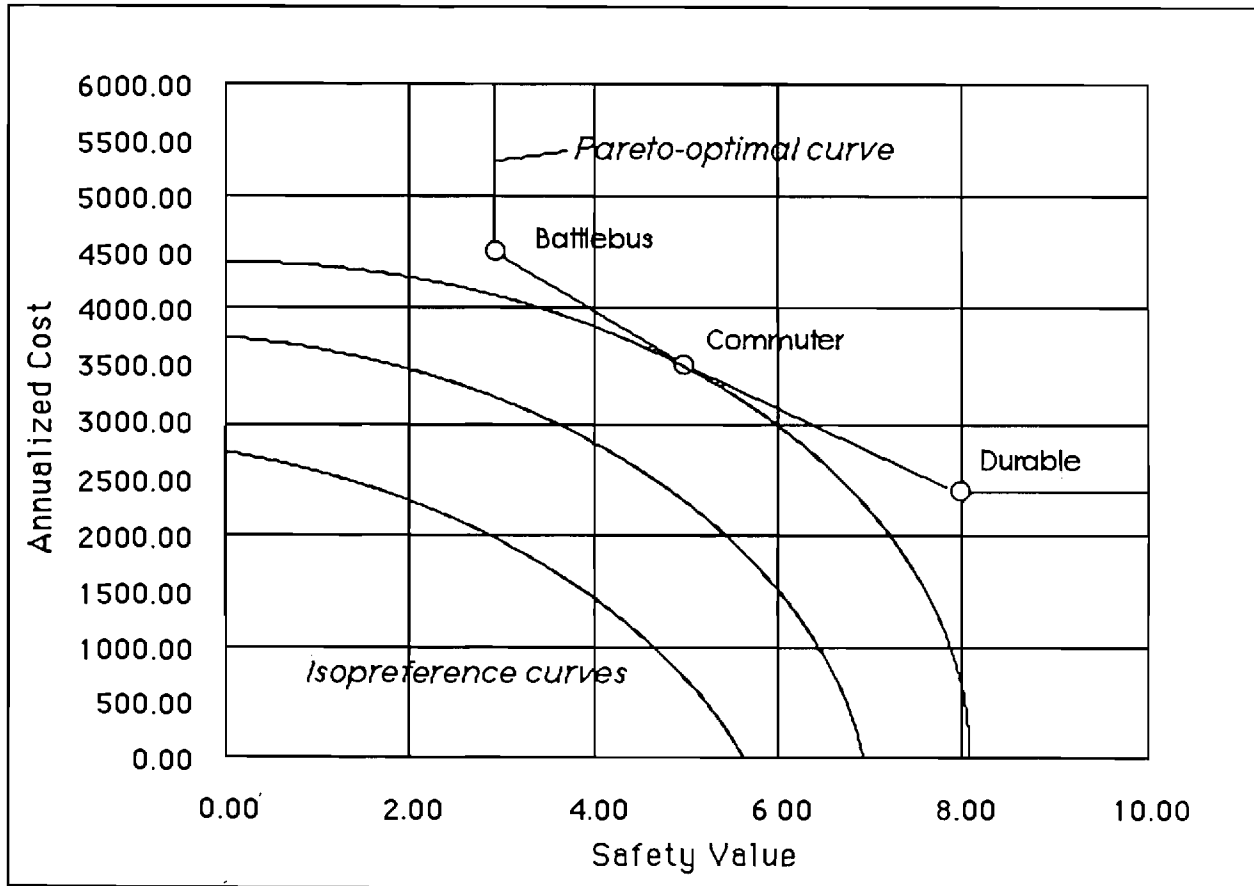


Figure 18.4. Pareto optimal and isopreference curves in the solution space.

A two-objective decision problem can be expressed formally very simply as

$$\min_{a \in A} [f_1(a), f_2(a)]$$

where a is an individual alternative, A is the set of all alternatives, and $f_1(a)$ and $f_2(a)$ are the objective functions for the first and second objectives, respectively. In our automobile example, the set of alternatives A is defined by the automobiles listed in first column in Table 1. The first objective function (safety) is defined by combination of the first and second columns in the table and the second objective function (cost) is defined by the combination of the first and third columns.

As the name implies, generating techniques generate the set of nondominated solutions and assess the tradeoffs between objectives at various levels of objective accomplishment.

No attempt is made to incorporate preferences. This is essential if no single decision maker can be identified for the problem. Generating methods contribute in the analysis of decision problems by reducing the set of all alternatives, feasible and infeasible, to the Pareto optimal solutions illustrated in the previous example.

In the constraint method, one objective is optimized while the remaining objectives are constrained to some specified value. This generates one point on the nondominated frontier. The constraint values are then changed and the optimization repeated. This generates a second point on the nondominated frontier. The entire process is repeated until the entire nondominated solution set is generated, one point at a time.

- | |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <ul style="list-style-type: none">A. Nondominated solution generating techniques<ul style="list-style-type: none">1. Constraint method2. Weighting method3. Multiple objective dynamic programming4. Multiple objective simplex method5. Noninferior set estimation methodB. Techniques involving a priori complete elicitation of preferences<ul style="list-style-type: none">1. Optimal weights2. Utility theory3. Policy capture4. Techcom methodC. Techniques involving a priori partial elicitation of preferences<ul style="list-style-type: none">1. Lexicographic approach2. Goal programming3. ELECTRE method4. Compromise programming5. Surrogate worth tradeoff method6. Iterative Lagrange multiplier methodD. Techniques involving the progressive elicitation of preferences<ul style="list-style-type: none">1. Step method2. Semops method3. Trade method4. Pairwise comparisons5. Tradeoff cutting plane methodE. Visual attribute level displays<ul style="list-style-type: none">1. Objective achievement matrix displays2. Graphical displays3. Mapping |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|

Table 2. A taxonomy of multiple objective decision-aiding techniques (Deason, 1983).

18.4

Using the constraint method, we solve the following problem repeatedly, with different values of $K(i)$ at each iteration i :

$$\min_{a \in A} f_1(a)$$

subject to:

$$f_2(a) \leq K(i)$$

A systematic procedure for implementing the constraint method is illustrated in Table 3. At the first iteration, a very large value is chosen for $K(1)$. This relaxes the constraint on $f_2(a)$.

In our example, the solution to this scalar optimization problem is the safest alternative irrespective of cost, $a_{opt}(1) = \text{Battlebus}$. At the next iteration, we let:

$$K(2) = f_2(a_{opt}(1)) - 1 = f_2(\text{Battlebus}) - 1 = \$4699$$

This makes *Battlebus* infeasible, as well as all of the more expensive alternatives (in this case, *Aggressor*). This procedure is repeated until at the last iteration there are no feasible solutions.

Iteration i	$K(i)$	$a_{opt}(i)$	$f_1(a_{opt}(i))$	$f_2(a_{opt}(i))$
1	infinity	<i>Battlebus</i>	3	\$4700
2	\$4699	<i>Commuter</i>	5	\$3500
3	\$3499	<i>Durable</i>	8	\$2400
4	\$2399	none feasible		

Table 3. Solution of the example two-objective problem using the constraint method.

18.5

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Exercise

In the automobile problem, the safety value and cost listed for the *Aggressor* and *Fashionable* designs are for the standard models, equipped with seatbelts. Each of these models also can be equipped with optional airbags. For the *Aggressor*, the airbag option improves the safety value to 2 at an additional cost of \$200 a year. For the *Fashionable*, the airbag option improves the safety value to 5 at an additional cost of \$100 a year. Use the constraint method to determine the new nondominated set of alternatives.

Solution

The alternatives for the modified problem are:

Aggressor (standard)	4	\$5000
Aggressor (with airbag)	2	\$5200
Battlebus	3	\$4700
Commuter	5	\$3500
Durable	8	\$2400
Fashionable (standard)	7	\$4200
Fashionable (with airbag)	5	\$4300
Exciter	9	\$3100

The constraint method yields:

Iteration i	K_i	$a_{opt}(i)$	$f_1(a_{opt}(i))$	$f_2(a_{opt}(i))$
1	infinity	Aggressor (with airbag)	2	\$5200
2	\$5199	Battlebus	3	\$4700
3	\$4699	Commuter	5	\$3500
4	\$3499	Durable	\$2400	
5	\$2399	none feasible		

18.4 Using Formal Evaluation Models

Evaluations of technology range from the totally informal -- tacit (internal) models with no explicit measurements -- to the formalized, computer models. This chapter has emphasized formal models, not to make choices per se, but to help rationalize the decision process by making criteria, alternatives, and estimates explicit. Such models may, at times, help integrate divergent values by clarifying positions and suggesting common grounds. Other times, they may help disaggregate values by separating criteria and helping parties recognize multiple objectives. Example 18.2 describes an intriguing evaluation scheme.

Computer programs can facilitate evaluation. This chapter has suggested several statistical measures -- linear models (e.g., regression), means, standard deviations, standardization of measures, and basic matrix manipulations; all can be assisted by widely available statistical packages. Special models for ISM, policy capture, and the Analytic Hierarchy Process may be useful. Interactive computer packages aim to facilitate the planning process by combining geographical information with criteria measures (Cocks and Ive, 1988) or by supporting stepwise qualitative assessment (White et al., 1985). In Bali, an interactive computer model helped farmers, priests, and development agency officials assess the relative merits of modern farming methods (high-yielding rice, bigger dams, pesticides) vs. ancient methods even as multi-million dollar investments took place. The model allowed users to try various policies (sensitivity analyses). They discovered that the traditional methods worked better (Cowley, 1989). Most importantly, the computer model fostered participation as diverse parties found a basis for informed dialogue.

18.5 PARTICIPATION and MEDIATION

18.5.1 Participation

Participation is the best guarantor of acceptance of an evaluation. Without acceptance, it is virtually impossible to implement any decision effectively. Hence, participation in technology evaluation makes good sense within an organization (e.g., concerning the choice of a component within a new technology product) and externally (e.g., stakeholder involvement in assessing a controversial new facility proposed for a community).

Example 18.2 The "AIMTECH" Study

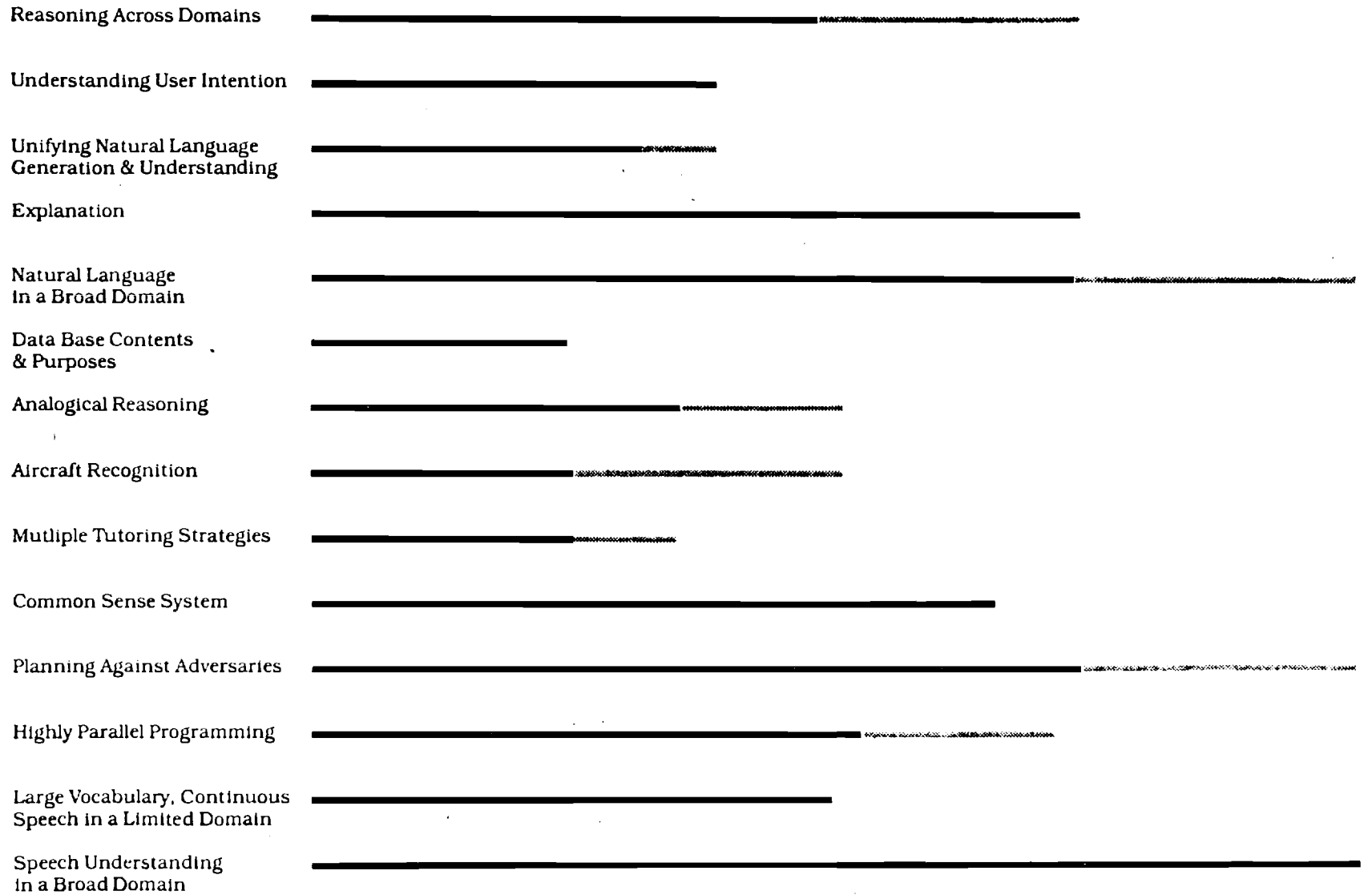
The "AIMTECH" study (MacAulay-Brown, Inc., 1985) forecast advances in artificial intelligence technologies. The study methodology is intriguing as it combined needs analysis for three target areas with identification of contributing technological milestones, and an evaluation scheme to help set priorities. For instance, requirements in one of the target areas, pilot/aircrew automation, included achievement of 11 milestones. Illustrated below for two technologies are the sorts of estimates provided for each:

<u>Factor</u>	<u>Highly Parallel Programming</u>	<u>Large Vocabulary Continuous Speech Recognition in a Limited Domain</u>
Probability of Success	.5--.9	.8
Years Required	10--15	4--10
Person-Years of Effort required (over current funded baseline)	64	40--70
Cost (\$ millions)	9.6	6--10.5

The estimates are displayed in various arrays. One display charts the minimum and maximum time requirements for each of the milestones as parallel "time lines" (see Figure 18.5). This gives a quick visual sense of the likely roadblocks to achieving a given target that depends on several of them.

Another compelling chart lists each of the milestones required to achieve a given target; one quickly grasps the magnitude of resources required to meet the target. These data provide the prospective technology manager with a beginning basis for developing a return on investment analysis.

85 86 87 88 89 90 91 92 93 94 95 96 97 98 99 00 01 02 03 04



2500
~~2000~~

Time Line for Milestones

Figure 4

18.5

(? - EXCERPT OR FULL)

— Minimum time expected

- - - - - Maximum time expected

Participation can begin at various stages. In particular, one can consider involvement from the beginning of an assessment vs. later involvement restricted to the evaluation per se. Early involvement can increase commitment and build trust, but consumes more resources.² Later involvement uses resources more efficiently, but can raise issues that suggest redoing earlier assessment steps at even greater cost and time lost.

Participation can take many forms. This section focuses on "public" participation in technology assessment, but should be suggestive of mechanisms and concerns in "internal" participation also. Two keys to public participation are (Susskind, 1983):

- * Defining those interests with a legitimate stake
[e.g., consider those involved in previous such assessments; survey concerned government agencies and knowledgeable individuals for nominations of interests who should be involved; establish a participation steering committee to determine representation]
- * Injecting additional participants into an ongoing assessment process
[e.g., what conditions to set on late-joiners, whether earlier agreements are to be reopened].

Novel representation arrangements include advisory committees (Arnstein, 1975). Planning cells engage small groups, chosen to reflect the perspectives of major interests, to work intensively for a short period of time to express value preferences (Peters, 1986). Marks (1986) describes a case involving such commitment to participation that one might describe it as developing a participatory planning function in which TA becomes a component, rather than participation serving as a component in TA.

Participation can fulfill various functions (Redelfs and Stanke, 1988):

- * Informing the participants
[re the issue and/or the decisionmaking process]
- * Informing decisionmakers
- * Collaborative decisionmaking
[cooperatively or through adversarial processes, such as legal actions to block a development].

²Pitfalls abound. In one technology assessment, a six-member public advisory group interacted abrasively with the professional assessment staff due to severe value differences and consequent lack of trust (Arnstein, 1975).

Bregha (1989) notes that the benefits of "competition" in the assessment process require that the participants have sufficient resources to challenge establishment information and conclusions.

18.5.2 Mediation

Substantial participation often generates conflict. Mediation (third party involvement with more or less authority) seems a good candidate to work out conflicts to generate acceptable development plans (Susskind, 1983).

Susskind et al. (1987) present sequences of steps to follow during pre-negotiation, negotiation, and post-negotiation phases. Special concerns include:

- * Taking time to assure all parties understand the issues and the alternatives fully [possibly also providing training in negotiation]
- * Actively directing the energies of all parties toward a consensus arrangement
- * Keeping constituents abreast of negotiations as they progress
- * Preempting escalation of disputes due to selective perceptions
- * Developing incentives for good faith bargaining [including bounding of the concerns of "opponents," and getting formal authorities to accede to agreements to be reached]
- * Devising mechanisms to bind all parties to their agreements [legal contracts].

Unfortunately, environmental mediation efforts rarely lead to successful agreements. Buckle and Thomas-Buckle (1986) studied 81 attempted mediations of environmental conflicts associated with technological development. From the perspective of the mediators:

- * in 73 cases mediation was rejected before a second meeting
- * in only 3 cases was a stable agreement implemented.

On the positive side, in 40 of the cases, participants credited the mediation effort with helping them to improve their relationships with other parties at interest and/or understanding of the matter at dispute.

SUGGESTED SOURCES

Clark, W.C., and Munn (1986), Sustainable Development ??
Gross, J. and Rayser (1985), Measuring Culture ??
Saaty ??
Others ??

EXERCISES

Ex. 18.1 Consider Example 18.2. Take the position of the Air Force Program Manager responsible for these two component activities to help develop pilot/aircrew automation. Present and interpret the data given to justify your budget for "next year." Do this embedded in a funding scenario in which, to some extent, you compete with others for available resources. May the most persuasive win!

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