DECISION ANALYSIS APPLICATIONS IN THE OPERATIONS RESEARCH LITERATURE, 1970-1989

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In order to provide a guide to source material for practitioners interested in applying decision analysis methods, this paper surveys applications of decision analysis published from 1970 through 1989. In addition, it presents references for useful decision analysis methods that are often omitted from introductory textbooks. As used in this article, the term *decision analysis* refers to a set of quantitative methods for analyzing decisions which use expected utility as the criterion for identifying the preferred decision alternative. To be included in this survey, an application had to explicitly analyze alternatives for a decision problem using judgmental probabilities and/or subjectively assessed utility functions. The paper classifies the applications into five areas: energy, manufacturing and services, medical, public policy, and general. It further subclassifies energy applications into bidding, product and project selection, regulation, site selection, and technology choice. Those in manufacturing and services are subclassified into budget allocation, product planning, strategy, and miscellaneous. Applications in public policy are subclassified into standard-setting and miscellaneous. The paper notes articles that present significant detail about methodological and implementation issues, including problem structure/formulation, decision trees, probability and utility assessment, communication/facilitation, and group decision making.

This article surveys applications of decision analysis that appeared in major English language operations research journals and other closely related journals from 1970 through 1989. These are classified by application area, as well as by methodological or implementation issue. In addition, references are presented for useful decision analysis methods that are often not covered in introductory textbooks. The intent is to provide a guide to relevant source material for operations research practitioners facing a situation where decision analysis might potentially be applicable. Decision analysis provides tools for quantitatively analyzing decisions with uncertainty and/or multiple conflicting objectives. These tools are especially useful when there is limited directly relevant data so that expert judgment plays a significant role in the decision making process. Such situations include government policy making and regulation, strategic business decisions, and such risky personal decisions as selecting a treatment for a serious medical problem.

It is of particular note that many decision analysis applications address decisions with strategic or policy implications. These are generally characterized by one or more of the following characteristics: multiple conflicting objectives, limited directly relevant data, multiple interested stakeholders, alternatives that differ from each other qualitatively as well as quantitatively, uncertainties that pose significant organizational risks, and long time-horizons. As the applications show, decision analysis provides approaches to address these issues quantitatively in a practical, as well as logically defensible, manner. We emphasize this point because the recent report by the prestigious Committee On The Next Decade in Operations Research (1988), as well as follow-up comments (Wagner et al. 1989), do not mention decision analysis and barely mention the type of strategy/policy questions considered by many applications surveyed in this article. This leaves the impression that operations research methods can only address repetitive, operational/tactical problems. In fact, this is not true as the applications surveyed below make clear.

Section 1 defines decision analysis and provides references to further information on basic decision analysis methods. Section 2 surveys 86 decision analysis applications by application area, while Section 3 summarizes the methodological and implementation issues emphasized by each application. Table I lists the articles by application area, while Table II lists them by methodological and/or implementation issue.

1. DECISION ANALYSIS

As used in this article, the term *decision analysis* refers to a set of quantitative methods for analyzing decisions based on the "axioms of consistent choice" (Pratt,

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Raiffa, and Schlaifer 1964, Keeney 1982). These methods use expected utility as the criterion for identifying the preferred decision alternative, and they guarantee that complex decisions will avoid such undesirable characteristics as intransitivity of preferences (i.e., willingness to serve as a "money pump") (von Winterfeldt and Edwards 1986). Decision analysis is *normative*, rather than *descriptive*. That is, it provides a systematic quantitative approach to making better decisions, rather than a description of how unaided decisions are made. As Howard (1988) notes, the focus is on "transforming opaque decision problems into transparent decision problems by a sequence of transparent steps," and the approach "offers the possibility to a decision-maker of replacing confusion by clear insight into a desired course of action."

Decision analysis applications begin with the determination of the decision alternatives to be analyzed and specification of the evaluation measures (attributes) to be used to measure the degree of attainment of each decision objective. Howard (1988), Keller and Ho (1988) and McNamee and Celona (1987) discuss the development of alternatives, and Keeney (1988) and Keeney and Raiffa (1976) discuss the determination of evaluation measures. The specification of alternatives and evaluation measures is usually followed by construction of an initial model of the performance of each decision alternative with regard to each evaluation measure. Influence diagrams can aid in developing such models (Howard 1988, Kirkwood 1990, Howard and Matheson 1984a, McNamee and Celona 1987). Once the initial model is constructed, sensitivity analysis is often conducted to determine which uncertainties potentially affect the decision. Tornado diagrams can be useful for presenting the results of the sensitivity analysis (Howard 1988, McNamee and Celona 1987).

Decision trees (Holloway 1979, Samson 1988) can provide a useful modeling approach for the uncertainties in a decision. For realistic decision situations, decision trees are often too large for hand construction or analysis. Specialized software is available to assist with building and analyzing tree models (Celona and McNamee 1988, Cheung and Kirkwood 1989, Texas Instruments, Inc. 1985). Decision tree models of situations with continuous random variables may require development of discrete approximations for the continuous probability distributions. Keefer and Bodily (1983) and Miller and Rice (1983) review practical and accurate approximation methods. In situations where expert judgment is used to determine probability distributions, care must be taken to avoid the well documented difficulties that people have in accurately expressing their uncertainty (Dawes 1988). Spetzler and Staël von Holstein (1975) and Merkhofer (1987) summarize probability assessment methods.

For decisions where attitude toward risk taking or tradeoffs among conflicting objectives are important, utility functions are used to analyze these aspects of the decision. Howard (1988) notes that in situations with a single evaluation measure the exact form of the utility function often does not change the decision. He also shows some evidence of a systematic relationship between company size and attitude toward risk taking. In situations with multiple objectives, sensitivity analysis often shows that only a few tradeoffs affect the final decision. Keeney and Raiffa (1976) and Keeney (1977) discuss development of a multiattribute utility function in detail.

The level of detail for the models used in decision analysis applications varies. In some studies, highly detailed structural models (sometimes referred to as *system* or *process* models) are developed for the decision situation, while in others less emphasis is placed on this. The structural models for many decisions must account for possible reactions of other stakeholders to the decision that is made. Such methods as discrete choice analysis (Amemiya 1981, Ben-Akiva and Lerman 1985) can be used to model these reactions.

2. SURVEY OF DECISION ANALYSIS APPLICATIONS

The following journals were exhaustively reviewed from 1970 through 1989 to determine decision analysis application articles (the numbers in parentheses are the number of application articles identified in each journal):

- *Decision Sciences* (4)
- *European Journal of Operational Research* (5)
- *IEEE Transactions on Systems, Man, and Cybernetics* (formerly the *IEEE Transactions on Systems Science and Cybernetics*) (7)
- *Interfaces* (18)
- *Journal of the Operational Research Society* (formerly *Operational Research Quarterly*) (18)
- *Management Science* (10)
- *Omega* (3)
- *Operations Research* (15)
- *Operations Research Letters* (0), and
- *Risk Analysis* (6).

The identified articles are classified into these applications areas and subareas:

- Energy
  - Bidding
  - Product and Project Selection
  - Regulation

- Site Selection
- Technology Choice

- Manufacturing and Services
  - Budget Allocation
  - Product Planning
  - Strategy
  - Miscellaneous
- Medical
- Public Policy
  - Standard Setting
  - Miscellaneous
- General

Those application articles presenting significant detail about a particular decision analysis methodological or implementation issue are noted in Section 3.

There is some subjectivity in deciding whether a particular application is actually decision analysis. To be included here, an application had to explicitly analyze alternatives for a decision problem using judgmental probabilities and/or subjectively assessed utility functions. When there is ambiguity about whether an article meets this requirement, this usually revolves around: 1) whether probabilities were judgmentally assessed, or 2) whether conceptually correct methods were used to determine a utility function over multiple evaluation measures. Ambiguous cases were resolved by including the article if, on balance, it took a decision analysis approach.

There is also some subjectivity in deciding whether an article reports an application. A majority of the surveyed articles report case histories of the use of decision analysis to address a specific decision problem. Other articles report on analysis performed to provide background for policy making. In a few cases, there is no application but the material is of direct interest for applications.

The application areas are considered in alphabetical order with the exception that the General category is discussed last. Under each application area, the subareas are discussed in alphabetical order with the exception that the Miscellaneous subarea is discussed last for areas containing this subarea. Within each subarea, articles are considered in alphabetical order by authors' last names with the exception of articles addressing the same application and the medical applications. (The nature of the health-related issues considered by the medical articles leads naturally to cross-categorizing these as shown below.) The articles are listed by application area in Table I.

The surveyed journals have published a wide variety of decision analysis applications, but applications also appear in other places. Keeney (1982) references several applications that have appeared outside the operations research literature. Krischer (1980) reviews medical applications prior to 1980. Keeney and Raiffa (1976) and Bell, Keeney and Raiffa (1977) include a number of applications with multiple objectives. French (1989) reprints several applications that originally appeared in the *Journal of the Operational Research Society*, including one prior to the period covered in this survey. Howard and Matheson (1984b) include applications to investment and strategic planning, research and development, and social policy. Ulvila and Brown (1982) summarize other applications.

Some decision analysis applications appear only in consultant or government reports. While many of these are proprietary, two organizations have sponsored substantial decision analysis work for which reports are available. The Electric Power Research Institute has funded decision analysis applications in areas of interest to the electric power industry, and reports on this work are available. Contact the Technical Information Center, Electric Power Research Institute, 3412 Hillview Avenue, P. O. Box 10412, Palo Alto, California 94303 (telephone: (415) 855-2411). The National Technical Information Service (NTIS) of the U.S. Department of Commerce indexes reports for decision analysis work conducted by or for U.S. federal agencies. The NTIS issues a *Government Reports Annual Index*, and these are available at research libraries.

Energy

Energy applications are subcategorized into bidding, product and project selection, regulation, site selection, and technology choice.

Bidding. Bell (1984) analyzes a coal company's selection of a method to haul coal. The alternatives considered are making a bid to salvage a grounded ship, purchase of a new ship, or subcontracting for delivery. A decision tree is constructed, and expected net present value is used as the evaluation measure to determine the preferred bid price for the grounded ship. The analysis considers potential bids by a competitor.

Dyer and Lorber (1982) consider the evaluation of potential subcontractors. Eleven evaluation criteria are identified for use in evaluating three subcontractor proposals to conduct a program planning project. Since each subcontractor had completed a test project before the final proposal evaluation was conducted, there was little uncertainty about subcontractor performance. Thus, uncertainty is not considered in the final evaluation. A measurable value function is used to combine the evaluation criteria. The analysis shows that varying weights for evaluation measures does not affect the final evaluation results. Sarin, Sicherman and Nair (1978) consider proposal evaluation in the context of large-scale solar total energy experiments. Seventeen evaluation measures are

Table I
Articles Listed By Application Area

Energy

Bidding: Bell (1984), Dyer and Lorber (1982), Sarin, Sicherman and Nair (1978).

Product and Project Selection: Crawford, Huntzinger and Kirkwood (1978), Kirkwood and Sarin (1985), Madden, Hyrnick and Hodde (1983), Peerenboom, Buehring and Joseph (1989).

Regulation: Judd and Weissenberger (1982), Keeney and Smith (1982), Lathrop and Watson (1982), Lincoln and Rubin (1979), von Winterfeldt (1982).

Site Selection: Allett (1986), Gregory and Lichtenstein (1987), Hobbs (1980), Hosseini (1986), Keeney (1979), Keeney (1987), Kirkwood (1982), Merkhofer and Keeney (1987).

Technology Choice: Golabi, Kirkwood and Sicherman (1981), Keeney and Sicherman (1983), Keeney, Lathrop and Sicherman (1986), North and Stengel (1982).

Manufacturing and Services

Budget Allocation: Brooks and Kirkwood (1988), Keefer and Kirkwood (1978), Ozernoy, Smith and Sicherman (1981).

Product Planning: Longbottom (1973), Phillips (1982), Ronen and Pliskin (1981), Smallwood and Morris (1980).

Strategy: Digman (1980), Dyer and Lund (1982), Higgins (1982), Lock (1982), Ulvila, Brown and Packard (1977).

Miscellaneous: Belton (1985), Wells (1982), Winter (1985), Wooler (1982).

Medical

Alemi and Angliato (1989), Betaque and Gorry (1971), Bodily (1977), Clarke (1987), Forst (1974), Fryback and Keeney (1983), Mehrez and Gafni (1987), Pliskin, Ronen and Feldman (1987), Pliskin, Shepard and Weinstein (1980), Ronen, Pliskin and Feldman (1984), Sanchez de Rivera (1980), Shachtman (1980), Torrance, Boyle and Horwood (1982), Venta and Venta (1987), Zalkind and Shachtman (1983)

Public Policy

Standard Setting: Anandalingam (1987), Anandalingam (1989), Edwards (1977), Harvey (1983), Jensen, Tome and Darby (1989), Keeney and Ozernoy (1982), Ulvila and Snider (1980), van Steen (1987).

Miscellaneous: Anandalingam and Olsson (1989), Bodily (1978), Chen et al. (1979), Cohan et al. (1984), Edwards and von Winterfeldt (1987), Manne, Richels and Weyant (1979), Peck (1980), Sarin (1983), Ulvila (1987), Ulvila (1988), Ulvila and Seaver (1982), Wenstop and Carlsen (1988).

General

Dalkey (1981), Dyer and Miles (1976), Farmer (1987), Heian and Gale (1988), Janssen and Daniel (1984), Longbottom and Wade (1973), Luna and Reid (1986), Pearman (1987), Pollock and Chen (1986).

combined using a multiplicative utility function. Eight evaluators assigned values to the evaluation measures for each proposal.

Product and Project Selection. Crawford, Huntzinger and Kirkwood (1978) conduct a decision analysis of a power company's choice from among several tower/conductor alternatives for a proposed 765 KV electric transmission line. A deterministic analysis is first conducted, and a sensitivity analysis on uncertain elements shows that the uncertainty might affect the preferred alternative. Thus, a complete probabilistic analysis is done. There are three financial evaluation measures and one environmental evaluation measure. Kirkwood and Sarin (1985) consider selection of borehole plugging materials for underground radioactive waste storage. They develop a pairwise comparison procedure for ranking alternatives when only partial information is known about the weighting constants for the various evaluation measures. This procedure determines the degree of ranking of the various alternatives that is possible when there is only partial information about the tradeoffs among the various alternatives. The analysis identifies a subset of the borehole plugging materials to be given more detailed study.

Madden, Hyrnick and Hodde (1983) discuss the choice between fabric filters and electrostatic precipitators for controlling sulfur dioxide emissions from a coal-fired electric power generating plant. The final decision was made by comparing the cumulative probability distribution functions for each product choice. Peerenboom, Buehring and Joseph (1989) describe the use of a hierarchical decision analysis procedure to develop a portfolio of environmental and health research programs for a commercial-scale synthetic fuels facility. The overall areas of concern in evaluating the 88 proposed projects were project comprehensiveness, relevance, and cost effectiveness.

Regulation. A complication of regulatory decision analysis is deciding whose preferences or values should be used in the decision making. The articles on energy regulatory decision making discussed below address policy issues related to regulatory actions and illustrate the

use of decision analysis methods for this type of decision. Judd and Weissenberger (1982) consider the problem of regulating nuclear material safeguards. Costs and uncertainties associated with various nuclear material control and accounting systems are considered. In addition, potential adversaries of such systems are modeled as well as the consequences of various adversary actions. The analysis of the resulting decision tree model shows that selecting the optimal safeguards system requires consideration of the tradeoffs between the cost of the system and the degree of risk of material diversion.

Lathrop and Watson (1982) apply an expected utility approach to develop risk indices for uncertain health-effect consequences of a nuclear waste management system. Preferences of different interested groups are combined into an overall group function with this approach in order to set regulations, but the method has not actually been used in setting regulations. Lincoln and Rubin (1979) consider cross-media environmental regulation. This arises when regulations to reduce one pollution type (e.g., air) may lead to increases in other types of pollution (e.g., water or land). Thus, tradeoffs must be made between several interdependent emissions. The authors illustrate how multiattribute utility theory could be applied to this problem. The results for an illustrative coal-fired generation scenario show that the key consideration is the tradeoff between solid waste and SO_2 emissions. The implication is that no single regulation or technology is optimal with respect to all pollutants.

Another regulatory model is found in Keeney and Smith (1982). This article examines the impact on nuclear facility operators of regulations for nuclear material control and accounting. Evaluation considerations include employer impact, implementation costs, and regulatory uncertainty. The article shows the usefulness of decision analysis methods for incorporating values into the analysis of a complex policy problem. Von Winterfeldt (1982) considers regulation of chronic offshore platform oil discharge in the United Kingdom. Three separate models are developed for governmental, environmental, and operator stakeholders in the regulatory process. These models are used to evaluate different regulatory procedures for chronic offshore oil discharge from the standpoints of the three interested parties.

Site Selection. Allett (1986) presents an illustration of how decision analysis might be applied to coal mine siting. This article presents less detail than the other siting studies discussed below, but a strength is its comparison of multiattribute decision analysis with cost benefit analysis for the analysis of environmental impacts. Hobbs (1980) discusses a nuclear power plant siting problem in the state of Maryland. The focus is to investigate the importance of evaluation measure weights in the final decision. After brief reviews of different methods for selecting these weights, two methods are compared using a set of 18 evaluation measures determined by five siting experts. Significantly different decisions are made using the two methods.

Hosseini (1986) considers selection of a location for a wildcat oil well. Considerable detail is provided on the analysis of geological and engineering uncertainties, as well as those due to economic and political factors. Judgmental probabilities are used to analyze these uncertainties, and a decision tree is used to evaluate the net present value of two potential well sites based on the assessed probabilities as well as the producer's attitude toward risk taking.

Keeney (1979) presents a multiattribute decision analysis to select a site for a pumped storage facility in the Southwest United States. Evaluation measures for cost, transmission line distance, and two environmental impact considerations are used to assess ten candidate sites. Preferences of key company personnel are obtained. Kirkwood (1982) summarizes a siting study for a 2,500 megawatt nuclear power plant in the western United States. An initial screening process is used to eliminate areas with obvious undesirable characteristics. In this study, the screening process is decoupled into a search for sources with adequate water availability and a search for plant sites that meet certain requirements on health and safety, environmental impact, and systems cost and reliability. Candidate water sources and plant sites are then recoupled for evaluation by a multiattribute decision analysis process involving nine evaluation measures.

Merkhofer and Keeney (1987) present a multiattribute decision analysis conducted to aid the U.S. Department of Energy in its selection of three locations to study in more detail as potential sites for a mined geologic repository for nuclear waste. Five locations that had previously been recommended are evaluated with regard to health and safety, environmental, socioeconomic, and cost factors. The article discusses the role of this decision analysis in the decision making process of the Department of Energy. Gregory and Lichtenstein (1987) review the Merkhofer and Keeney study as well as another report by the Department of Energy on repository site selection. Keeney (1987) extends the work in Merkhofer and Keeney (1987) to explicitly consider portfolio aspects of the selection of three sites. He considers possible probabilistic interdependencies among the sites, as well as sequential study strategies for the sites.

Technology Choice. Both energy producers and energy regulators have applied decision analysis to ascertain proper routes of development for energy-related technologies. Golabi, Kirkwood and Sicherman (1981) combine decision analysis and optimization methods to

evaluate solar energy project proposals. There are no significant uncertainities because the technologies involved are proven. The goal of the selection process is to choose an optimal combination of projects to meet U.S. Department of Energy objectives. Technical quality and two programmatic considerations (budget and diversity) are used as measures of project acceptability. A measurable value function approach is used to develop an overall measure of the technical quality of the projects. Programmatic considerations are incorporated as constraints in a 0-1 linear integer programming optimization approach to determine the final set of projects to be funded.

Studies performed for specific electric utilities are found in Keeney and Sicherman (1983) and Keeney, Lathrop and Sicherman (1986). Both studies utilize the Electric Power Research Institute's technology choice model as an analysis tool. Keeney and Sicherman consider the choice between coal and nuclear generating technologies, while Keeney, Lathrop and Sicherman consider the choice between selecting current coal generating technology or waiting for development of advanced technology.

North and Stengel (1982) use a decision tree model with a single evaluation measure (benefits minus costs) to analyze the choice between the alternatives of tokamak and magnetic fusion test facilities. The extent of uncertainties regarding fusion development is reflected by the 11,000 end-points on the decision tree.

Manufacturing and Services

The manufacturing and services applications are classified into budget allocation, product planning, strategy, and miscellaneous.

Budget Allocation. Brooks and Kirkwood (1988) present a multiattribute decision analysis of a public utility's strategies for dealing with local area networking to link their microcomputers. The existence of multiple interested groups and little hard technical data or expertise compound the problem. A five-step methodology is used which considers nine evaluation measures.

Keefer and Kirkwood (1978) consider the allocation of a department's annual product engineering budget. Various organizational pressures as well as departmental budgetary limitations are considered. The lack of natural evaluation measures means that special evaluation scales need to be constructed for some of the evaluation considerations. A multiattribute utility function is determined for the department director, and the final decision model is a nonlinear optimization model. Ozernoy, Smith and Sicherman (1981) review a decision analysis application to select a computerized geographic information system for a professional consulting firm. A screening process is used to reduce the initial list of 92 potential systems to a final list of five candidates. A multiattribute utility function is developed to rank the final candidates.

Product Planning. Longbottom (1973) considers the analysis of a refrigeration firm's future resource requirements for two noncompeting refrigerated container product lines. The author notes the importance of good communication and company commitment for the acceptance of the analysis. Phillips (1982) presents a "requisite" decision modeling approach for deciding whether to continue producing an existing marine product which faces a possible future commercial ban, or to redesign the product. The requisite modeling approach emphasizes an iterative process, including group discussions, to ensure that no part of the problem is omitted from the analysis. The article includes a discussion of typical pitfalls encountered in decision analysis applications.

Ronen and Pliskin (1981) consider a system reliability decision in the Israeli microelectronics industry. The decision involves whether or not to include redundancy in a diode array circuit as well as the choice of a specific packaging technology. Two analyses are conducted, one considering only cost, and one considering three evaluation concerns (cost, damage, and flexibility). Smallwood and Morris (1980) consider the integrating role of the analyst in interorganizational decision making. Their analysis considers the potential need for increased manufacturing capacity to produce consumables used by a new photocopier. A decision tree model is used, with various submodels providing information for the tree.

Strategy. Digman (1980) presents a simplified analysis of strategies to regain market share in the airline industry following settlement of a strike. In addition to decision analysis, such approaches as game theory and Markov models are considered for analyzing this problem. The application is illustrative of how to form a real-world decision problem into a classroom case discussion. Dyer and Lund (1982) analyze new strategies for merchandising gasoline and other products through full-facility service stations. The decision analysis led to a significant change in marketing strategy which had a large impact on sales.

Higgins (1982) presents two case studies; one involving pricing of advertising space by a newspaper publisher in light of anticipated competitors' actions, and one involving a litigation decision by a food retailer. Both are board level decisions. While the article does not contain much detail about the specific analyses, there is a good discussion of the use of decision analysis at the upper levels of management. Lock (1982) presents an analysis of the potential need to increase a mens shoe

firm's business activity. Eight alternative strategies and twelve evaluation measures are considered.

Ulvila, Brown and Packard (1977) analyze a firm's opportunity to invest in the patent rights for a flight safety product. Uncertainties about product acceptability, government regulatory rulings, and potential defense contract awards are considered in a decision tree model. Judgmental probabilities are obtained by decomposing uncertain quantities and assessing conditional distributions. Review of the decision tree model leads to development of additional decision alternatives.

Miscellaneous. Belton (1985) uses a multiattribute value function approach to assist in selecting, from a short-list of three, the company with which to place a contract for the development of a computerized financial management system. The article includes a discussion of the reaction of participants in the analysis process, as determined by a post-analysis questionnaire.

One of the remaining three decision analysis applications in the manufacturing and service industries deals with the general use of decision analysis in a large diversified English firm (Wells 1982), while the last two applications are in the personnel field (Winter 1985 and Wooler 1982). Wells reports on the successful use of decision analysis in the Imperial Group since 1975, especially the use of decision trees for problem structuring and understanding. A specific application to a distribution problem in the food division is considered in addition to the general discussion.

Winter analyzes a heavy industrial manufacturer's labor contract bargaining strategy over multiple time periods. The major uncertainty concerns union decisions to strike or settle. A decision tree approach is coupled with dynamic programming to optimize each strategy for each possible bargaining period. Winter reports high user confidence in the approach due to increased communication and identification of the risks associated with the alternative strategies. Wooler discusses two computerized decision aids to assist in career choice. His experience shows that the decision analysis aids reduce anxieties generated by attempting to informally analyze career options with many conflicting objectives.

Medical

Much medical decision analysis work has appeared in the medical decision making literature, which is outside the scope of this survey article. Krischer (1980) surveys medical decision analysis applications published between the mid-1960s and the late-1970s, mainly in the medical literature. Studies which have appeared in the operations research literature range from the decision to operate (Clarke 1987) to equipment selection (Pliskin, Ronen and Feldman 1987, and Ronen, Pliskin and Feldman 1984) to diagnosis of disease (Betaque and Gorry 1971, Sanchez de Rivera 1980, and Venta and Venta 1987). These applications can also be classified by whether they deal directly with patients and illness (Clarke 1987, Fryback and Keeney 1983, Mehrez and Gafni 1987, Sanchez de Rivera 1980, Venta and Venta 1987, and Zalkind and Shachtman 1983) or with the physician (the remainder of the applications considered in this section).

Before considering the applications articles in more detail, note that four articles provide general background on the use of decision analysis in medical decision making. Forst (1974) reviews four of the conditions needed to assume the existence of a decision maker's utility function. Pliskin and Pliskin (1980) discuss implementation issues. They argue that the decision tree analysis structure is attractive to physicians and that judgmental probability assessment provides insight in situations where data are not available. However, they say that there are still many problems to overcome to practically apply decision analysis when the decision directly involves a patient. Specifically, they note the difficulty of determining an appropriate utility function to use for a patient's decision problem and the impracticality of determining the patient's utility function in most cases.

Torrance, Boyle and Horwood (1982) provide a review of multiattribute utility theory and discuss the conditions necessary for the existence of an additive or multiplicative utility function. Finally, Venta and Venta (1987) discuss the use of decision trees for a decision problem with a single evaluation measure, although the theoretical development is dispersed within the specific application they consider.

A number of applications address the patient's utility function. Clarke (1987) assumes a utility function for the patient in a case involving the decision to operate for appendicitis. Here, the condition of the patient precluded the direct assessment of his/her utility function. Forst (1974) argues that the patient's utility function should be considered when determining the merits of medical malpractice cases. Mehrez and Gafni's (1987) study takes into account the patient's quality and length of life in deciding on an optimal treatment strategy. Similarly, Pliskin, Shepard and Weinstein (1980) develop a utility function over life years and health status to assist in selecting treatments for coronary artery and chronic kidney disease. Sanchez de Rivera (1980) includes length of life as the primary evaluation measure when identifying disease and prescribing treatment for jaundiced patients. Torrance, Boyle and Horwood (1982) aggregate the utilities of 87 subjects for physical, social activity, emotional, and health attributes into a

multiattribute health state classification index. Finally, Zalkind and Shachtman (1983) develop a nonmonetary tradeoff method for determining one's personal value for death in the context of deciding whether to accept a swine influenza vaccination. Although no utility function is explicitly formulated, values are assessed for tradeoffs between probabilities of reaction to the shot, death, and outbreak of an epidemic.

The remainder of the medical decision analysis applications deal with the physician or some other interested party as the decision maker. Alemi and Agliato (1989) analyze the decision by a bank to provide incentives to its employees to use a preferred provider organization for health services; Betaque and Gorry (1971) analyze the diagnosis and treatment of acute renal failure; Bodily (1977) considers the optimal utilization level of frozen blood in a blood bank; Fryback and Keeney (1983) consider assessment of the trauma severity of injuries; Pliskin, Ronen and Feldman (1987) and Ronen, Pliskin and Feldman (1984) analyze the choice of an appropriate cardiac pacemaker; Shachtman (1980) considers whether to undertake a national evaluation study on nosocomial infection control; and Venta and Venta (1987) analyze the choice of a diagnostic strategy for deep-vein thrombosis.

All the studies that involve probabilities rely on existing data bases or other readily available published data to assess the probabilities except for Alemi and Agliato (1989), Betaque and Gorry (1971), and Mehrez and Gafni (1987). Roughly two-thirds of the studies use a single evaluation measure with a decision tree. Note that Clarke (1987), Fryback and Keeney (1983), Mehrez and Gafni (1987), and Pliskin, Shepard and Weinstein (1980) propose models for decision making but do not apply them to actual applications. The remainder of the articles involving specific models report actual results from applications. In addition, Sanchez de Rivera (1980) and Venta and Venta (1987) are able to develop simple decision rules as a result of their analyses of jaundice and deep-vein thrombosis, respectively, while Betaque and Gorry (1971) report the development and application of a computerized aid for diagnosis.

Public Policy

The public policy articles can be separated into those dealing with standard setting and those dealing with other miscellaneous issues.

Standard Setting. Anandalingam (1987) evaluates acid rain regulation. An objectives hierarchy is developed including economic, environmental, socioeconomic, and other objectives. The intent of this framework is to structure negotiations between states to identify compromise regulations for acid rain. Anandalingam (1989) extends this work by using multiattribute utility functions within a Nash bargaining model. Edwards (1977) considers several standard setting situations including an application of decision analysis for the California Coastal Commission to choose among building development requests, an evaluation of research recommendations for the Office of Child Development, and an evaluation of the possibility of having two different water quality standards instead of one. All three of these applications include successful resolution of interpersonal disagreement among multiple expert decision makers using a multiattribute value assessment procedure.

Harvey (1983) considers approaches to a proposed regulation by the U.S. Department of Transportation requiring the use of daylight running lights on all new highway vehicles. The study does not assign a specific value per fatality prevented but rather determines ranges of values of this quantity for which each alternative is most preferred. Jensen, Tome and Darby (1989) examine whether residential smoke detectors should be required by law. Extensive sensitivity analysis is conducted to account for deficiencies in available data. Keeney and Ozernoy (1982) analyze the definition of an air quality standard for ambient carbon monoxide. The objective is to develop a standard such that the most sensitive population group (those with heart related illnesses) will not suffer from adverse health effects due to the allowed pollution level. Uncertainties about population densities, existing ambient concentrations, and dose/response relationships are considered along with the values of U.S. Environmental Protection Agency decision makers.

Ulvila and Snider (1980) model the international negotiating situation faced by the U.S. in attempting to negotiate standards for marine pollution. Role playing by U.S. Coast Guard personnel as well as special interest groups is used to determine tradeoffs among multiple objectives to use in modeling the positions of various countries involved in the negotiations. These are used to identify compromise solutions in the standards setting negotiations that might be acceptable to various countries. Van Steen (1987) develops a procedure to analyze the desirability of allowing transportation of certain classes of hazardous materials through tunnels in The Netherlands. The paper argues that decision analysis offers the appropriate perspective for dealing with acceptable risk problems, and includes an approach for providing insight into value judgments required to arrive at a decision.

Miscellaneous. Anandalingam and Olsson (1989) apply a three-step methodology to a decision concerning the future fresh water supply for a municipality. Two screening steps are used to reduce the number of alternatives that need to be considered in the final step which

uses a multiattribute value function. Bodily (1978) incorporates the preferences of three interest groups (concerned citizens, administrators, and service personnel) into an analysis of the call response time for police services that takes into account goals for efficiency and quality of service. Chen et al. (1979) develop a "value oriented social decision analysis" method to integrate the preferences of interested parties into the political decision making process considering the installation of a solid waste shredding facility. The objective of this analysis is to make the preferences of the affected parties clearer to the person making the decision.

Cohan et al. (1984) cite three applications of decision analysis to deciding on prescribed forest burns in the Southwest United States. Three types of decisions are considered: treatment selection, planning, and execution. A three component model is used, including decision trees to analyze sequential decisions and uncertainties, a component reflecting the interaction between humans and the forest, and a value model for tradeoffs among conflicting objectives. Edwards and von Winterfeldt (1987) present an iterative and interactive procedure using multiattribute utility functions for formally including the values of various stakeholder groups in public risk debates. The approach is applied to three separate public policy issues: the future development of Germany's energy system, offshore oil leasing policies for southern California, and the siting of water control dams in central Arizona.

Manne, Richels and Weyant (1979) review the application of decision analysis to government research and development policy decisions concerning synthetic fuels and breeder reactors. Peck (1980) argues that decision analysis can be an effective communication tool in considering the effects of both a nuclear power generation moratorium and funding of advanced nuclear reactor concepts. This illustrative article combines such analysis with other previously developed energy system models. Sarin (1983) conducts a decision analysis to formulate and evaluate alternative policies to address seismic safety problems faced by the city of Los Angeles with regard to its old masonry buildings. Tradeoffs between upgrade costs and safety (reduced injuries and deaths in the event of an earthquake) are examined from the viewpoint of building owners, renters, policy makers and planners, and the public-at-large.

Ulvila (1987, 1988) found it impractical to assess a utility function for the U.S. Government, but the results of his analysis of the new ZIP + 4 automation technology turned out to be insensitive to uncertainties, making determination of a utility function unnecessary. Used as the basis for a report to Congress, the model addresses technological and economic uncertainties, as well as the uncertain degree of the voluntary use of the new zip code system by business. Ulvila and Seaver (1982) analyze the water supply problems of various Boston suburbs. They develop an evaluation model including seven criteria important to three interested groups of communities affected by a proposed project. Tradeoffs among evaluation criteria are elicited for each group.

Wenstop and Carlsen (1988) focus on a development strategy for 542 proposed Norwegian hydroelectric projects. A study by the Norwegian Ministry of Environment had ranked the proposed projects, where high rankings were achieved by those projects exhibiting low cost and minimal conflict. Wenstop and Carlsen deemed that study to be irrational, thus prompting their multiattribute utility analysis. The article and an accompanying letter from officials of the Ministry of Environment illustrate the complexities of decision analysis in a political setting.

General

Nine articles do not fit into the four categories discussed above. Dalkey (1981) uses decision analysis in an attempt to resolve Hamlet's famous decision problem "to be or not to be." Dyer and Miles (1976) consider trajectory decisions for the two 1977 Mariner Jupiter/Saturn space missions. Collective choice rules were applied to this large-group decision problem to select a pair of trajectories to meet science investigation objectives while keeping within mission constraints. Farmer (1985) compares several multiattribute utility approaches for modeling external auditor perceptions of the reliability of a firm's internal control systems. Janssen and Daniel (1984) analyze the American football decision to either run/pass or kick for conversion in the closing moments of a close game.

Longbottom and Wade (1973) interviewed personnel from seventeen selected United Kingdom firms in the summer of 1971 to investigate the use of decision analysis. They determined that deterministic sensitivity analysis was the primary tool used at that time. Decision trees, judgmental probability estimates, and risk analysis methods were also generally used. Capital investment was the most common application area, followed by marketing. Luna and Reid (1986) present a decision tree analysis approach for individuals attempting to select from available mortgage instruments. Heian and Gale (1988) extend Luna and Reid's mortgage selection model to include the borrower's time preferences and attitude toward risk.

Pearman (1987) provides a recent comparison of U.K. and U.S. decision analysis applications. Through interviews and an appraisal of the literature, he found that the U.K. lags the U.S. in applications of decision analysis.

Table II
Articles Addressing Methodological and Implementation Issues

Problem Structuring/Formulation

Anandalingam (1987), Anandalingam (1989), Anandalingam and Olsson (1989), Belton (1985), Betaque and Gorry (1971), Bodily (1977), Dyer and Lorber (1982), Dyer and Lund (1982), Dyer and Miles (1976), Edwards and von Winterfeldt (1987), Fryback and Keeney (1983), Keeney (1979), Keeney and Sicherman (1983), Keeney and Smith (1982), Kirkwood (1982), Merkhofer and Keeney (1987), North and Stengel (1982), Ozernoy, Smith and Sicherman (1981), Peerenboom, Buehring and Joseph (1989), Smallwood and Morris (1980), Ulvila and Snider (1980), van Steen (1987), Wenstop and Carlsen (1988), Wooler (1982).

Decision Trees

Alemi and Agliato (1989), Bell (1984), Betaque and Gorry (1971), Chen et al. (1979), Clarke (1987), Cohan et al. (1984), Crawford, Huntzinger and Kirkwood (1978), Digman (1980), Hosseini (1986), Janssen and Daniel (1984), Jensen, Tome and Darby (1989), Judd and Weissenberger (1982), Keeney (1987), Keeney, Lathrop and Sicherman (1986), Keeney and Ozernoy (1982), Kirkwood (1982), Luna and Reid (1986), Madden, Hyrnick and Hodde (1983), Manne, Richels and Weyant (1979), North and Stengel (1982), Peck (1980), Phillips (1982), Pliskin, Ronen and Feldman (1987), Ronen and Pliskin (1981), Ronen, Pliskin and Feldman (1984), Sanchez de Rivera (1980), Sarin (1983), Shachtman (1980), Smallwood and Morris (1980), Ulvila (1987), Ulvila, Brown and Packard (1977), Venta and Venta (1987), von Winterfeldt (1982), Wells (1982), Winter (1985), Zalkind and Shachtman (1983).

Probability Assessment

Betaque and Gorry (1971), Crawford, Huntzinger and Kirkwood (1978), Dalkey (1981), Hosseini (1986), Jensen, Tome and Darby (1989), Keefer and Kirkwood (1978), Keeney, Lathrop and Sicherman (1986), Keeney and Sicherman (1983), Longbottom (1973), Madden, Hyrnick and Hodde (1983), North and Stengel (1982), Ronen and Pliskin (1981), Sanchez de Rivera (1980), Ulvila (1987), Ulvila, Brown and Packard (1977).

Utility Assessment

Anandalingam (1989), Anandalingam and Olsson (1989), Betaque and Gorry (1971), Bodily (1978), Brooks and Kirkwood (1988), Crawford, Dyer and Lorber (1982), Dyer and Lund (1982), Dyer and Miles (1976), Edwards (1977), Farmer (1987), Fryback and Keeney (1983), Golabi, Kirkwood and Sicherman (1981), Huntzinger and Kirkwood (1978), Keefer and Kirkwood (1978), Keeney (1979), Keeney, Lathrop and Sicherman (1986), Keeney and Sicherman (1983), Keeney and Smith (1982), Kirkwood (1982), Merkhofer and Keeney (1987), Pliskin, Ronen and Feldman (1987), Pliskin, Shepard and Weinstein (1980), Ronen and Pliskin (1981), Ronen, Pliskin and Feldman (1984), Sanchez de Rivera (1980), Torrance, Boyle and Horwood (1982), van Steen (1987), Zalkind and Shachtman (1983).

Communication/Facilitation

Alemi and Agliato (1989), Belton (1985), Chen et al. (1979), Dyer and Lund (1982), Dyer and Miles (1976), Edwards and von Winterfeldt (1987), Gregory and Lichtenstein (1987), Keefer and Kirkwood (1978), Keeney (1987), Lock (1982), Madden, Hyrnick and Hodde (1983), Merkhofer and Keeney (1987), Peck (1980), Peerenboom, Buehring and Joseph (1989), Phillips (1982), Pollock and Chen (1986), Smallwood and Morris (1980), Ulvila (1988), Ulvila, Brown and Packard (1977), Ulvila and Snider (1980), Wells (1982), Wenstop and Carlsen (1988), Winter (1985).

Group Decision Making

Bodily (1978), Dyer and Miles (1976), Edwards (1977), Edwards and von Winterfeldt (1987), Golabi, Kirkwood and Sicherman (1981), Keeney, Lathrop and Sicherman (1986), Lathrop and Watson (1982), Lincoln and Rubin (1979), Sarin (1983), Sarin, Sicherman and Nair (1978), Torrance, Boyle and Horwood (1982), Ulvila and Snider (1980), von Winterfeldt (1982).

As reasons for this, he cites: 1) the natural time lag in the dissemination of the method because it was primarily developed in the U.S., 2) more extensive decision analysis education in the U.S. due to the large number of M.B.A. programs, and 3) cultural and organizational differences which make the U.S. more receptive to the method.

Finally, Pollock and Chen (1986) found difficulties in attempting to apply decision analysis to the "black stink" water pollution problem in Shanghai, China. Generation of action alternatives and accounting for uncertainties was almost impossible because of cultural pressures to avoid confrontation by not deviating from previously stated or assumed goals.

3. METHODOLOGICAL AND IMPLEMENTATION ISSUES

Many of the articles surveyed provide significant detail about decision analysis methodological or implementation issues. Specifically, several articles address each of the following issues: problem structuring/formulation, decision trees, probability and utility assessment, communication/facilitation, and group decision making. Table II shows articles that address each issue.

Articles are included in the problem structuring/formulation category if they provide an objectives hierarchy and/or explain the structuring process in significant detail. Articles are included in the decision tree category if they pictorially present a decision tree and discuss its use. Articles are included in the probability assessment category if probabilistic dependence/independence questions are discussed and/or there is substantial discussion of judgmentally elicited distributions. Likewise, articles in the utility assessment category discuss lottery questions to elicit utility functions, pictorially present the resulting utility functions, and/or explicitly describe assessment of tradeoffs among evaluation measures.

Those articles included in the communication/facilitation category consider such issues as the success or failure of the analysis, reflections on the analysis by involved parties, or the role of the analyst. Finally, articles included in the group decision making category deal with aggregation of several individual's preferences into a single function.

4. CONCLUDING COMMENTS

This survey provides a guide to decision analysis applications appearing in major English language operations research journals and other closely related journals from 1970 through 1989. These applications cover a wide range of decision problems in both the public and private sectors. It is worth reiterating the comment made at the beginning of the article that many of the applications address strategic or policy decisions. Thus, they provide counterexamples to the often-stated criticism that operations research addresses lower level operational problems successfully, but not the strategic issues that are the central concern of top management in business and government.

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