The Analytic Hierarchy Process – An Exposition

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1. The Analytic Hierarchy Process and its foundation

The foundation of the Analytic Hierarchy Process (AHP) is a set of axioms that carefully delimits the scope of the problem environment (Saaty 1986). It is based on the well-defined mathematical structure of consistent matrices and their associated right-eigenvector's ability to generate true or approximate weights, Merkin (1979), Saaty (1980, 1994). The AHP methodology compares criteria, or alternatives with respect to a criterion, in a natural, pairwise mode. To do so, the AHP uses a fundamental scale of absolute numbers that has been proven in practice and validated by physical and decision problem experiments. The fundamental scale has been shown to be a scale that captures individual preferences with respect to quantitative and qualitative attributes just as well or better than other scales (Saaty 1980, 1994). It converts individual preferences into ratio scale weights that can be combined into a linear additive weight w(a) for each alternative a. The resultant w(a) can be used to compare and rank the alternatives and, hence, assist the decision maker in making a choice. Given that the three basic steps are reasonable descriptors of how an individual comes naturally to resolving a multicriteria decision problem, then the AHP can be considered to be both a descriptive and prescriptive model of decision making. The AHP is perhaps, the most widely used decision making approach in the world today. Its validity is based on the many hundreds (now thousands) of actual applications in which the AHP results were accepted and used by the cognizant decision makers (DMs), Saaty (1994b).

For all that has been written about AHP (http://www.ExpertChoice.com contains references to over 1000 articles and almost 100 doctoral dissertations), there is also much misunderstanding. It is our belief that the real essence of AHP is not generally understood. AHP is more than just a methodology for choice - although it has been successfully applied in thousands of choice decisions. It is not just another analysis tool, although analysis is the first word in its title. The best way we can describe AHP is to describe its three basic functions: (1) structuring complexity, (2) measuring on a ratio scale, and (3) synthesizing. We will look at these functions in detail after reviewing a bit of AHP's history. We will also look at some of the controversy about AHP that has appeared in the academic literature.

2. History of the development of AHP

In the late 1960’s, Thomas Saaty, one of the pioneers of Operations Research, and author of the first Mathematical Methods of Operations Research textbook and the first queueing textbook, was directing research projects for the Arms Control and Disarmament Agency at the U.S. Department of State. Saaty's very generous budget allowed him to recruit some of the world's leading economists and game and utility theorists. In spite of the talents of the people Saaty recruited (three members of the team, Gerard Debreu, John Harsanyi, and Reinhard Selten, have since won the Nobel Prize), Saaty was disappointed in the results of the team's efforts. Saaty[1996] later recalled:

> Two things stand out in my mind from that experience. The first is that the theories and models of the scientists were often too general and abstract to be adaptable to particular weapon tradeoff needs. It was difficult for those who prepared the U.S. position to include their diverse concerns … and to come up with practical and sharp answers. The second is that the U.S. position was prepared by lawyers who had a great understanding of legal matters, but [who] were not better than the scientists in accessing the value of the weapon systems to be traded off.

Years later, while teaching at the Wharton School, Saaty was troubled by the communication difficulties he had observed between the scientists and lawyers and by the apparent lack of a practical systematic approach for priority setting and decision making. Having seen the difficulty experienced by that the world's best scientists and lawyers, Saaty was motivated to attempt to develop a simple way to help ordinary people make complex decisions. The result was the Analytic Hierarchy Process – a synthesis of existing concepts that attests to Saaty's genius through its power and simplicity.

There is ample evidence that the power and simplicity of AHP has led to a widespread acceptance and usage in the United States as well as throughout the world. In addition to Expert Choice, there have been several other successful commercial implementations of AHP, one with financial backing of the Canadian Government. Many of the world's leading information technology companies now use AHP in the form of decision models provided by the Gartner Group's[1], Decision Drivers[2]. The American Society for Testing and Materials (ASTM) has adopted AHP as a standard practice for multiattribute decision analysis of investements related to buildings and building systems[3]. The AHP process is taught in numerous Universities and used extensively in organizations such as the Central Intelligence Agency that have carefully investigated AHP's theoretical underpinnings.

3. The Three Primary AHP Functions

AHP has been applied in a wide variety of applications – multi objective decision making being just one. A look at the three primary functions of AHP, structuring complexity, measurement, and synthesis helps in understanding why AHP is such a general methodology with such a wide variety of applications.

Structuring Complexity

Saaty sought a simple way to deal with complexity. Simple enough so that lay people with no formal training could understand and participate. He found one thing common in numerous examples of the ways humans had dealt with complexity over the ages – that was the hierarchical structuring of complexity into homogeneous clusters of

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[1] http://www.gartner.com
[2] http://www.decisiondrivers.com
[3] ASTM Designation E: 1765-95 "Standard Practice for Applying Analytical Hierarchy Process (AHP) to Multiattribute Decision Analysis of Investments Related to Buildings and Building Systems.

factors. Saaty was not the first to observe the importance of hierarchical structuring in human thought:

Herbert Simon [1972], wrote:

> "Large organizations are almost universally hierarchical in structure. That is to say, they are divided into units which are subdivided into smaller units, which are, in turn, subdivided and so on. Hierarchical subdivision is not a characteristic that is peculiar to human organizations. It is common to virtually all complex systems of which we have knowledge. ... The near universality of hierarchy in the composition of complex systems suggest that there is something fundamental in this structural principle that goes beyond the peculiarities of human organization. An organization will tend to assume hierarchical form whenever the task environment is complex relative to the problem-solving and communicating powers of the organization members and their tools. Hierarchy is the adaptive form for finite intelligence to assume in the face of complexity."

In his book [1969] on "Hierarchical Structures" L.L. Whyte expressed this thought as follows:

> "The immense scope of hierarchical classification is clear. It is the most powerful method of classification used by the human brain-mind in ordering experience, observations, entities and information. ... The use of hierarchical ordering must be as old as human thought, conscious and unconscious..."

Measurement on a Ratio Scale

Whereas earlier decision making methodologies relied on lower levels of measurement (Electre using ordinal measurement and MAUT interval measurement) Saaty's mathematical training convinced him that ratio scales would most accurately measure the factors that comprised the hierarchy. This also was not a new idea. According to Stevens' [1946] measurement classification scheme, there are four levels of measurement. The levels, ranging from lowest to highest are Nominal, Ordinal, Interval, and Ratio. Each level has all of the meaning of the levels below plus additional meaning. For example, a ratio measure has ratio, interval, ordinal and nominal meaning. An interval measure does not have ratio meaning, but does have interval, ordinal and nominal meaning. Ratio measure is necessary to represent proportion. Whereas the proportions in Monet's paintings, for example, are representative of the world as most people see it, Picasso's paintings are treasured for their thought provoking qualities, but are not good models of the real world. In keeping with his search for as simple a methodology as possible, Saaty proposed using judgments of the ratios of each pair of factors in the hierarchy to derive (rather than assign) ratio scale measures.

Any hierarchically structured methodology (like AHP and MAUT) must use ratio scale priorities for elements above the lowest level of the hierarchy. This is necessary because the priorities (or weights) of the elements at any level of the hierarchy are determined by multiplying the priorities of the elements in that level by the priorities of the parent element. Since the product of two interval level measures is mathematically meaningless, ratio scales are required for this multiplication. Whereas AHP also utilizes ratio scales for even the lowest level of the hierarchy (the alternatives in a choice model), MAUT utilizes an interval scale for the alternatives. Thus the resulting priorities for alternatives in an AHP model will be ratio scale measures whereas those in a MAUT model will be only interval scale measures. The ratio scale, being a higher level of measurement, is particularly important if the priorities are to be used not only in choice applications, but for other types of applications such as resource allocation. A detailed discussion of the ratio scales developed by AHP is presented in Section 8 below.

Synthesis

Analytic, the first word in AHP's name, is a form of the word analysis, which means separating a material or abstract entity into its constituent elements. Analysis is the opposite of synthesis, which involves putting together or combining parts into a whole. Because complex, crucial decision situations, or forecasts, or resource allocations often involve too many dimensions for humans to synthesize intuitively, we need a way to synthesize over many dimensions. High level corporate decisions meetings may have vice presidents of finance, marketing, operations, information systems, and human resources sitting around a conference table, each 'armed' with the results of analyses that their departments have performed. Each may also have reached a different conclusion as to what is best for the organization. The impasse usually is not because of a lack of good analyses, but a lack of ability to synthesize the analyses that have been made.

Numerous courses at Universities teach analysis of one sort or another. Many organizations have departments or divisions with the word analysis in their title. We speak of financial analysis, marketing analysis, operations analysis, and process analysis. Organizations have become quite good at doing analysis. Few organizations, however, know how to synthesize! Although AHP's hierarchical structure does facilitate analysis, an even more important function is AHP's ability to help us measure and *synthesize* the multitude of factors in a hierarchy. We know of no other methodology that facilitates synthesis as does AHP!

4. Why AHP is so widely applicable

Any complex situation that requires structuring, measurement, and and/or synthesis is a good candidate for AHP. However, AHP is rarely used in isolation. Rather, it is used along with, or in support of other methodologies. For example to synthesize the results of other methodologies such as in deciding how many servers to employ in a queueing situation taking into account waiting times, costs, and human frustrations, or to derive probabilities for a decision tree. Broad areas where AHP has been successfully employed include: selection of one alternative from many; resource allocation; forecasting; total quality management; business process re-engineering; quality function deployment, and the balanced scorecard – many of these will be illustrated below.

5. Principles and Axioms of the Analytic Hierarchy Process

Having discussed the three basic functions of AHP, we turn our attention to the three related basic principles of AHP: decomposition, comparative judgments, and hierarchic composition or synthesis of priorities [Saaty 1994b]. The decomposition principle is applied to structure a complex problem into a hierarchy of clusters, sub-clusters, sub-sub clusters and so on. The principle of comparative judgments is applied to construct pairwise comparisons of all combinations of elements in a cluster with respect to the parent of the cluster. These pairwise comparisons are used to derive 'local' priorities of the elements in a cluster with respect to their parent. The principle of hierarchic composition or synthesis is applied to multiply the local priorities of the elements in a cluster by the 'global' priority of the parent element, producing global priorities throughout the hierarchy and then adding the global priorities for the lowest level elements (usually the alternatives).

All theories are based on axioms. The simpler and fewer the axioms, the more general and applicable the theory. AHP is based on three relatively simple axioms. The first axiom, the reciprocal axiom, requires that, if $P_C(E_A,E_B)$ is a paired comparison of elements A and B with respect to their parent, element C, representing how many times more the element A possesses a property than does element B, then $P_C(E_B,E_A) = 1/P_C(E_A,E_B)$. For example, if A is 5 times larger than B, then B is one fifth as large as A.

The second, or homogeneity axiom, states that the elements being compared should not differ by too much, else there will tend to be larger errors in judgment. When constructing a hierarchy of objectives, one should attempt to arrange elements in clusters so that they do not differ by more than an order of magnitude in any cluster. (The AHP verbal scale ranges from 1 to 9, or about an order of magnitude. The numerical and graphical modes of Expert Choice accommodate almost to two orders of magnitude, allowing a relaxation of this axiom. Judgments beyond an order of magnitude generally result in decreased accuracy and increased inconsistency).

The third axiom states that judgments about, or the priorities of, the elements in a hierarchy do not depend on lower level elements. This axiom is required for the principle of hierarchic composition to apply. While the first two axioms are, in our experience, completely consonant with real world applications, the third axiom requires careful examination, as it is not uncommon for it to be violated. Thus, for example, in choice applications, the preference for alternatives is almost always dependent on higher level elements (the objectives), the importance of the objectives *might* be dependent on lower level elements (the alternatives). For example, in choosing a laptop computer, if the alternatives were almost the same weight but differed greatly in speed, then speed might be more judged to be more important than weight. But if the laptop computers were almost the same speed but differed greatly in weight, then weight might be judged to be more important than speed. (In either case, the relative importance of speed and weight is subjective). When such dependence exists, the third axiom of AHP does not apply. We describe such situations by saying that there is feedback from lower level factors to higher level factors in the hierarchy. There are two basic ways to apply AHP in those choice situations where this third axiom does *not* apply -- that is, when there is feedback. The first involves a supermatrix calculation [Saaty 1980, Saaty 1996] for synthesis rather than AHP's hierarchic composition. For simple feedback (between adjacent levels only), this is equivalent to deriving priorities for the objectives with respect to each alternative, in addition to deriving priorities for the alternatives with respect to each objective. The resulting priorities are processed in a supermatrix, which is equivalent to the convergence of iterative hierarchical compositions. While this approach is extremely powerful and flexible, a simpler approach that we have found to work well in practice, is to make judgments for lower levels of the hierarchy before the upper levels, or, alternatively, to reconsider judgments at the upper levels after making judgments at the lower level). In either approach, the brain performs the feedback function by considering what was learned at lower levels of the hierarchy when making judgments for upper levels. Thus, an important rule of thumb is to make judgments in a hierarchy from the bottom up, unless one is sure that there is no feedback, or one already has a good understanding of the alternatives and their tradeoffs.

A fourth axiom to AHP, introduced later by Saaty, says that individuals who have reasons for their beliefs should make sure that their ideas are adequately represented for the outcome to match these expectations. While this axiom might sound a bit vague, it is important because the generality of AHP makes it possible to apply AHP in a variety of ways and adherence to this axiom prevents applying AHP in inappropriate ways. We will illustrate this a bit later.

Ockham's razor contends that the simplest of two or more competing theories is preferable. Most AHP theorists and practitioners feel that AHP's axioms are simpler and more realistic than other decision theories. In addition, AHP is applicable to areas besides choice decisions (such as forecasting and resource allocation) and the ratio scale measures that AHP produces makes it more powerful than other theories that rely on ordinal or interval measures.

6. Overview of AHP Applications

The following applications illustrate the wide breath of areas to which AHP has been applied.

Choice

Choice decisions involve the selection of one alternative from a set of alternatives under consideration. Typical choice problems include product selection, vendor selection, organizational structure decisions and policy decisions. Some recent applications include:

Xerox

The Xerox Corporation uses AHP for R&D decisions on portfolio management, technology implementation, and engineering design selection. AHP is also used to help make marketing decisions regarding market segment prioritization, product-market matching, and customer requirement structuring. Tim Carroll, who has facilitated over 50 major decisions with AHP at Xerox, observes that intuitive decisions are much more easily overturned than decisions made with AHP because the latter are based on a body of facts and criteria that people have carefully discussed and agreed to. To date, none of the major decisions made with AHP at Xerox have been overturned.

British Columbia Ferries

British Columbia Ferry Corporation in Canada, uses AHP to in the selection of products, suppliers and consultants. B.C. Ferries is a provincial crown corporation that provides passenger and vehicle ferry service to 42 ports of call throughout coastal British Columbia. Its 40 vessels operate year round and carry more than 22 million passengers and 8 million vehicles annually. Carol Wyatt, Manager of Purchasing, Planning and Technical Services uses AHP for many different applications including determining the best source for fuel (the single largest expense for B.C. Ferries); contracting professional services such as legal, banking, insurance brokers, and ship designers; evaluating major computer systems; selecting service providers such as grocery suppliers, and vending and video game companies; hiring consultants; and evaluating various product offerings. According to Ms. Wyatt, interdepartmental teams gain an improved understanding of each others' concerns and perspectives regarding the decision about to be made. Everyone stays focused on the goal at hand, eliminating much of the circular discussion and dissension that often occurs with interdepartmental teams using traditional evaluation and decision methods. And, most importantly, the decision is more readily accepted as each member of the team has participated in the decision making process.

Management Reorganization at Edgewood

The U.S. Army Chemical and Biological Defense Agency and the Edgewood Research Development and Engineering Center (ERDEC) in Maryland, used AHP to select the new management structure for the ERDEC Research and Technology Directorate. A number of management arrangements was considered ranging from an empowered team concept, with current office chiefs providing technical oversight, to having the technical planning done by a board composed of high grade office chiefs, and back again to a modified office/team line style. The objectives, requirements and constraints were boiled down to seven objectives (criteria): 1) empower teams, 2) comply with existing government regulations, 3) allow technical integration among the organizational elements,4) maintain current grades of personnel, 5) have a clear understanding of duties and responsibilities, 6) flatten the organization by reducing the layers of management, 7) allow rapid implementation. This evaluation showed how difficult it is to adopt new and unorthodox organizational arrangements within the constraints of existing government regulations and grade level requirements.

John H. Heitz and Miles C. Miller, "Selection of Best Reorganizational Arrangement for the Research and Technology Directorate using the Expert Choice Decision Program", Report # ERDEC-SP-005, Aberdeen Proving Ground, Maryland 21010.

NASA

A NASA/DOE decision conference to recommend a power source for the first lunar outpost used AHP to consider criteria such as as Safety, Performance, Reliability, and Flexibility in evaluating alternatives ranging from photo-voltaic cell farms to nuclear reactors. One alternative was called "power beaming" and involved actually beaming power to the surface of the moon where photo voltaic cells would convert this laser light energy back into electrical energy. Participants included people from many of the National Laboratories, the Air Force, NASA, and HQ Department of Energy. The conference was facilitated by Peter Beck, a facilitator for The Analytic Sciences Corporation.

Choosing the Lunar Lander Propulsion System

NASA's Lyndon T. Johnson Space Center in Houston, Texas, used AHP to perform a study to select a propulsion system for the Lunar Lander. Thirteen alternative vehicle configurations were compared to a reference vehicle, the First Lunar Outpost Lander, to explore the impacts of various propellant combinations, propellant feed systems, and staging options on vehicle and mission trade parameters. Robert J. Moreland and Jerry B. Sanders of the Propulsion and Power Division facilitated the evaluation and involved management , through a couple of iterations, in selecting the criteria and making judgments in the first two levels of the hierarchy. During the process a cohesive position evolved at Johnson Space Center that melded many different personalities. Moreland and Sanders observed that there was little argument with the conclusions because after people agreed on the assumptions they found it difficult to argue with the conclusions. However, there was a surprise in the results. Before they began the study, Moreland and Sanders thought that recently developed complex propulsion systems would be the preferred choice for the next trip, but, in fact, they found that simpler more reliable systems were better because low risk was so important. The recommended systems were the CIF5/N2Hr pressure fed concept, a highly reliable, simple and compact design, and the LO2/LH2 IME concept, strong on high performance, with high reliability and simplicity. These two together were found to allow NASA the best flexibility to support a variety of future space exploration programs.

*Robert J. Moreland & Jerry B. Sanders, "Lunar Lander and Return Propulsion System Trade Study: Methodology with Results" , American Institute of Aeronautics and Astronautics 93-2606, AIAA/SAE/AS*ME/ASEE*, 29th Joint Propulsion Conference*, 1993.

Prioritization/Evaluation

Prioritization applications involve determining the relative merit of a set of alternatives, as opposed to selecting one alternative as in choice applications. When prioritizing alternatives, the order, intervals, and ratios of the resulting priorities are of interest in addition to knowing which alternative has the highest priority. Since AHP derived priorities are ratio measures, the priorities can be used in selecting a combination of alternatives or in allocating resources. (Specific examples of resource allocation applications will be given later.)

In general, an *evaluation* entails making an estimate or measurement. Whereas at least two items must be considered in a prioritization, an evaluation can, in theory, be performed on something in its own right. In practice, however, it is very difficult, if not impossible, to evaluate something with multiple dimensions unless it is compared to other things or to a standard. Thus, an evaluation is often performed as a prioritization. A few prioritization/evaluation applications of AHP are presented next.

University of Santiago of Chile

After submitting 10 research proposals to the Government of Chile in 1991, none of which were funded, Professor Mauricio Escudey, Vice Rector of the University of Santiago of Chile, used AHP to help develop proposals in 1993. The first model was used to rank projects according to their likely success of being funded based on what were thought to be the important criteria to the Government. After the initial ranking, the top contenders were selected and a consultant was brought in to help strengthen the proposals on those criteria where they were weakest. Three projects were submitted and after a four month process of evaluation by the Government of Chile, all three projects were funded for a total of almost $3 million dollars. The University of Santiago was the only university to achieve a 100% level of success.

Royal Institute of Technology, Stockholm

AHP was applied to screen working fluids for heat engines using both hard engineering variables and soft data at the Royal Institute of Technology, Stockholm, Sweden. Dr. Jinyue Yan, originally from Tianjin, China, considered the requirements of thermodynamics, technology, economics, and the environment. His main criteria were: power output, capital cost, operational cost, and environmental influence, with 24 subcriteria in a 5 level decision structure. Dr. Yan used detailed engineering factors to judge 23 fluids such as methylene chloride, isobutane, water, and ammonia.

Rockwell International

The Space Systems Division uses AHP in its Computer Aided Systems Engineering Tool Set (CASETS) environment. CASETS provides a common product development framework with integrated software tool support. Within CASETS, AHP is used for criteria weighting, utility functions, and sensitivity analysis. CASETS has been applied to NASA and Department of Defense projects that include development of new space launch vehicles, surveillance satellites, and SDI architecture studies.

Environmental Impact Evaluations

Claudio Garuti of Fulcrum Ingenieria Ltd., Chile used AHP as part of a methodology for environmental impact evaluations of big projects such as highways and classification and selection of projects in a pollution reduction plan for ports in Chile. The environmental impact evaluations had three phases: (1) identification of alternatives, (2) evaluation of the alternatives considering all possible components (ecological, anthropological, economical, social, technical,...), and (3) reducing or eliminating the environmental impacts of the best alternative(s). In 1987 a new 100 kms highway for heavy traffic was projected between the cities of Florence and Bologna. When the environmental impact evaluations started, the highway path was already given. The team divided the path in sectors of 100 meters each, the components of the highway over which the impacts would be evaluated in a detailed manner. The objective of the study was to "minimize the natural and anthropological impacts of the highway on the environment." A hierarchy of six levels was formed with a total of 36 terminal objectives or leaves. The main objective was decomposed into the three sub-objectives: minimizing the natural and aesthetic impacts, minimizing the socio-economic impacts and minimizing the conflicts with the regulation zone plan. One of the striking benefits of using this approach for the highway was that it enabled the teamwork leader to obtain general consensus among the participants

General Motors

Car designers on the General Motors' Advanced Engineering Staff use AHP to evaluate design alternatives, perform risk management, and arrive at the best and most cost-effective automobile designs.

Evaluating Superfund Effectiveness

AHP has been applied to evaluate the effectiveness of the House of Representatives sponsored Superfund Bill HR2500. The work was performed by Larry Deschaine, Manager of Industrial Programs for Apex Environmental, Inc., in partnership with a major industrial trade association, to provide house members with a basis for decision making. Mr. Deschaine evaluated the remedy selection portion of HR2500 which involves a five factor balancing test to determine a remedy's effectiveness: reliability, risks, community acceptance and cost. To establish a baseline for comparison purposes, he used information contained in 50 Records of Decision (ROD) that detailed remedies selected under the current Superfund process. The ROD database was statistically similar to the National Priority List. Remedies evaluated ranged from groundwater pump and treat to fences and bottled water or no action. AHP helped in determining that HR2500 would be fully protective of human health and the environment while achieving a 35% cost savings.

U.S. Navy Submarines Executive Office

The Executive Office, Submarines, uses AHP to determine the factors that drive the selection of electronic equipment that is installed on submarines. By using AHP to analyze factors critical to submarine missions and to analyze alternative solutions, the Navy highlights critical issues and reduces the time frame to make equipment selections.

Trout Fishing in Alaska

Rainbow trout are not indigenous to interior, northern or northwest Alaska. Nevertheless, they are popular with anglers, and some members of the public have been advocating that the Alaska Fish and Game Department stock rainbow trout in Alaskan streams. In response to this demand the Department studied selected streams near Fairbanks and applied AHP to evaluate stream suitability as a habitat for rainbow trout including reproduction considerations and overwinter survival.

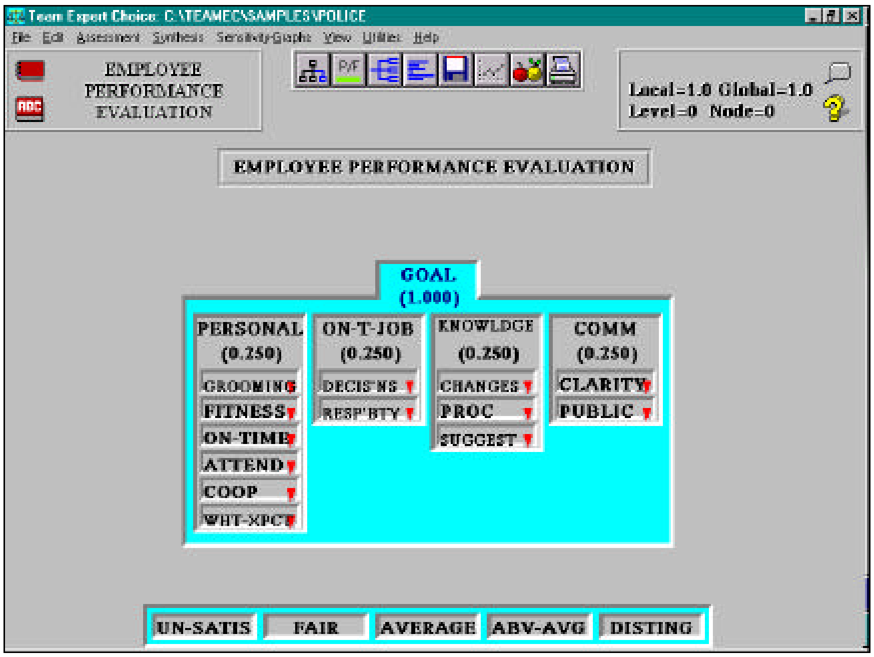
Margaret F. Merritt, <u>Ranking Selected Streams in Interior Alaska on the Basis of Suitability for Sustaining an Introduced Rainbow Trout Population</u>, presented at the TIMS XXXII conference, June, 1994, Anchorage, Alaska.

Evaluating Architecture Alternatives and Assessing Risks at the FAA

Martin Marietta Air Traffic Systems applied AHP to evaluate alternatives architecture for a communication system under review for capital investment by the Federal Aviation Administration (FAA). The application was facilitated by Krishna Bachu in a group setting of 30 experts representing many divisions of regions of the FAA. AHP was used to identify the preferred alternative without having to perform a lengthy and time-consuming cost-benefit analysis process. The AHP model finally agreed upon by the group had a combination of subjective and objective factors. The hierarchical model included costs, operational characteristics, schedule and technical risks, safety, coverage, diversity, spectrum, flexibility, etc., as main and sub criteria.

Police Officers Evaluation

The Waltham, Massachusetts Police Department (WPD) needed a way to combine and analyze the new officer evaluation ratings under multiple criteria. Ido Millet, of Bentley College worked with the WPD to structure an AHP model with four major criteria, and twelve sub-criteria and five rating intensities. Previously, each officer had been evaluated on each of the twelve criteria, using a scale of 1 to 5. Since the ratings had already been done, Dr. Millet devised a conversion program to convert existing ratings into Expert Choice ratio scale weights. The results were used to generate a variety of management reports and graphs.



This system allows the WPD to identify and track a variety of concerns. At the same time, the system provides a tool for management to articulate priorities and communicate performance expectations to the officers. The WPD has begun holding workshops on their personnel evaluation approach for other police departments in the area.

Software Development Productivity

Twenty or more years ago, computer programming managers, straight from manufacturing assembly lines, paid their programmers by the number of lines of code they wrote, thus rewarding results that were the opposite of what they should have wanted. It has not gotten much better since then. We still do not know how to measure productivity in programming. Don Petkov and his colleagues at the University of Natal in South Africa have pinpointed many of the factors involved in software productivity, and laid out their relationships in an AHP hierarchy for prioritizing software development productivity factors. The first level criteria were: technical attributes, project attributes, developer attributes, and user attributes. In the next level are 18 factors that affect these criteria such as management commitment, requirements volatility, and user involvement.

"Prioritizing Software Development Productivity Factors using the Analytic Hierarchy Process", Petkov, D., G.R. Finnie, and G.E. Wittig, Journal of Systems and Software,North Holland, 1993.

Investment Analysis

A.K. Simpson & Co., Pittsburgh, was asked to advise a financial group with regard to investment merits of a robotics and automated assembly company which specializes in applications for automobile manufacturing. They performed a 90 minute AHP evaluation with the cooperation of the target's CEO. This procedure closely tracks normal investment banking "due diligence", and gains several benefits: speed, group interaction, and an explicit overall ranking for each competitor.

Resource Allocation

An effective allocation of resources is a key to achieving an organization's strategic as well as tactical objectives. Resource allocation is also a key to the operation of any 'system'. Churchman [1979] observed that a necessary condition for conceiving of something as a 'system' is that there is a decision maker who - via *resources* - can produce changes.

> "In organizations, the decision-making function is the responsibility of management. In order to execute its responsibility, an organization's management requires information about the resources available to it and their relative effectiveness for achieving the organization's purpose. Resources are acquired, allocated, motivated and manipulated under the manager's control. They include people, materials, plant and equipment, money, and information."

Information about what resources are available to management is usually easy to ascertain. Much more difficult to ascertain is the relative effectiveness of resources toward the achievement of the organization's purpose, or purpose*s* to be more accurate, since all organizations have multiple objectives. Resource allocation decisions are perhaps the most political aspect of organizational behavior. Because there are multiple perspectives, multiple objectives, and numerous resource allocation alternatives, a process such as AHP is necessary to measure and synthesize. Specifically, in order to make resource decisions that best achieve an organization's multiple objectives, an organization must be able to:

Identify / design alternatives (e.g., alternative R&D projects, or operational plans for alternative levels of funding for each of the organization's departments)

Identify and structure the organization's goals into objectives, subobjectives, sub-subobjectives, and so on

Measure (on a *ratio* scale) how well each alternative contributes to each of the lowest level subobjectives

Find the best combination of alternatives, subject to environmental and organizational constraints.

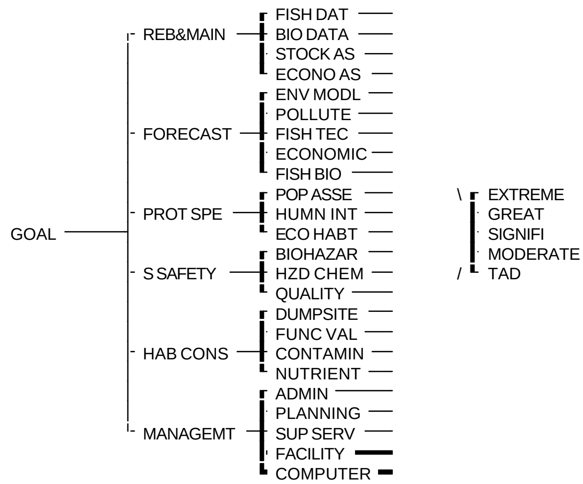
AHP has been instrumental in numerous resource allocation decisions – some involving billions of dollars. A few of these are described next.

Budget Allocation at Woods Hole Fisheries

The Northeast Fisheries Science Center (NEFSC) is a federal government organization that conducts multi-disciplinary marine research on the northeastern U.S.

continental shelf, concentrating primarily on human and environmental factors that affect the abundance, distribution, health, and food quality of commercially important fish and shellfish species. Research activities are directed at both the immediate needs of resource managers dealing with volatile public use issues, and longer term monitoring and analysis of trends in the abundance, health, and habitat quality of fish and shellfish populations. Under the supervision of Ambrose Jerald, the AHP was used to evaluate and prioritize existing components of the NEFSC research program to assure adequate support for those components considered to be vital to the Center's mission at the expense of cutting or redirecting low priority components. As there were numerous projects, the model helped the managers rationally evaluate information about each project. Once the research projects were prioritized the results were used with an optimization model to allocate budgetary resources. Given strictly limited budget resources, this method enabled managers to turn qualitative appraisals of how various activities relate to the center's goals into quantitative decisions which support the allocation of funds.

Prioritize operations relative to strategic plan



Abbreviation	Definition
GOAL	
ADMIN	Resource needs (fiscal/personnel) to administer NEFC research
BIO DATA	Biological data from NEFC research vessels (age&growth,fecundity)
BIOHAZAR	Fish and invertebrate biohazards (algal blooms, PSPs, etc.)
COMPUTER	Computer support (hardware, software, consultation, contracts)
CONTAMIN	Contaminant effects on population (organic and inorganic)
DUMPSITE	12 and 106 mile studies
ECO HABT	Ecological roles/habitats (food habits, spatial distrib. etc...)
ECONO AS	Economic assessments
ECONOMIC	Bio-economic models
ENV MODL	Enviornmental models (biotic and abiotic mechanisms)
EXTREME	
FACILITY	Facilities, equipment, supplies, maintenance
FISH BIO	Fisheries biology
FISH DAT	Fisheries data from the commercial and recreational industry
FISH TEC	Fishery forecasting model (technical interactions, etc.)
FORECAST	Advance fishery forecasts and ecosystem models (goal 3)
FUNC VAL	Functional value of habitat to LMRs

Customer and Company Values at Scarborough Public Utilities

Conventional cost-benefit analysis leaves out the most important part: the values of the company and its customers. A more modern method for evaluating projects, programs and alternatives, value-based analysis, is being used by the Scarborough Public Utilities Commission in Ontario, Canada. Daria Babaie-Azadi and his colleagues at Scarborough are using a three part process. The first task is the ‘cost-justification’ test which checks the economic feasibility of the different projects under consideration. It is a conventional cost-benefit study used to filter out unsuitable projects and provide decision makers with a comparison of rates of return. The second task is to apply the ‘value-based judgment test’ which incorporates the company’s objectives and goals as well as customers’ values into the model using AHP. The final task is an optimization process which maximizes the benefits offered by competing projects, programs and alternatives using a zero-one programming technique. A value-based analysis like this incorporates the company's prioritized objectives, concerns and needs, as well as those of its customers, to assist decision makers with investment planning, commercial policy, and development policy.

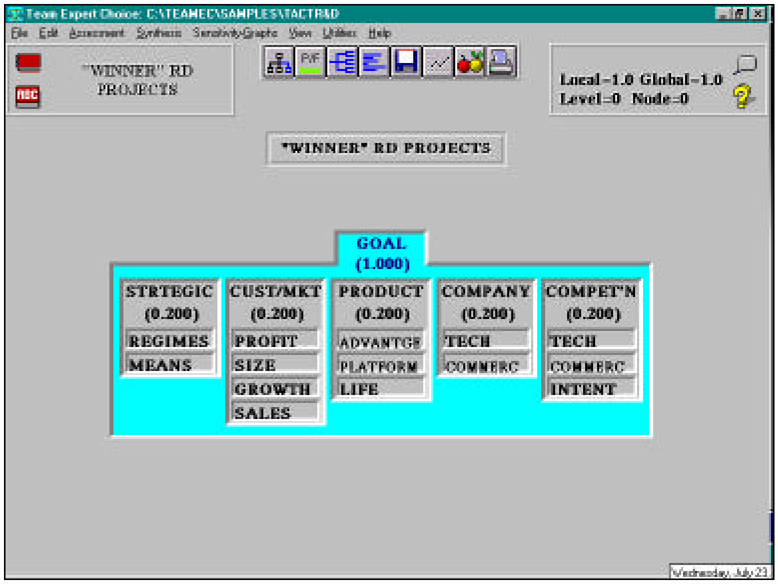
Daria Babaie-Azadi, Faraz Chaudhery, Kim Allen, Joe Bailey Scarborough Public Utilities Commission, Ontario, Canada

Air Force Medical Services Reorganization

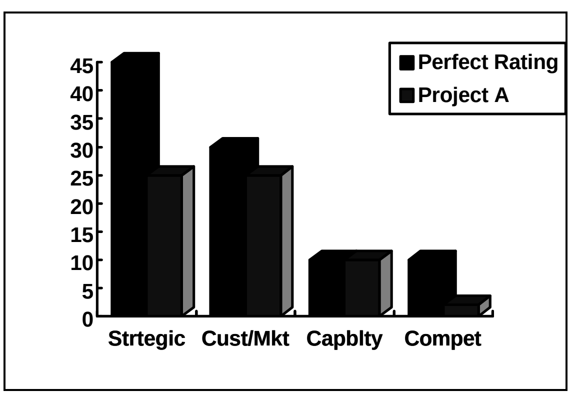
Twenty five Air Force Medical Services Generals and Colonels (including the Air Force Surgeon General) participated in joint decision making using AHP for reallocating resources throughout the entire Air Force medical community. The decision session was facilitated by Barbara Christoph of PUMA systems and lasted an incredible twelve hours. According to Ms. Christoph, the process gave them a comprehensive, dynamic picture of the decision to be made and kept them focused on the objectives to be achieved. One participant commented "I've never before spent a whole day sitting in the same room in the same chair and felt good about it."

Tactical R&D Project Evaluation and Funding at Air Products

Allocating scarce resources among diverse projects is a continual problem facing R&D management. The Air Products and Chemicals company uses a systematic project selection process based on AHP to identify and build consensus around the key issues for success, communicate these factors to improve project proposals, and help to extend limited funding to maximize project progress and completion. Decision-makers select and weigh criteria in a structured framework based on the Analytic Hierarchy Process. Project champions then propose their projects within that framework. Project strengths and weaknesses are clearly identified by using profiles of the project ratings for each criterion. Thus, strong projects are fully funded, weak projects are not funded, and intermediate projects are funded to resolve weakness. Merrill Brenner of Air Products observed, "By using the project strengths and weaknesses that we've determined from the model to change their scope and emphasis we have turned weak projects into major money making successes."



Abbreviation	Definition
ADVANTGE	ADVANTAGE TO THE CUSTOMER
COMMERC	COMMERCIAL STRENGTHS
COMPANY	COMPANY CAPABILITIES
COMPET'N	COMPETITOR FACTORS
CUST/MKT	CUSTOMER/MARKET FACTORS
GROWTH	MARKET GROWTH
INTENT	STRATEGIC IMPORTANCE TO COMPETITORS
LIFE	DURABILITY OF PRODUCT
MEANS	WAYS IN WHICH WE PREFER TO OPERATE
PLATFORM	CAN BE EXTENDED INTO OTHER PRODUCTS
PRODUCT	PRODUCT CHARACTERISTICS
PROFIT	PROFITABILITY
REGIMES	TYPE OF BUSINESS IN WHICH WE WILL PARTICIPATE
SALES	POTENTIAL SALES
SIZE	AMENABLE MARKET SIZE
STRTEGIC	STRATEGIC FACTORS
TECH	TECHNICAL STRENGTHS



A typical summary profile showing how project A (light bars) measures up against a project with perfect ratings (dark bars).

Merrill S. Brenner, Air Products and Chemicals, Inc., Tactical R & D Project Prioritization, Research Technology Management, Sept. - Oct., 1994.

Prioritizing Telecommunications for Long Range R & D Planning

AHP was used to prioritize, forecast and allocate resources for the Korea Telecommunication Authority (KTA), the primary common carrier in Korea. The process, developed by Chang-Kyo Suh, Eui-Ho Suh and Kwang-Churn Baek, was divided into two major phases. During the first phase, the task force constructed a six level hierarchical model of all relevant factors, identifying critical categories at each level and their relationships. During the second phase, 40 representatives from R&D-related divisions in KTA went through the hierarchical structure and derived a priority matrix for each level. In order to set the baseline budget level selection and the scope of research activities, they used the following steps: 1) prioritize the technology, 2) estimate the required budget, 3) devise the resource allocation index, 4) forecast the total R&D budget, 5) set the R&D investment index, 6) decide the R&D budget, and 7) allocate the budget among the 10 core technologies. Based on this research, a two-phased DSS for R&D portfolio selection was developed.

IEEE Transactions on Engineering Management, Vol. 41, No. 3, August 1994.

Savannah River Site Remediation

Management of a multi-site remediation portfolio was simplified and optimized with an AHP based decision support computer model developed under the auspices of the DOE Enhanced Work Planning (EWP) initiative at the Savannah River Site. The model, developed by Larry Deschaine, organizes the key project quantitative information (cost and savings) and qualitative information (estimate of implementation complexity) into an overall framework for evaluation. The information is then processed using a hybrid Linear Programming/Expert Choice Analytic Hierarchy Process analysis technique to designate an optimal selection of projects for a specified funding level. The model is currently being applied to a portfolio of 116 site remediation projects at the Savannah River Site and results indicate that with an initial site wide investment of $3 million, an annual cost savings of over $18 million can be realized. The model framework is general enough to facilitate cross-pollination into other multi-project EWP initiatives.

Selection of Water-Supply Projects Under Drought

Proposed water-supply projects may be evaluated with respect to one or more objectives and in the context of one or more operating environments. Such evaluation is commonly considered a technical exercise and reserved for technical specialists. However, since preferences and judgments are required to identify and weigh relevant objectives and to assess the characteristics and likelihoods of different possible environments, project evaluation is unavoidably value-laden and thus should not be considered an exclusively technical enterprise. Mark A. Ridgley, of the University of Hawaii at Manoa, Honolulu, HI, has used AHP to help make environmentally sensitive decisions. His article, "Selection of Water-Supply Projects under Drought" appeared in the *Journal of Environmental Systems, Volume 21, Number 3, 1991-2*. Ridgley's model is able to handle evaluations of importance that are inherently value-laden and likely to be political. It takes into account the likelihood of droughts of different magnitude and duration and the effect they have on overall system goals. The approach has two main parts. First, an AHP model is used to measure the attractiveness of candidate projects with respect to different objectives and scenarios regarding drought and water demand.

The second part employs these measures in an optimization model to identify the correspondingly best set of projects.

Benchmarking

Comparison or benchmarking of key business processes with other best-of-breed companies and organizations is instrumental in gaining or maintaining a competitive advantage [Eyrich 1991]. In order to evaluate and assure that one has the best processes (and decide what improvements are needed), it is necessary to make comparisons with other best-of-breed companies and organizations. Comparisons should be made with the best regardless of industry membership or geography. Finding out what other companies are doing to operate their key business processes, setting the right goals, and achieving those goals, is a key strategy that helps put an enterprise on the road to being *best*. This involves the evaluation and synthesis of many factors, both quantitative and qualitative. Benchmarking is one of the categories on which firms are evaluated for the Malcom Baldridge Quality Award.

IBM AS400 Benchmarking

Henry Eyrich, as part of the Silverlake team at IBM Rochester MN, applied AHP to benchmark IBM’s computer integrated manufacturing processes against other best of breed companies throughout the world, regardless of industry membership or geography. This effort helped in making the AS400 project one of the most extremely profitable IBM ventures as well was winning the Malcom Baldridge Award.

The Silverlake team felt it was important to thoroughly understand processes that were to be benchmarked before contacting companies with which to make comparisons. Without proper preparation, each member of a benchmarking team would have had their own list of priorities to focus on and the utility of the results would be minimal. In order to maximize the return on benchmarking resources and achieve significant results, a consensus had to be developed as to what it means to be "best". This involved the evaluation and synthesis of many factors. The AHP methodology was used by the IBM Rochester Minnesota's computer integrated manufacturing (CIM) process team to articulate what needed to be accomplished to be the best. The approach consisted of the following steps:

1. Develop a hierarchical structure or model of the CIM processes and define relationships.
2. Compare the relative importance of hierarchical factors.
3. Synthesize the comparisons to arrive at overall weights for deciding what requirements were the most important for success.

The Silverlake Project - Transformation at IBM, Oxford University Press, New York, 1992.

Eyrich, H.G., "Benchmarking to Become the Best of Breed," Manufacturing Systems magazine, April 1991.

Square D Company

The Square D Company, located in Palatine, IL used AHP to structure their sheet metal forming process. This structuring, conducted under the direction of Dr. Nandu N. Thondavadi, Technical Director Manufacturing Systems, resulted in the identification and ranking of 38 parameters needed to be best of breed. Since structuring the sheet metal process, Square D has benchmarked internally and with other companies, and has structured other processes as well.

Carlson Travel Network

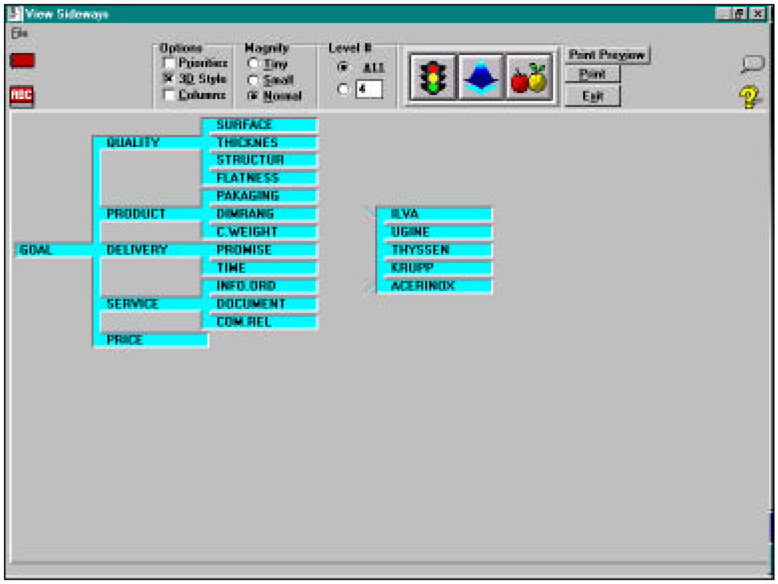
Staff at the corporate business center of Carlson Travel Network-Commercial, located in Minneapolis, used AHP to identify and prioritize approximately 44 requirements needed to successfully manage their corporate business center. Carlson benchmarked this process. Mr. John Riener, President, Carlson Travel Network-Commercial, and Ms. Pam Haack, Directory, Quality Management, brought a group of client commercial travel managers into their corporate headquarters to complete an AHP hierarchy for the travel management process. This work articulated what critical success factors and requirements are needed to manage corporate travel. It also calculated the relative importance of each critical success factor and requirement. Customers advised Carlson that this approach not only facilitated benchmarking, but helped focus on the most important job requirements.

Quality Management

The basic functions of AHP –structuring complexity, measurement, and synthesis over multiple dimensions – are applicable to numerous aspects of quality management and TQM. Quality is multi-dimensional, as is illustrated by the hierarchy of Malcom Baldridge criteria [United States Department of Commerce, 1996] that include seven major criteria: Leadership, Information Analysis, Strategic Planning, Human Resource Development and Management, Process Management, Business Results, and Customer Focus and Satisfaction. Some of these criteria are quantitative and some are qualitative and AHP provides a way to synthesize quantitative and qualitative factors..

Quality Evaluation in the Steel Industry

The Stainless and Magnetic Steel Divisions of the ILVA company of Italy, in response to increased competitiveness of foreign steel producers, needed to monitor the quality as perceived by Italian customers. Natalino Dazzi, of Iretecna of Milan, Italy, used AHP for customer evaluation on divisional performance. AHP was used to conduct interviews with the most relevant customers who were asked to compare ILVA's performance with that of its competitors. Several models similar to the model shown below were constructed and grouped according to the special steel end-use sector (eg. stainless pipe producer, household appliances, vessels). Each sector was prioritized in accordance with its relevance for ILVA as well as each customer. The global model (including all sector models, not shown) is used to continuously monitor ILVA's performance quality as perceived by the from the different market points of view.



Abbreviation	Definition
C.WEIGHT	COILS WEIGHTS
COM.REL	COMMERCIAL RELATIONS
DIMRANG	DIMENSIONAL RANGE
DOCUMENT	DOCUMENTS RELATIVE TO THE ORDER
FLATNESS	FLATNESS ERRORS
INFO.ORD	INFORMATION ON ORDER
PAKAGING	PACKAGING MATERIALS
PROMISE	PROMISE OBSERVANCE
STRUCTUR	MECHANICAL CHARACTERISTICS
SURFACE	SURFACE ASPECT
THICKNES	THICKNESS TOLERANCE
TIME	DELIVERY TIME

Improving Yields in a Steel Company

Latrobe Steel Company, a subsidiary of the Timken Company, used AHP in its continuous quality improvement program. A consulting company in Pittsburgh facilitated a series of meetings with Latrobe Steel's experts to extract their knowledge and to build a hierarchical cause and effect AHP model to focus on key areas that needed to be controlled in order to improve the process. The goal was to increase yields during the ingot-to-billet stages of processing. AHP helped relate the key variables to each other with respect to their effect on yields. The result was a significant improvement in yields. In addition, the model served as a learning tool, emphasized team effort concepts, provided structure to group decisions and provided the necessary platform for a continuous improvement agenda.

Public Policy

Public Policy decisions are complicated not only because they involve competing objectives, but also because they impact multiple economic sectors and sometimes overlapping jurisdictions. Communication of competing constituencies' objectives (and their relative importance) is necessary in developing policies that are acceptable to more than one constituency. Traditional dialogs tend to focus on alternatives, rather than objectives. The structure provided by AHP allows competing constituencies to better understand each other and to develop ‘win – win’ solutions.

Formulating Policies for the Sea of Japan

The Environment and Policy Institute, East-West Center, Honolulu, Hawaii, uses AHP in regional seas management. Daniel J. Dzurek modeled the processes and influences to understand what is important in the formulation of particular marine policies. Marine policy formulation is usually difficult because of overlapping jurisdictions and the multiple economic sectors involved. In seas in which many countries have interests, such as the Sea of Japan, the problems multiply. AHP presented a useful framework for discussing the problems of regional seas management by experts and policy makers from the countries of the area.

Managing the Kenai River Chinook Salmon Fishery

The Cooperative Fish and Wildlife Research Unit of the Alaska Department of Fish and Game, applied the Analytic Hierarchy Process (AHP) to the management of the world class recreational fishery for Chinook Salmon in the Kenai River, Alaska. Management of this fishery is complicated by the conflicting objectives of multiple stakeholders. This leads to conflict. The demands on the river have led to the development of separate regulations and allocations among recreational users. Besides the recreationalists, multiple landowners - private, native, commercial and government - have a stake in the lands adjacent to the Kenai River. Managing these lands is complicated even more because their jurisdiction is divided among several federal, state and municipal agencies. In addition, active environmental groups are concerned about the degradation of the river habitat.

Peggy Merritt of the Fish and Wildlife Research Unit, along with Keith Criddle, of the University of Alaska Fishery Economics Center developed an AHP model through an iterative interview process with individuals who represented the perspectives of 15 different stakeholders in 10 different interest categories. The model consisted of 75 issues and 107 options, 93 of which were unique. The emphasis that was placed by the stakeholders on political, social and economic concerns not commonly within the domain of fishery managers was striking. Despite the differences among the stakeholders, the study identified some broadly supported management options. The Department plans to subsequently use AHP to evaluate streams for suitability for introducing rainbow trout.

This study was presented in October 1992 at the International Symposium on Management Strategies for Exploited Fish Populations in Anchorage, Alaska, sponsored by the University of Alaska Sea Grant Program. It is published in the symposium proceedings,.

Florida Water Management District

The South Florida Water Management District applied AHP in a water quality model for blue-green algal blooms in Lake Okeechobee. The AHP was shown to be useful in finding the sources of differences in opinion. Making this difference of opinion explicit provided a constructive basis for discussion about what is most important with respect to the overall interests of the South Florida Water Management District.

Health Care

Health care decisions are often complex, value laden, and involve numerous players and uncertainties. Patients rely on Physicians for their expertise while Physicians often have to make assumptions or guess about Patient feelings relative to pain and discomfort, willingness to pay un-reimbursed costs, and fear of the unknown. Patients, Physicians, Health Care Insurers, Employers and Society often have competing objectives. AHP is useful in structuring the complexity of health care decisions and ascertaining values and preferences of those involved in health care decision making.

Patient Versus Physician Preferences

Patients with acute upper gastrointestinal hemorrhage can undergo upper gastrointestinal endoscopy to determine the source of the bleeding. Is this expensive test worth it? For 75-80% of patients standard treatment stops the bleeding with neither patient nor doctor needing to know its exact location. Of course, endoscopy plays an important role in the management of those patients who continue to bleed despite standard medical therapy. Still, why has diagnostic endoscopy become routine? Either it is being overused, or it is providing physicians and their patients with benefits not measured in the clinical studies. Drs. James G. Dolan, Donald R. Bordley and Heidi Miller of the University of Rochester School of Medicine in Rochester, New York, used AHP to determine which view is preferred. The goal was to choose the best diagnostic management of acute upper gastrointestinal bleeding.

The objectives were:

1) Minimize cost
2) Identify exact cause of bleeding
3) Avoid test complications
4) Avoid poor outcome from bleeding
5) Minimize length of stay

The alternatives were:

1) Immediate endoscopy
2) Routine endoscopy
3) Upper GI X-Ray
4) No routine test

Twenty-five patients recovering from a recent hemorrhage and 22 primary care physicians participated using AHP to make individual judgments in the model to choose their preferred diagnostic management from the alternatives. Immediate endoscopy was preferred by 92% of the patients and 55% of the physicians. Comparing this to the 85% rate of endoscopy at the hospital suggests that the current high rate of diagnostic endoscopy is not because of the physicians, but because of the patients. Patients want to know where they are bleeding, even if this information will not affect the prognosis or the management of their case. The patients ranked *identifying the cause of bleeding* the second most important objective after *avoiding a poor outcome* from the acute bleeding episode. While patient preference should be taken into account, still we need to ascertain whether this justifies the costs, in dollars and side effects, of routine diagnostic endoscopy. In our society's current debate regarding the proper use of medical technology and the allocation of health care resources, a full understanding of all benefits and risks of medical procedures is essential.

James G. Dolan, Donald R. Bordley, Heidi Miller, "Diagnostic Strategies in the Management of Acute Upper Gastrointestinal Bleeding: Patient and Physician Preferences", J. of General Internal Medicine, v. 8, October, 1993. Please address correspondence and reprint requests to: Dr. Dolan: Rochester General Hospital, 1425 Portland Avenue, Rochester, NY 14621.

Selecting Teams to Respond in Medical Disasters

The Madigan Army Medical Center of Tacoma, Washington, used AHP to very quickly determine the type of medical personnel (civilian or military specialized response teams) to activate and dispatch in case of a disaster. An earthquake, for example, may predominantly cause casualties from collapsed buildings but it may also be complicated by fires to a variable degree. Thus burn teams as well as orthopedic and general surgical teams need to be dispatched early on. Barbara Guller, MD. COL, MC, USAR developed an AHP model containing five different natural disasters. Four different injury mechanisms (building collapse, fire, etc.) were evaluated with respect to each type of disaster. The lowest level of the model contains seven alternatives for the best medical response team. The model can not only be used for a particular disaster and is sensitive to the prevalence of injury mechanisms occurring with the disaster but it can also be used for medical force planning.

Developing a Merit Compensation Plan

The University of Pittsburgh Anesthesiology & Critical Medicine Foundation uses AHP for merit compensation decisions. The AHP model, developed by David Tkach, CPA, MBA and D. Ryan Cook, MD, MBA, incorporated department goals and objectives including: 1) leadership in clinical service, 2) strong, competitive residency programs, 3) recognition as a major, productive academic department, both within the university and nationwide, and 4) stability at the organizational and financial levels. The plan was constructed to support the objectives of a large academic anesthesiology department, not necessarily those of a private practice group. Criteria for additional compensation included: 1) standard salary, 2) increases for promotion in academic rank, and 3) board certification along with paid incentives for outside research grants. Thus, faculty evaluation for re-appointment, promotions and tenure, and merit pay are parallel processes. The scoring matrix consisted of clinical service, administration, education and scholarship components, each with three or four subcomponents. The Anesthesiology & Critical Medicine Foundation staff was confident that the model was supported by sound theory and by changing certain details of the model, won faculty acceptance.

Medical Group Management Journal, September/October 1991.

Using the AHP to Develop and Disseminate Medical Guidelines

James G. Dolan and Donald R. Bordley, Associate Professors of Medicine, University of Rochester, and Members of the General Medicine Unit, Rochester General Hospital, Rochester, NY, used AHP to develop and disseminate medical practice guidelines. Among the many problems perceived with practice guidelines, one stands out as fundamental: Practice guidelines which are directed at a large group of patients have a different focus than clinical practice, which is directed at one patient at a time. A method, such as AHP, for reconciling these different viewpoints must be developed for practice guidelines to be truly effective in improving medical care.

“Using the Analytic Hierarchy Process (AHP) to Develop and Disseminate Guidelines” in the QRB Journal, December 1992.

Strategic Planning

Strategic planning has many facets, several of which are facilitated with AHP. J. Heizer, B. Render (*Production and Operations Management: Strategies and Tactics*, Allyn Bacon, 1993 p25,26) describe the strategy development process as follows:

> "In order to develop an effective strategy, organizations first seek to identify opportunities in the economic system. Then we define the organization's mission or purpose in society -- what it will contribute to society. This purpose is the organization's reason for being, that is, its **mission.** Once an organization's mission has been decided, each functional area within the firm determines its supporting mission. .. "We achieve missions via strategies. A **strategy** is a plan designed to achieve a mission. .. A mission should be established in light of the threats and opportunities in the environment and the strengths and weakness of the organization."

AHP can assist an organization in selecting among alternative missions, in selecting among alternative strategies, and in allocating resources to implement the chosen strategy. Strategic planning involves a 'forward process' of projecting the likely or logical future and a 'backward' process of prioritizing desired futures. The backward process affords people an opportunity to expand their awareness of what states of the system they would like to see take place, and with what priorities. Using the backward process, planners identify both opportunities and obstacles and eventually select effective policies to facilitate reaching the desired future.

Managing National Park Service Resources

Managers for the National Park Service and other agencies are charged with managing a wide array of natural resources, including measurable commodities, esthetic values, and ecosystem processes. However, there is often no calculable standard (such as economic value) by which to compare the importance of these resources. In addition, there are often so many different planning objectives and individual projects that it is difficult to keep track of all of them, let alone develop a program that emphasizes each properly. David L. Peterson, of the National Park Service and Daniel L. Schmoldt, of the USDA Forest Service, University of Washington, Seattle used AHP in strategic planning to integrate multiple objectives in order to create a course of action. Developing a natural resource inventory and monitoring program in national parks is an example of such a planning activity. Because the completion of all program activities is constrained by time and money, it is critically important to develop a plan of inventory and monitoring activities that makes the "best" use of available agency resources. AHP helps structure this multicriteria decision making problem. Inventory and monitoring program objectives and decision criteria are organized into a hierarchy. The resulting priority values for all inventory and monitoring projects are used as each project's contribution to the overall program. Priorities developed in the AHP, along with budget and personnel constraints, are formulated as a zero/one integer programming problem, which are solved to select those projects that produce the best overall program. This approach is being applied to national parks in the Pacific Northwest region of the U.S.

3M

3M Office Product Division consultant Tom Swails uses AHP for strategic planning and group decision making. In particular, Swails uses AHP to deal with critical business objectives to be met by strategies which must be implemented by programs and projects. A computerized version of AHP gives him the ability to iterate -- to quickly adjust to changes in judgments or other information. Swails also uses AHP in groups to stimulate discussion and to help people visualize "what-if" planning.

Strategic Planning in the Military

Military planners have recently had to downsize. Major Daniel B. Carpenter of the United States Marine Corps and Lieutenant Donald J. Ebner of the United States Navy write, "As military budgets continue to dwindle, prudent planning and wise use of assets will be the highest priority for military planners." Carpenter and Ebner developed a model for selecting bases for realignment or closure. The main criteria in their model were value, in terms of current and future mission requirements, return on investment with regard to extent and timing of potential costs and savings, and economic impact on communities. The criteria, adopted by DOD in 1991, were based on the work of the 1988 Base Realignment and Closure Commission.

Daniel K. Carpenter and Donald J. Ebner, Using Software Applications to Facilitate and Enhance Strategic Planning, Naval Postgraduate School, Monterey, CA, Sept., 1993.

7. Detailed AHP applications

Two detailed AHP applications are presented in this section.

7.1 AHP at the Inter-American Development Bank[4]

In addition to use in face-to-face meeting environments, the AHP process has also been successfully used in distributed group decision support environments. This section presents one of several applications of AHP in distributed group decision support environments at the Inter-American Bank, a large multibillion-dollar international financial organization. The Inter-American Development Bank (IDB), a modern, sophisticated organization with about 1,500 employees, organized both advisory committees and project teams to work on six important decisions:

- selection of the best alternative for the automation of its investment activities
- selection of the best alternative for the automation of its account reconciliation process
- selection of the best alternative for the implementation of an electronic image management system
- selection of an external audit company
- selection of a provider of VSAT (satellite) communications
- selection of a provider of Health Care Services

The advisory committees were composed primarily of managerial level members who were in charge of the organizational units that were either responsible for the internal support of, or dependent on the use of the solution to be implemented. The initial role of an advisory committee was to provide guidance to the project team about project goals and objectives, the decision making process, and the schedule to be followed. The advisory committee members were responsible for assessing the relative importance of the decision objectives. The project teams were composed of staff or external consultants

[4] The author's wish to thank Dr. Lauro Lage-Filho for the account of this application.

working for the IDB's units represented in the advisory committees. Project team members had the best knowledge of the details of the problem to be solved and were responsible for evaluating the preference for the alternatives with respect to the criteria previously established or approved by the advisory committees. Subsequently, the advisory committees would review and approve the technical evaluations performed by the project teams and prepare recommendations to support the recommended alternative. We will describe the account reconciliation process project next.

The IDB had been operating its bank accounting reconciliation function through a manual process requiring the work of seven officers for ten working days each month. The process is complex because of a large and increasing number of accounts (about 250), a majority of them dealing in U.S., Canadian, Japanese, or European currencies.

The IDB's accounting division proposed the automation of the IDB reconciliation project with the following rationale:

> The Accounting Division believed that the maximum level of efficiency in the IDB reconciliation process had been achieved given the constraints of the accounting system and personnel; however, additional improvements needed to be made to the reconciliation process to increase productivity and free staff resources to be assigned to other accounting control work. The Accounting Division has concluded that the most cost-effective approach to increase productivity was to implement an electronic bank reconciliation system. Electronic bank reconciliation has been utilized by financial institutions for several years. Discussions with users and vendors indicated that an electronic bank reconciliation process could automate the matching of transactions and significantly improve research and processing of outstanding exception items.

The advisory committee accounting division identified numerous benefits of this automation project, including: (1) savings in staff time corresponding to more than $100,000 per year; (2) ability to cope with the expected future increase of transactions without hiring additional staff; (3) faster resolution of outstanding problems; (4) daily account balancing for critical bank accounts; and (5) more effective managerial controls.

The distributed group decision support environment used by the IDB consisted of employing Lotus Notes and Team Expert Choice to implement Herbert Simon's Intelligence, Design, Choice model for decision making. The methodology is depicted in Table 1.

Table 1 -- Methodology

Intelligence Phase

- Discuss a preliminary problem statement in order to:
  obtain an enriched and consensual view of the problem.

Design Phase

- Discuss an initial list of alternatives in order to:
  obtain a revised list of alternatives;
  obtain an initial set of objectives/criteria.
- Discuss an initial set of objectives/criteria in order to:
  obtain a revised set of objectives/criteria.

Choice Phase

- Structure one or more AHP/Expert Choice models in order to:
  obtain common (group) Expert Choice model(s).
- Elicit individual judgments.
- Incorporate the geometric mean of the individual judgments into the combined Team Expert Choice model and synthesize the priorities.
- Discuss and approve the final results and analyses.
- Document the decision for justification and control.

The distributed group decision support methodology was presented to members of the advisory committee and project team in a four-hour, "hands-on" seminar. Concepts of AHP were presented as well as techniques for making the computer conference more effective. In order to illustrate the methodology, participants were asked to tackle a personal decision problem using the proposed methodology. The participants worked on a new house acquisition decision currently being considered by one of the participants. The exercise was very realistic and positively motivated the participants.

Description of the Methodology

The intelligence, design and choice phases of the decision methodology are described next.

Intelligence Phase

Simon's intelligence, concerned with identifying the problem or opportunity, was conducted entirely through a Lotus Notes computer conference, although a mixture of face-to-face and computer conference sessions is possible. Regardless of the mode, it is important to give the group the opportunity to discuss, understand, and define the problem fully. During the intelligence phase, the group can reframe the problem or even define a new one.

The problem statement resulting from the computer conference read:

> The team will evaluate and select an account reconciliation package to automate the reconciliation process conducted by the accounting section of the IDB. The system will match bank statements transactions received via SWIFT or manually entered from printed statements to cash transactions recorded in the general ledger, helping to identify discrepancies and assist in the subsequent investigations.
>
> The system to be selected should also be able to handle other types of reconciliation but the initial scope of the project will be limited to the general ledger - bank statement reconciliation.

In addition to producing a problem statement, a schedule of activities was also developed as follows:

10/14	Introduce methodology to participants
10/15	Implement computer conference
10/18-10/27	Attend vendors' demonstrations of the alternatives
10/19-11/04	Clarify Problem Statement and Objective
	Discuss alternatives' pros and cons
10/28-11/05	Structure AHP model
11/08	Approve AHP model
	Establish relative importance of objectives (AC members, in groups)
	Establish preference for the alternatives (PT members, individually)
	Consolidate evaluations (geometric means)
11/12	Discuss and approve results (PT)
	Discuss results and present recommendation to the AC

Design Phase

Simon's design phase is concerned with identifying or designing alternative solutions. Some problems have a list of alternatives defined a priori, while other problems do not and will benefit from the definition of objectives before any alternative is even considered. This is because the relationship between alternatives and objectives is highly iterative – the list of alternatives likely will change and will be affected by the defined set of objectives and the importance of the objectives is often dependent on the alternatives being considered. For these reasons, the design phase was expanded to include the definition of objectives as well as alternatives.

Five half-day vendor demonstrations of alternatives were made during a two week period. Advisory committee and project committee members attending these sessions used the computer conference to comment on the pros and cons of the demonstrated alternatives. They entered their comments as soon as possible, preferably the same day of the session. A computer conference instruction advised participants to enter their own comments before reading the comments of others in order to better capture first impressions. Subsequently, an interactive exchange of ideas followed.

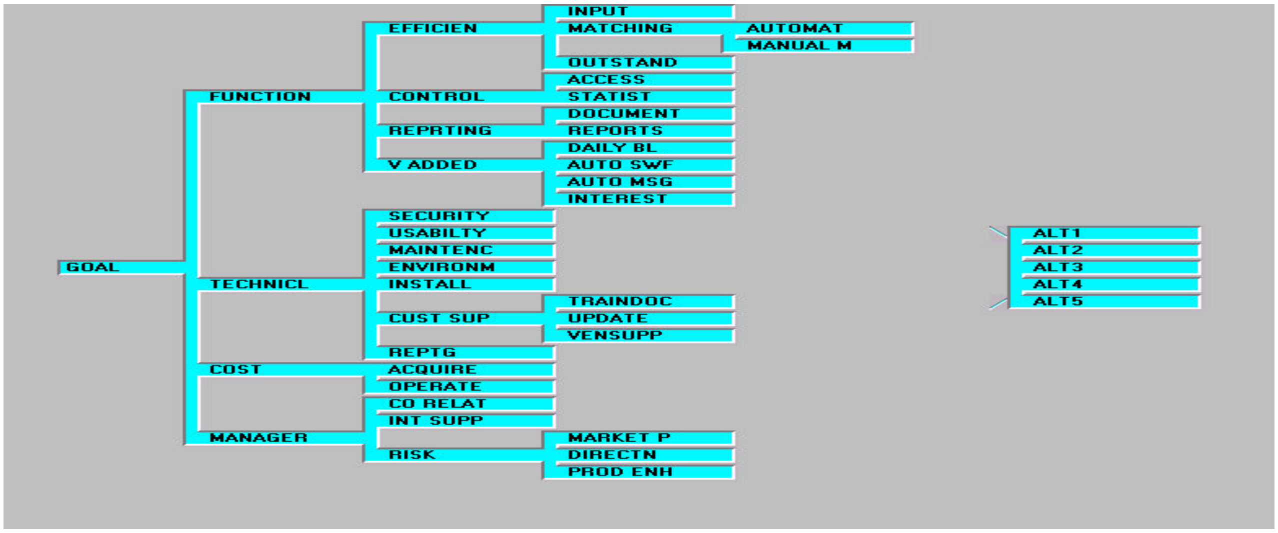
Choice Phase

The Analytic Hierarchy Process served as the foundation of the choice phase. One of the strengths of the AHP is to provide a clear, organized, and logical view of the decision problem. However, there is no one 'right' view as a problem can be represented in several ways and the group members must exert some creativity[5].

[5] Saaty, T. L. 1990. How to make a decision: The Analytic Hierarchy Process. European Journal of Operational Research 48, 9-26.

The structuring of the AHP model started immediately after the end of the demonstration period. There were four two-hour face-to-face meetings in addition to the highly active computer conferencing. Pros and cons developed during the design phase were used to identify objectives for the model. The more experienced group members offered suggestions and the ensuing group discussion regarding the proposed models lead to an improved, well understood, and agreed upon group model. The objectives were clustered into a hierarchical representation shown in Figure 1.

The goal, or first level of the model, is to select the best alternative that meets the IDB's need for Bank reconciliation. Below the goal are levels that include the objectives and sub-objectives (sometimes referred to as criteria) to be used to evaluate the relative preference of the alternatives.



ACCESS	On-line access to financial data
ACQUIRE	Acquisition Cost
AUTO MSG	Automatic generation of internal notes
AUTO SWF	Automatic generation of SWIFT messages
AUTOMAT	Automatic matching capabilities
CO RELAT	Company Relations
CONTROL	To better control, analyze, and review financial transactions
COST	Cost
CUST SUP	Customer Support
DAILY BL	On-line inquiry of daily Bank balances
DIRECTN	Direction
DOCUMENT	To better document the reconciliation process and related actions
EFFICIEN	To increase the efficiency of the reconciliation process
ENVIRONM	Environment
FUNCTION	Functional Requirements
INPUT	Flexibility of receiving different types of input
INSTALL	Installation
INT SUPP	Internal Support
INTEREST	Interest calculation on average balances
MAINTENC	Maintenance
MANAGER	Managerial Considerations
MANUAL M	Manual matching capabilities
MARKET P	Market Penetration
MATCHING	Matching criteria process
OPERATE	Operational Cost
OUTSTAND	Timely and accurate identification of outstanding items
PROD ENH	Product Enhancement
REPORTS	Quality and quantity of reports available
REPRTING	To better document and report recon process & related actions
REPTG	Reporting Capability
RISK	Risk
SECURITY	Security
STATIST	Statistical reports
TECHNICL	Technical Requirements
TRAINDOC	Training and Documentation
UPDATE	Software Update
USABILTY	Usability
V ADDED	To acknowledge value added features provided to ACO & other Sects
VENSUPP	Vendor Support

Figure 1 - AHP Model

The major objectives include *functional requirements, technical requirements, cost,* and *managerial considerations*:

> *Functional requirements* cover the users' business needs, including specific requirements in Matching Efficiency, Control and Reporting. Additionally, *functional requirements* considers "value added" features of the alternatives, such as automation of internal and external message creation, availability of daily balance reports, and interest calculation.
>
> *Technical requirements* address important system features, such as security, usability, maintainability, computing environment, installation process, customer support, and reporting capabilities. The majority of these sub-objectives are further broken down to enable a complete and detailed analysis.
>
> *Cost considerations* encompass acquisition and operational costs. Acquisition cost is the cost of hardware and software required to install the software package. Operational cost is the cost to operate and support the system over a five year period.
>
> *Managerial considerations* focus on company relations, internal support and risk appraisal. The company relations sub-objective is further subdivided into the flexibility of the company and its business orientation. The *risk appraisal* sub-objective is further broken down into *market penetration, direction,* and *product enhancements.*

The lowest level of the model contains the alternatives to be evaluated.

Evaluating the Alternatives

After the advisory committee approved the model, evaluations were made about the relative preference of the alternatives with respect to each of the lowest level sub-objectives. These evaluations were made primarily by project team members. The evaluators were grouped according to their area of expertise. Prior to the evaluation, the group members organized the computer conference messages about the alternatives' pros and cons according to the relevant sub-objective(s). Additional information was added when appropriate. Guidance for the evaluation was provided via the computer conference. Evaluators were advised to maintain their focus on the sub-objective being considered and to refer to the computer conference discussions related to that aspect of the AHP model being evaluated. The computer conference database had 47 items with 484 responses – a printout of the conference generated 146 single-spaced pages.

Group members worked both jointly and separately in making judgments about the preferences for the alternatives with respect to the lowest level sub-objectives. Although there are advantages to making judgments in a group atmosphere, there are also advantages in having the group members make judgments separately.

Comparisons of the alternatives with respect to sub-objectives under *Functional Requirements* and *Technical Requirements* sub-objectives were made in two steps. First, the evaluators worked separately. When working separately, they were better able to think thoroughly about those aspects of the problem that they were designated to consider. They also had an opportunity to do their analysis and, therefore, to contribute their knowledge at their most productive time and pace. They were protected from being disturbed by other members. And they were better able to use resources generally not available to them at meetings (e.g. their computers, applications, and files; access to external databases; access to colleagues and experts). Finally, they were fully prepared to discuss theirs and other members' evaluations.

When their individual evaluations were complete, they were combined by taking the geometric means of individual judgments. This established a convenient starting point for the group discussion that followed. The preferences for the alternatives reflected in the combined model were analyzed by the group members and compared with those in their individual models. This was done for each sub-objective immediately above the alternatives' level in the AHP models. There were two interesting possibilities. First, in those cases where a majority of the evaluators established their preference in the "same direction" (i.e., alternative A is preferable to alternative B to some degree). In this case, the geometric mean results are usually readily accepted by the group. Nevertheless, it was desirable to ask the dissidents to explain their reasoning. The discussion often led to a deeper understanding of the subject and lead to a higher degree of consensus. Second, those cases where the evaluators were divided into two (or three) groups according to their preference for an alternative indicated either an incomplete or superficial discussion of the subject in the computer conference (or face-to-face meeting), or the need to modify the model, or possibly redefine the objective.

The evaluators chose to work together when establishing the preference for the alternatives under the other *Cost* and *Managerial Considerations* objectives of the AHP model.

Determination of the Importance of the Objectives

The determination of the relative importance of the first level objectives (*Functional Requirements, Technical Requirements, Cost,* and *Managerial Considerations*) and of the sub-objectives related to *Cost* and *Managerial Considerations*) were made by members of the advisory committee, grouped accordingly to the division of the IDB that they represented.

Members of each group worked together and used Team Expert Choice to derive the priorities of the objectives/sub-objectives. The geometric means of these priorities were calculated to represent the position of the advisory committee. The relative importance of the sub-objectives under *Functional Requirements* were established by the group from the IDB's accounting division and the importance of the sub-objectives under *Technical Requirements* were established by the group from the IDB's financial MIS division. In order to avoid influencing those evaluating the alternatives, the final priorities of the combined model were not calculated until the preference for the alternatives had been established.

Synthesize, Sensitivity analyses, and Recommendation

The project team held a two hour meeting to synthesize, discuss, and validate the results. They reviewed the priorities of the main objectives derived by the advisory committee and discussed the results under each of these main objectives. Any significant differences between individual evaluations and the combined model were reviewed and justified, and Team Expert Choice sensitivity analysis tools were used to support the final decision by the group. The project team agreed that ALT5 should be recommended. Later that day, in another two hour meeting, the Project Team recommended ALT5 to the Advisory Committee. After thoroughly discussing the results under each of the main objectives in the model and making extensive use of the sensitivity analysis graphs, the advisory committee unanimously approved the recommendation. Following the successful completion of the project, an AHP model to compare the distributed group decision support environment used in the project to the conventional face-to-face group decision making process they had used before was developed and distributed to project participants. The project participants perceived the distributed group decision support approach as preferable to the conventional, structured, face-to-face approach for group decision making involving important and complex, real-world, decision problems. Specifically, the new approach contributed to: (1) decreasing the time to reach a decision (consensus was achieved in little more than a month, whereas previously, the IDB had been unable to achieve consensus in over a year) (2) increasing the depth of analysis, (3) increasing the degree of participation and consensus, (4) increasing task-oriented communication and (5) decreasing the domination by a few members. The decision-makers perceived an increase in the quality of the decision and were more satisfied with the new group process.

7.2 AHP For Future Navy Sea-Based Platforms[6]

In March of 1996, the Undersecretary of Defense for Acquisition authorized the Navy to enter concept exploration for a new sea-basing platform designated as CVX. The general missions of sea-based platforms are to:

- Provide credible, sustainable, independent forward presence during peace time without access to land bases;
- Operate as the cornerstone of a joint and/or allied maritime expeditionary force in response to crises; and
- Carry the war to the enemy through joint multi-mission offensive operations by:
  - Being able to operate and support aircraft in attacks on enemy forces ashore, afloat, or submerged independent of forward-based land facilities;

[6] Earl Hacker, Whitney, Bradley & Brown, Inc.,Vienna, VA 22182

– Protecting friendly forces from enemy attack, through the establishment and maintenance of battlespace dominance independent of forward-based land facilities; and
– Engaging in sustained operations in support of the United States and its Allies independent of forward-based land forces.

To develop this sea-based aviation platform the Navy has created a long-term program to assess alternative platforms and technologies that balances risk and affordability and actively solicits Fleet and industry participation.

In order to support CVX development with an affordable and timely solution, the CVX Strategy-to-Task-to-Technology Process was adopted. The goal of this process is to develop an investment strategy for research and development that will support acquisition of a new class of carriers and meet the needs of the Navy in the 21st Century. This process embraces the concepts of Quality Function Deployment (QFD) . QFD is a systematic approach used by teams to develop products and the supporting processes based on the demands of the customer and the competitive marketplace. In developing a complex system such as an aircraft carrier, one of the most difficult tasks is to capture the warfighting needs in a series of specifications. The customer's vision is often different than what the engineer perceives are the requirements and priorities.

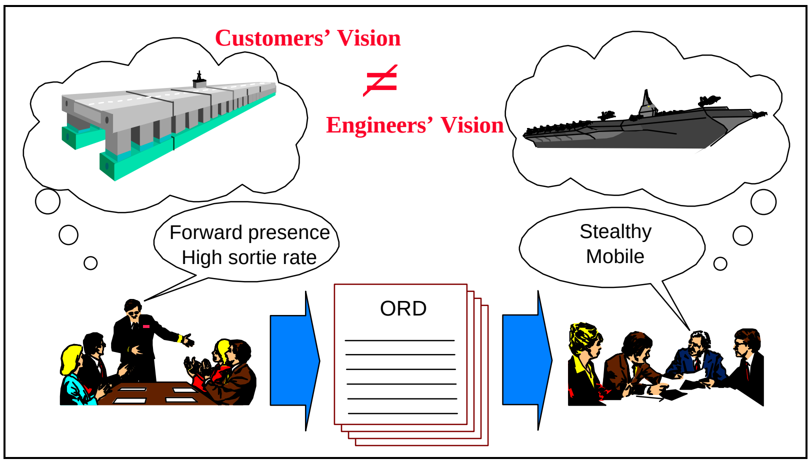


Figure 2 -- Typical Problem

QFD is essentially a communication tool. If implemented properly, the engineer gains an in-depth understanding of the real needs and priorities of the "Fleet" (customer) and the problem is solved.

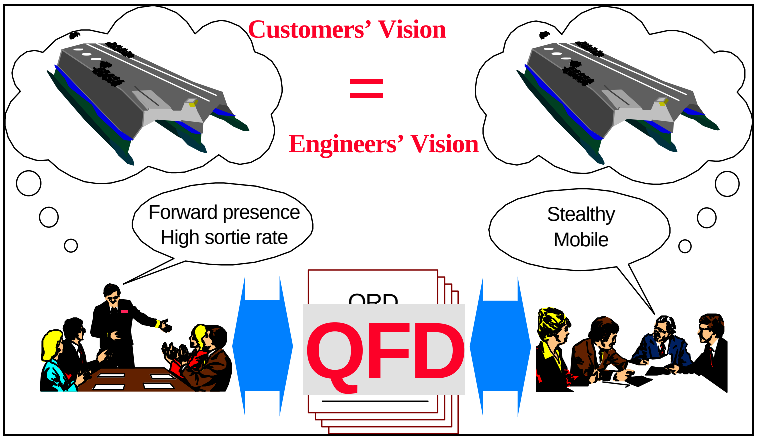


Figure 3 –Interfacing Customer and Engineering views with QFD

QFD is particularly useful for complex systems when there are multiple customers and users, conflicting user priorities, multiple feasible solutions, no quantified solutions in place, conflicting potential solutions, multiple disciplines involved, and no readily quantified user requirements. Such is the case with CVX. QFD is being used in the CVX process to document an objective definition of the users' need and priorities. As a result of early use of QFD in the investment strategy, the concurrent engineering process is strengthened through early definition of goals based on user needs, the visualization of complex system tradeoffs, highlighting of key issues, the gathering of "tribal" knowledge in a reusable database, early involvement of the Fleet and developers, and the early creation of teams and the facilitation of communications.

Figure 4 depicts the "house of quality" used in QFD.

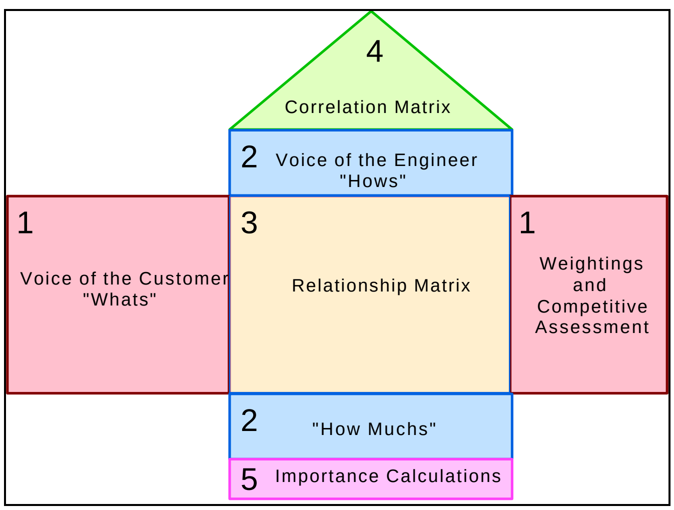


Figure 4 --House of QualityMethodology – AHP

The CVX process uses the Analytic Hierarchy Process (AHP) as a tool for capturing the voice of the "customer" -- the Fleet and integrating this with the voice of the design engineers and voice of the program management office. The methodology to accomplish this process consists of a thirteen-step process conducted in four phases as depicted in Figure 5.

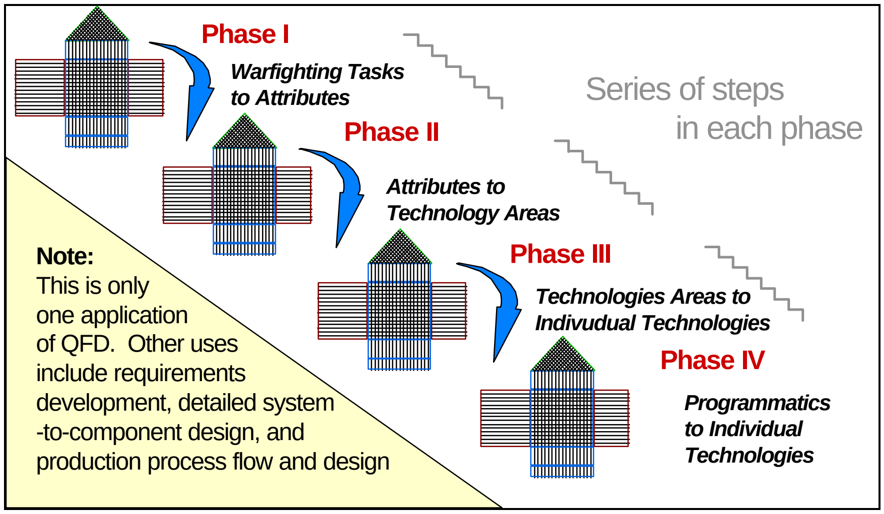


Figure 5—Methodology Phases

The CVX Strategy-to-Task-to-Technology process (STT) establishes explicit linkage between "warfighter" needs and technology solutions by combining Strategy-to-Task methodology, functional attributes of CVX, and enabling research and development technologies in a prioritization process. Its output is used to help guide budget discussions and provide a framework for determining those technologies to apply to CVX research and development. To implement this process *Team Expert Choice* software was used to develop a linkage between and priorities of warfighting tasks and carrier attributes, technology areas, and technologies within each technology area. Once the individual technology priorities were developed, an investment strategy was adopted.

Carrier Attribute Prioritization

The STT methodology developed by RAND provides a linkage between our national goals and the tactical tasks that CVX must be capable of accomplishing in 2013. Figure 6 provides an overview of this STT linkage. The Rand STT was refined by the U.S. Army and then modified for the joint arena and adopted by the Joint Chiefs of Staff as the Universal Joint Task List (UJTL).

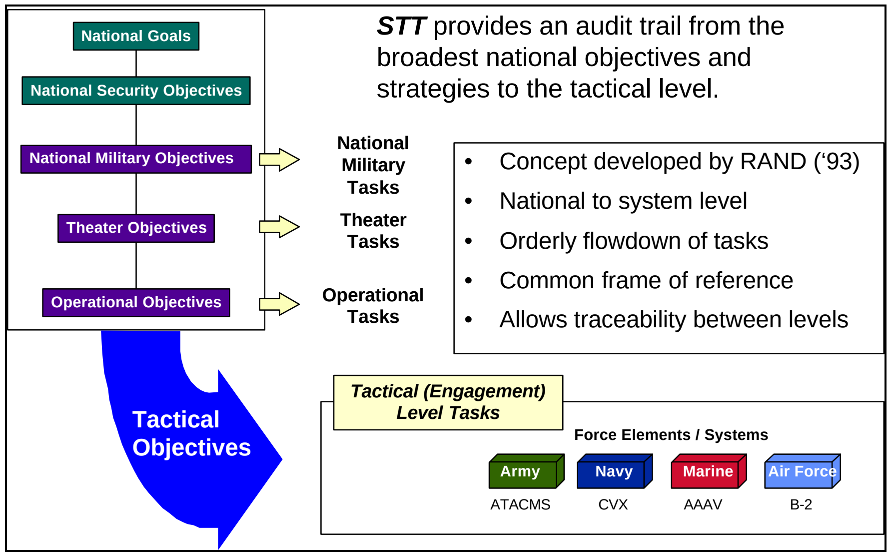


Figure 6--Strategy-to-Task

Step 1 - Determine Appropriate CVX Tasks

In **Step 1** of the process, the UJTL tactical tasks were arranged in a hierarchy model as described in the UJTL. The appropriate level of detail generally ran to the 3rd level of the UJTL hierarchy. The structure is depicted in Figure 7 .

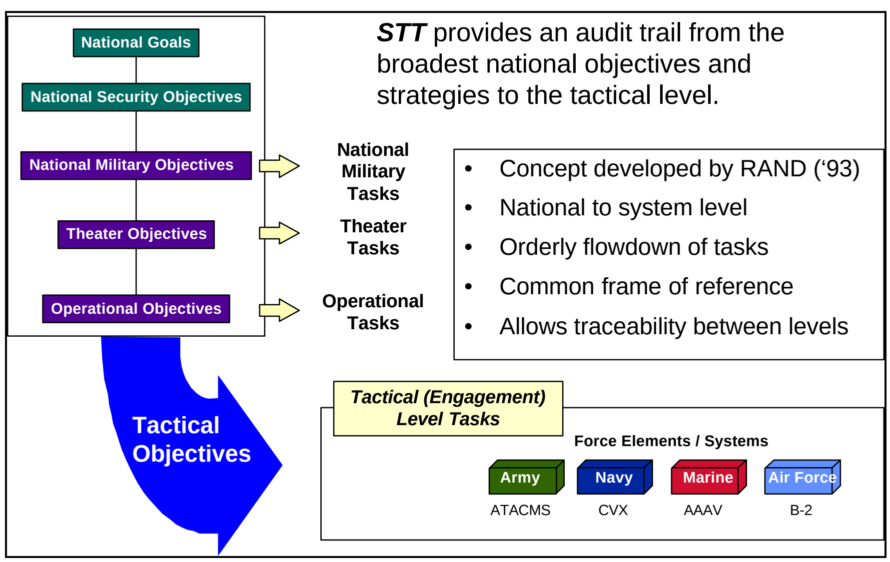


Figure 7 -- CVX Tasks

Step 2 - Prioritize CVX Tasks

Two Fleet Process Teams (FPTs) were created to prioritize CVX tasks – one on the East Coast and one on the West Coast. Each FPT was made up of "warfighters" -- active duty officers experienced in a wide range of naval aviation and naval surface fields. Once the AHP hierarchy was established and the task definitions agreed upon and understood, the FPTs validated and prioritized the tasks.

East Coast FPT	West Coast FPT
COMCARGRU 8	COMNAVAIRPAC
USS America	COMHSWINGPAC
USS Dwight D. Eisenhower	COMSEACTLWINGPAC
COMNAVAIRLANT	COMAEWWINGPAC
USS Enterprise	COMCARGRU 7
PEO CLA/PMA-378	HQMC APP
CINCLANTFLT	USS Constellation
PEO CLA/PMS-312	SWATSCOLPAC
COMCARGRU 4	COMTHIRDFLT
OPNAV N885	COMNAVSPECWARGRU 2
USS Theodore Roosevelt	COMCRUDESGRU 1
COMOPTEVFOR	
COMSECONDFLT	
HQMC APW	

Figure 8--Fleet Process Team Participation

The Analytical Hierarchy Process (AHP), using Team Expert Choice with electronic scoring devices, supported the STT-to-Technology Process problem of prioritizing many tasks by arranging them into several levels and then guiding participants through a series of pairwise comparison judgments to express the relative priorities or importance of the CVX tasks and sub-tasks in the hierarchy. Each comparison began with discussion, led by a facilitator and keypads were used so that participants could enter their judgments simultaneously.

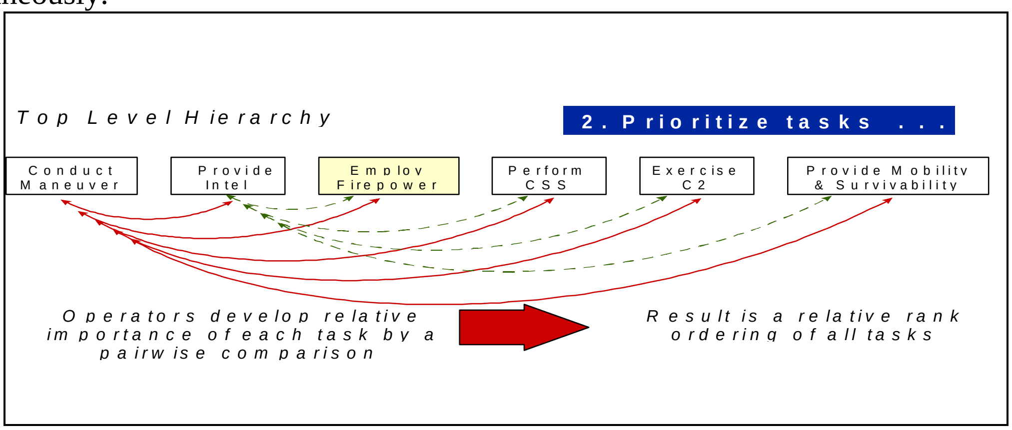


Figure 9--Pairwise Comparison

The many judgments of FPT participants were synthesized to derive a single priority for each of the CVX tasks and sub-tasks. Metrics such as the geometric mean of each set of judgments, the geometric variance, the distribution of individual participant votes, and the consistency of the group as a whole were examined. These metrics were helpful in guiding discussion when large variations and wide distributions existed. An example screen is depicted in Figure 10. The number of participants and the discussions prior to voting kept the voting results very consistent throughout the entire voting process. Following any discussion, participants were allowed to revote. This was very beneficial by pointing out areas of concern and misconceptions and for providing “duty experts" an opportunity to voice their opinions if they differed from the initial voting results.

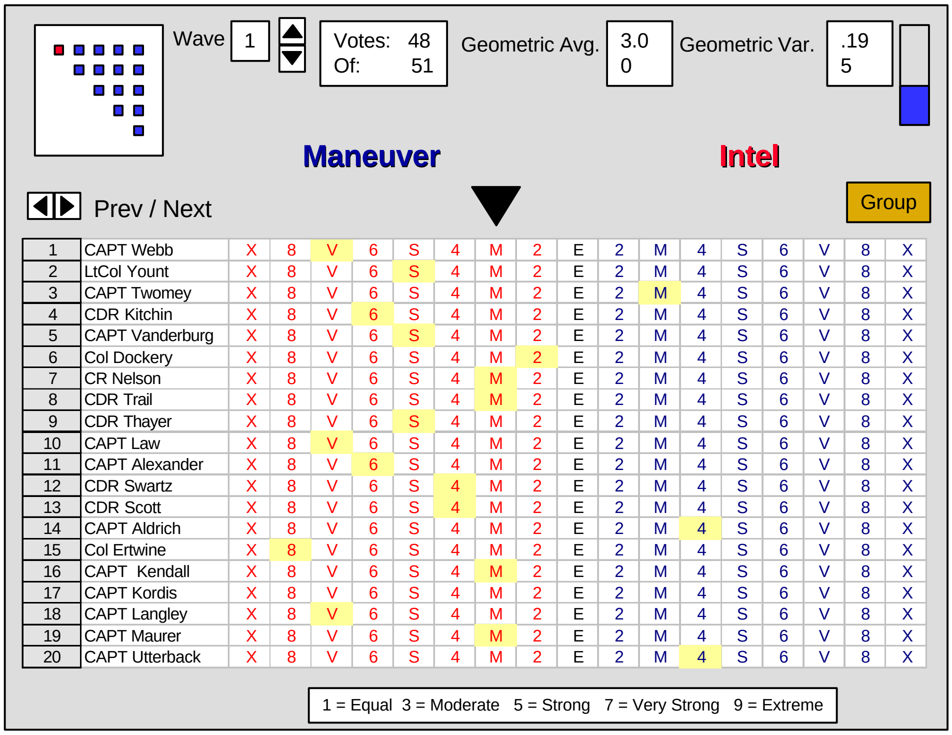


Figure 10--Typical Voting Screen

The prioritization of the tasks conducted on both coasts was merged into one model with one set of priorities and normalized. The resultant priorities of all the identified CVX tasks are a ratio scale. Figure 11 depicts the top 15 of the 63 lowest level CVX tasks and their relative priorities. The priorities shown in Figure 11 have been multiplied by 1,000 for readability.

Task		Priority
TA 3.3	Integrate Tactical Fires	86
TA 3.2.1.2	Conduct Strike, Surface, Subsurface, Air Defense / Aintiair Attack	74
TA 3.2.1.1	Conduct Fire Support / Close Air Support	47
TA 1.5	Coordinate Maneuver and Integrate with Firepower	44
TA 6.1	Maintain Mobility	42
TA 1.4.2	Occupy Combat Area	40
TA 6.3.1	Protect Against Combat Area Hazards	40
TA 4.3	Fix / Maintain Equipment	38
TA 4.1	Arm	30
TA 5.5	Employ Tactical C2W	30
TA 1.2	Negotiate Tactical Area of Operations	22
TA 5.1.1	Communicate Information	20
TA 4.2	Fuel	19
TA 3.1.2	Select Fire Attack System	18
TA 5.4.6	Synchronize Tactical Operations	18

Figure 11--Top 15 Prioritized CVX Tasks

Step 3 - Develop CVX Attributes

Step 3 required developing a list of attributes for CVX. CVX attributes are the means to accomplishing the previously prioritized tasks and include design characteristics and capabilities that contribute to successful performance of the operational tasks. The attributes were arranged into three groupings:

- Functions: characteristics or activities necessary in the performance of a task;
- Parameters: physical property that determines the behavior or capability to perform a task; and
- Operational Flexibility / Constraints: characteristic that effects the likelihood or degree of performing a task.

An initial attribute list was provided at the second meeting of the FPTs. The initial focus of this effort revolved around limiting the list to a workable number of attributes (30-40) and ensuring that the focus was broad and at the same level of detail. The FPTs met on each coast validating, adding, and deleting attributes. Figure 12 lists the finalized attributes. To validate each attribute, participants were asked three questions:

- Is the prospective attribute a what or a how (means);
- Is the prospective attribute at the right level of detail; and
- Is the prospective attribute covered as part of another attribute?

Functions	Parameters	Flexibility / Constraints
Signature management	Range	Deployment availability
Sensing	Speed	Accessibility
External communications	Endurance	Aircraft suitability
Internal communications	Ship reliability	Environmentally compliant
Data management	Ship maintainability	All weather & night Ops
Seakeeping	Logistics footprint	Degraded operations
Habitability	Hardening & protection	System commonality
Mission planning	Redundancy	Upgradeability
Weapon handling & storage	Agility	Shallow / littoral water Ops
Weapon & CM employment		Space flexibility
Launch & recovery		
A/C turnaround		
Material distribution & storage		
Training implementation		
Damage control and restoration		
Battle Group support		
Underway replenishment		
Aircraft maint / material support		

37 Attributes

Figure 12--Attribute Listing

Step 4 - Prioritize CVX Attributes

In **Step 4** the FPTs evaluated the degree of correlation between the attributes and the prioritized tasks through individual inputs. This was accomplished by using the ratings module of *Team Expert Choice*. Unlike pairwise comparison which is a relative measurement, the ratings module uses absolute measurement. To determine the degree of correlation between the attributes and the tasks, a set of standards or intensities are first developed. These intensities are shown in Figure 13 -- Strong, Medium, Some, Tad, and None. The ratio scales below each intensity were developed through the normal pairwise comparison to establish their relative values. For example, a Strong (1.000) task-to-attribute correlation is approximately three times a Medium (.367) correlation. Participants then compared each attribute to each task by selecting one of the intensities. The selected intensity value is multiplied by weighting of the task and then summed for each task to arrive at a total value for each attribute. These values are shown in the TOTAL column. Figure 14 depicts the CVX war-fighting attributes and their relative priorities.

Maneuver | Position | MovePrep

Strong 1 (1.000) | Medium 2 (.367) | Some 3 (.150) | Tad 4 (.062) | None 5 (.000)

	ATTRIBUTES	TOTAL	MANEUVER POSITION MOVEPREP	---------- ---------- MOVE	---------- ---------- TACPOSIT	---------- NEGOTIATE ----------	---------- NAVIGATE ----------	---------- DOMINATE CTRFIRES
1	Aircraft Turnaround	0.605	0.251	0.441	0.441	0.340	0.144	STRONG
2	Data Management	0.737	0.388	0.332	0.332	0.396	0.616	0.680
3	Internal Communications	0.793	0.474	0.443	0.443	0.583	0.764	0.729
4	External Communications	0.825	0.565	0.587	0.587	0.560	0.704	0.879
5	Habitability	0.255	0.243	0.180	0.180	0.260	0.173	0.147
6	Launch and Recovery	0.640	0.357	0.644	0.644	0.756	0.238	STRONG
7	Material Distribution	0.339	0.574	0.277	0.277	0.141	0.106	0.391
8	Mission Planning	0.700	0.355	0.454	0.454	0.455	0.557	0.910
9	Seakeeping	0.438	0.489	0.928	0.928	0.813	0.683	0.873
10	Sensing	0.630	0.365	0.650	0.650	0.910	0.789	0.976
11	Signature Management	0.482	0.271	0.511	0.511	0.668	0.332	0.855
12	Training Implementation	0.319	0.285	0.283	0.283	0.264	0.326	0.456
13	Wpns & CM Employment	0.563	0.205	0.645	0.645	0.668	0.125	0.976
14	Wpns Handling & Storage	0.480	0.533	0.338	0.338	0.298	0.056	0.867
15	Endurance	0.470	0.528	0.827	0.827	0.729	0.411	0.964

Figure 13--Task / Attribute Correlation Example

No.	CVX Attribute	Warfighting Priority	No.	CVX Attribute	Warfighting Priority
1	Reliability	0.837	20	Aircraft Suitability	0.478
2	External Communications	0.825	21	Aircraft Maint/Material Spt	0.472
3	Internal Communications	0.793	22	Endurance	0.470
4	All Weather/Night Capability	0.762	23	Logistics Support Footprint	0.442
5	Data Management	0.737	24	Seakeeping	0.438
6	Mission Planning	0.700	25	Shallow/Littoral Ops	0.436
7	Launch and Recovery	0.640	26	UNREP	0.433
8	Sensing	0.630	27	Hardening & Protection	0.414
9	Degraded Operations	0.625	28	Agility	0.374
10	Aircraft Turnaround	0.605	29	Range	0.366
11	Wpns & CM Employment	0.563	30	Speed	0.364
12	Ctl / Restore Damage	0.559	31	Material Distribution	0.339
13	System Commonality	0.545	32	Training Implementation	0.319
14	Maintainability	0.537	33	Habitability	0.255
15	Battle Group Support	0.533	34	Space Flexibility	0.239
16	Redundancy	0.510	35	Accessibility	0.217
17	Upgradeability	0.492	36	Deployment Availability	0.082
18	Signature Management	0.482	37	Environmental Compliance	0.056
19	Wpns Handling & Storage	0.480			

Figure 14-- Prioritized CVX Attributes

Following a synthesis of the results, discussion developed concerning the accuracy of the results. It was noted that the top six attributes were cross-functional. As discussions continued the participants understood that these top attributes correlated to many of the CVX tasks; whereas launch and recovery was more specific to firepower and underway replenishment. The point taken was not that launch and recovery was unimportant, but that attributes like external communications cut across most of the tasks the carrier must be capable of accomplishing.

Correlating Enabling Technologies to CVX Attributes and Prioritize

NAVSEA engineers will use previously cataloged potential technology investments to determine those technologies, which if pursued, could provide major increases in carrier effectiveness or efficiency. This will be accomplished by correlating the degree to which potential technology investments contribute to the prioritized CVX attributes. This list of relative technology priorities will aid in determining which potential enabling technologies can provide the best value for design of the CVX. Subsequently, AHP will be again applied to develop a strategy for funding technology investments within the constraints of CVX research and development funding.

8. Academic Debates

Althought AHP gained almost immediate acceptance by many academics and practitioners, it was a new methodology that threatened established methodologies in particular, Multi Attribute Utility Theory. This has led to numerous academic debates about AHP. Since most of the debates originated from academics schooled in MAUT, it was natural for them to base their arguments on their own paradigms & axioms- a phenomenon described in Kuhn's [1962] *The Structure of Scientific Revolution*. Of course, there is no reason why AHP *should* satisfy the axioms of MAUT, especially since the reasonableness of those axioms have been called into question from MAUT academics themselves (as discussed below).

Another reason for the academic controversy, in our opinion, is because AHP is not just a methodology for choice problems, but is applicable to *any* situation where structuring complexity, measurement, and synthesis are required. The application of AHP to forecasting problems, for example, requires a different perspective than for some choice problems. Some academics have attempted to formulate "fool-proof" ways of using AHP so that it 'automatically' produced results for the type of problem they had in mind. The difficulty with this is what may seem like a good idea for one problem domain could be inappropriate for another.

The debates have been worthwhile. Partly in response to these debates, Saaty introduced a forth axiom to AHP stating that individuals who have reasons for their beliefs should make sure that their ideas are adequately represented for the outcome to match these expectations (AHP has such flexibility). Forman [1993] introduced a second synthesis mode to AHP and Expert Choice, called the ideal synthesis mode which addresses choice situations in which the addition or removal of an 'irrelevant' alternative should not cause a change in ranks of the existing alternatives. This is discussed in detail below.

8.1. Transitivity and Rank Reversal vis-a-vis MAUT

The AHP has been criticized as it does not adhere to the multi-attribute utility theory (MAUT) axioms of transitivity and rank reversal. We challenge those who raise these criticisms with the following questions:

- Must we use a particular axiomatic (normative) model that tells us "what ought to be?"
- Should we strive for a descriptive method ("what is") even though we do not really know how humans make decisions?
- Must the axiomatic foundations of the so-called rational model of expected utility apply to all decision methodologies?
- Must we use an axiomatic-based model that forces transitivity to hold even though we know of situations where it need not hold?
- Do we forbid the use of a method that allows rank reversal of alternatives to occur even though there are reasonable real-world situations in which rank reversal can and should occur?

Two issues, that are fundamental to MAUT, are relevant here: (1) the transitivity of preferences and (2) rank reversal of alternatives. Expected utility theory (and rational decision making theory, in general) is grounded on the axiom of transitivity, that is, if A is preferred to B, and B is preferred to C, then A is preferred to C (or if A is three times as preferable than B and B is twice as preferable as C, then A is six times as preferable as

C). Also, MAUT researchers, noting that expected utility axioms do not allow rank reversal for what are known as irrelevant alternatives, have developed examples in which the AHP (as originally formulated) can and does reverse the rankings of the alternatives. We address these issues in turn.

8.2 Transitivity

The AHP comparison mode allows for inconsistent transitivity relationships. In the example above, a DM checking preferences may conclude that A is 8 times more preferable than C (or perhaps even that C is preferred to A). Under a single-criterion rubric, we might not ordinarily expect to have intransitive relations [Fishburn (1991) discusses how intransitive situations can arise for this case]. But, for multicriteria problems, it is often impossible not to have intransitivities, as the DM cannot simplify the complexities of the problem to achieve true transitivity. As pointed out by Tversky (1969, p. 45):"...the fact remains that, under the appropriate experimental conditions, some people are intransitive and these intransitivities cannot be attributed to momentary fluctuations or random variability;" and (p. 46): "When faced with complex multidimensional alternatives, such as job offers, gambles, or candidates, it is extremely difficult to utilize properly all the available information. Instead, it is contended that people employ various approximation methods that enable them to process relevant information in making a decision." Fishburn (1991, p. 113), states: "Transitivity is obviously a great practical convenience and a nice thing to have for mathematical purposes, but long ago this author ceased to understand why it should be a cornerstone of normative decision theory." Fishburn (1991, p. 120) offers the following reasonable real-life decision situation. (The reader is invited to think about the conclusion reached by Fishburn's DM and what solution the reader would choose.)

"Professor P is about to change jobs. She knows that if two offers are far apart on salary, the salary will be the determining factor in her choice. Otherwise, factors such as prestige of the university will come into play. She eventually receives three offers, described in part as follows:

	Salary	Prestige
x	$65,000	Low
y	$50,000	High
z	$58,000	Medium

On reflection, P concludes that x > y, y > z, and z > x, (where > means preferred to)."

Fishburn (1991, p. 130) concludes his discussion on nontransitive preferences with the following:

"Transitivity has been the cornerstone of traditional notions about order and rationality in decision theory. Three lines of research during the past few decades have tended to challenge its status. First, a variety of experiments and examples that are most often based on binary comparisons between multiple-factor alternatives suggest that reasonable people sometimes violate transitivity, and may have good reasons for doing this. Second, theoretical results show that transitivity is not essential to the existence of maximally preferred alternatives in many situations. *Third, fairly elegant new models that do not presume transitivity have been developed, and sometimes axiomated, as alternatives to the less flexible traditional methods* (emphasis added)."

Interestingly enough, Luce and Raiffa (1957, p. 25) state:

> "No matter how intransitivities exist, we must recognize that they exist, and we can take only little comfort in the thought that they are an anathema to most of what constitutes theory in the behavioral sciences today".

They also observe:

> "We may say that we are only concerned with behavior which is transitive, adding hopefully that we believe this need not always be a vacuous study. Or we may contend that the transitive description is often a 'close' approximation to reality. Or we may limit our interest to 'normative' or 'idealized' behavior in the hope that such studies will have a metatheoretic impact on more realistic studies. In order to get on, we shall be flexible and accept all of these as possible defenses, and to them add the traditional mathematician's hedge: transitive relations are far more mathematically tractable than intransitive ones."

The Analytic Hierarchy Process is not inhibited by the need for transitive relationships and instead of ignoring such relationships, provides a measure of inconsistency so that the decision maker can proceed accordingly. We sum the discussion on transitivity by paraphrasing the famous bumper-sticker due to Gump (1994): "Intransitivities Happen!"

8.3 Adding Irrelevant Alternatives and Rank Reversal

8.3.1 Rank Reversal when Adding Irrelevant Alternatives: Questions and Definitions

We next discuss the phenomenon of rank reversal when adding or removing irrelevant alternatives. In expected utility theory, that is, for a decision problem under uncertainty (dpuu), the axiomatic base includes an assumption like the following (Luce and Raiffa 1957, p. 288):

"Adding new acts (alternatives) to a dpuu, each of which is weakly dominated (preferred) by or is equivalent to some old act, has no effect on the optimality or non-optimality of an old act."
The above axiom is strengthened into the axiom that states the principle of the *independence of irrelevant alternatives*, Luce and Raiffa (1957, p288):
"If an act is non-optimal for a dpuu, it cannot be made optimal by adding new acts to the problem."

Two more questions arise here:

- Do real-life decision situations adhere to these axioms?
-Why should these axiom of expected utility theory apply to any other decision methodology?

With respect to rank reversal, our view is that it does happen in the real world. With respect to decision procedures, rank reversal can or cannot occur, that is, it can be ruled in or out, based on the axiomatic base of the decision procedure. In general, based on the DM's procedural decision rules and associated axioms, the DM can choose to rule certain aspects like transitivity and rank reversal in or out. This phenomenon of decision procedures is well-known and well-illustrated by Luce and Raiffa (1957) and Straffin (1993), based on the work of Milnor (1954). Here, the different decision models (rules) of Laplace, Wald, Hurwicz and Savage are compared, and, when they are combined with the decision axioms of Milnor, it is shown that they produce different answers and, for some, reversal of rank.

To sum up: There is no one basic rational decision model; the decision framework hinges on the whatever rules and axioms the DM thinks is appropriate. So then what is rational decision making? To answer we quote Watson and Buede (1987):

> "We will say that we are rational when, having adopted rules which our statements or actions conform to, we act in a way that is consistent with them. ... To be rational in decision-making, therefore, we will need to construct a set of rules that we will wish to adopt in determining what to do in complex decision-making situations; then we will satisfy our need for rationality by conforming to them. ... By our definition of rationality, however, it does not necessarily follow that people who do not abide by the precepts of decision theory are irrational; they may well have perfectly sensible rules of their own which they are following most rationally." (p. 12)

> "Rationality is defined in terms of adherence to a set of rules; there is no reason why a decision-maker ought to abide by the rules of decision theory, or indeed any rules for that matter!" (p. 54)

Still other definitions of rationality are possible. The definition of a rational decision as “one based on the achievement of objectives” does not lay out a set of rules, but rather guides the DM in selecting an appropriate set of rules and in constructing a model that conforms to those rules.

8.3.2 Multicriteria Prioritization in Open and Closed Systems

In the spirit of the above discussion, we next show, depending on the axiomatic base a DM chooses to operate under, how the AHP allows or disallows rank reversal.

The Analytic Hierarchy Process (AHP), as originally conceived by Saaty (1980), assumes what we will call a "closed" system in allocating priorities to alternatives. By a closed system we mean that the sum of the priority *distributed* to the alternatives from each lowest level (sub)criterion does not increase or decrease if new alternatives are added or existing alternatives are removed from consideration. Multi Attribute Utility Theory (MAUT) (Keeney and Raiffa 1976), on the other hand, employs what we will refer to as an "open" system because the sum of the priorities allocated to alternatives will increase or decrease as new alternatives are added or existing alternatives are removed. As will be illustrated below, the ranking of alternatives in a "closed" system can change when a new but dominated (or so called irrelevant) alternative is added to a decision. We will refer to a changing of rank when an irrelevant alternative is added to the decision as a rank reversal. Discussion of rank reversal in this section will be in the context of the introduction or removal of an irrelevant alternative. (The question of what happens when a relevant alternative, i.e., one that is not dominated on every criterion is added to or removed from a decision will be addressed later.)

A debate has been ongoing between practitioners of AHP and MAUT about whether the rank of alternatives should be *allowed* to change when an "irrelevant" alternative is added to the decision. AHP practitioners have argued that a change in rank is legitimate. MAUT practitioners have argued that it is not. Each side has presented examples where their argument has appeal. As we will see, both sides are correct, but under different circumstances. We will see that when dealing with a "closed" system, rank adjustment is not only legitimate, but is often desirable. Conversely, when dealing with an "open" system, rank adjustment should be precluded. Rank adjustment, or what MAUT practitioners call rank reversal, occurs when the ranking of a set of alternatives changes upon the introduction of a so called "irrelevant alternative" -- an alternative that is dominated by one or more previously existing alternatives. There are two basic misconceptions about this phenomenon. First, the description of such an alternative as "irrelevant" is misleading. Huber, Payne, and Puto (1982) state that "the very presence of [a] dominated alternative results in quite different choice probabilities among the remaining alternatives than in the pristine state, where such items are never considered." This is certainly true when using AHP relative measurement as any alternative is a fortiori relevant since all other alternatives are evaluated in terms of it. We illustrate this with an example in section 12 below.

The second misconception is about the effect that irrelevant alternatives "should" have in an evaluation. Some MAUT practitioners demand that "irrelevant" alternatives "should" not affect the ranking of other alternatives. This is sometimes referred to as an "independence of irrelevant alternative" assumption. For example, Dyer (1990) cautions about generating "rank orderings that are not meaningful with respect to the underlying preferences of the decision maker" when additional alternative(s) are introduced for consideration. Although it is possible for any algorithm to generate ranks that do not agree with the underlying preferences of a decision maker, there is nothing to have us believe that a rank adjustment is necessarily contrary to the underlying preferences of decision makers. Furthermore, the arbitrary prohibition of rank adjustment may *lead* to flawed results because there are many situations where a rank adjustment (reversal) is desirable.

8.3.3 The Cause of Rank Adjustment

Rank reversal in AHP does *not* occur because of eigenvector calculations, because of the nine point scale used in AHP, because of inconsistencies in judgments, nor because "exact" copies are included in an evaluation. Forman (1987) gives an example where there is perfect consistency and where the introduction of new alternatives causes a rank reversal. The example given by Belton and Gear (1982) has an "exact" copy, but a similar example by Dyer (1990) does not. Dyer argues that "The defense of the AHP on the grounds that copies should not be allowed as alternatives is without foundation, and cannot be supported on intuitive or on technical grounds." We agree -- in part. Copies should be allowed. The "defense" of AHP, or its strength, is that it *can* adjust rank when copies are introduced and this in fact can be supported on both intuitive and technical grounds as will be shown below.

Rank reversal can take place with *any* technique that decomposes and synthesizes in a relative fashion, regardless of whether it uses pairwise comparisons, eigenvector calculations, or demands perfect consistency. Rank reversal occurs because of an *abundance* or *dilution* effect (or what has also been called a *substitution* effect). This is discussed in Saaty (1990), Dyer (1990), Forman (1987), and Huber (1993), and illustrated below. Since value or worth is, more times than not, affected by relative abundance or scarcity, the ability for a methodology to adjust rank is often a desirable property.

Saaty (1991b), discusses conditions under which one might justifiably say that rank can and should be preserved and when it should not. While some authors (Belton and Gear (1982), Shoner and Wedley (1989), and Dyer (1990)) have suggested that the choice of a modeling approach be based on rank reversal considerations, we propose that a more fundamental and meaningful consideration is whether scarcity is or is not germane to the decision. If scarcity is germane then a closed system (distributive synthesis) is appropriate and rank reversal should be allowed to occur. If scarcity is not germane, then an open system (ideal synthesis) is appropriate and rank reversal should not be allowed to occur. Consequently, a robust decision methodology should be able to accommodate either situation. An extension to AHP to allow modeling both open and closed systems will be presented below. Other modifications to AHP, such as B-G modified AHP (Belton and Gear 1982) and Referenced AHP (Schoner and Wedley 1989) have been advocated in order to prevent rank reversal. While these modifications hold merit and are in fact the same as, or similar to, the open system (ideal synthesis) of AHP discussed below, the merit does not stem from preventing rank reversal nor should these modifications replace the conventional AHP since rank reversals are sometimes, perhaps even often, desirable.

8.3.4 Closed and Open Systems -- Scarcity and Abundance

In a "closed" system with a *fixed amount of resources*, scarcity is germane. The distribution of a country's gold, the allocation of a corporation's R&D budget, and the distribution of votes to political candidates are good examples. Suppose a newly formed country decided to distribute its gold reserve to identified segments of society based on criteria that included population and economic potential. If, after distributing the gold, suppose a previously overlooked segment of the society with a small population but great economic potential was identified. In order to make a distribution to this segment, gold would have to be taken back from the existing segments and redistributed. Because the previous distribution was made partly on the basis of population and economic potential, sectors that were highly populated but with relatively low economic potential would lose less than segments with relatively low population and high economic potential and a rank reversal could occur. Similarly, an independent candidate entering the race for the U.S. Presidency in which the Republican candidate had the lead might appeal more to Republican voters than to Democratic voters and a rank reversal might take place between the Republican and Democratic candidates.

In contrast, scarcity is not germane in an "open" system where *resources can be added or removed*. As an example, consider the distribution of a new country's currency. Suppose a new country were deciding how to distribute currency to identified segments of society based on criteria that included population and economic potential. If after distributing its currency, a new segment appears, more currency can be printed and distributed to the new segment based on its population and economic potential as well as other criteria. There is no need to take back currency from existing segments. While the percentage of wealth (in currency) of the previously existing segments would diminish because more currency was printed, the rank order of the segments would not change.

The assumptions of an open system can be better understood by defining a reference "unit of wealth". Suppose there were an alternative that was best on every criterion, an "ideal" alternative. A reference "unit" of wealth is the amount of wealth that this "ideal" alternative would receive. (This is in contrast with a utopian alternative which could be defined as having the best conceivable values on each attribute.) Each real alternative, or segment of society in this example, would receive some percentage of the reference "unit". Subsequently, the relative wealth of each alternative can be found by normalizing over all real alternatives.

In the currency distribution example, if a new segment of society is introduced and additional currency is printed for the new segment, the relative wealth of the segments after re-normalizing will change, but the ratios and rank order of wealth for previously existing segments will not change. The treatment of closed and open systems leads us to the following two AHP synthesis modes.

8.3.5 Closed and Open Synthesis Modes with AHP

We next discuss, in turn, Closed and Open Synthesis modes with AHP.

8.3.5.1 Closed System (Distributive Synthesis)

When priorities are distributed in an AHP hierarchy of criteria and subcriteria, the global priority of the goal (standardized to 1.0) is distributed to the criteria, and then to the lowest level subcriteria. (This also would be true for an MAUT hierarchy of objectives). In the original AHP implementation (which we will henceforth refer to as the closed system or distributive synthesis) the priorities of the lowest level subcriteria are *distributed* to the alternatives in the same fashion. If, for example, a criterion's global priority were .4 (see Figure 15) and the local priorities of the three alternatives under the criterion were .5, .3 and .2, the global priority of the criterion would be distributed to the three alternatives as global priorities of .2, .12, and .08 respectively. (See Figure 16).

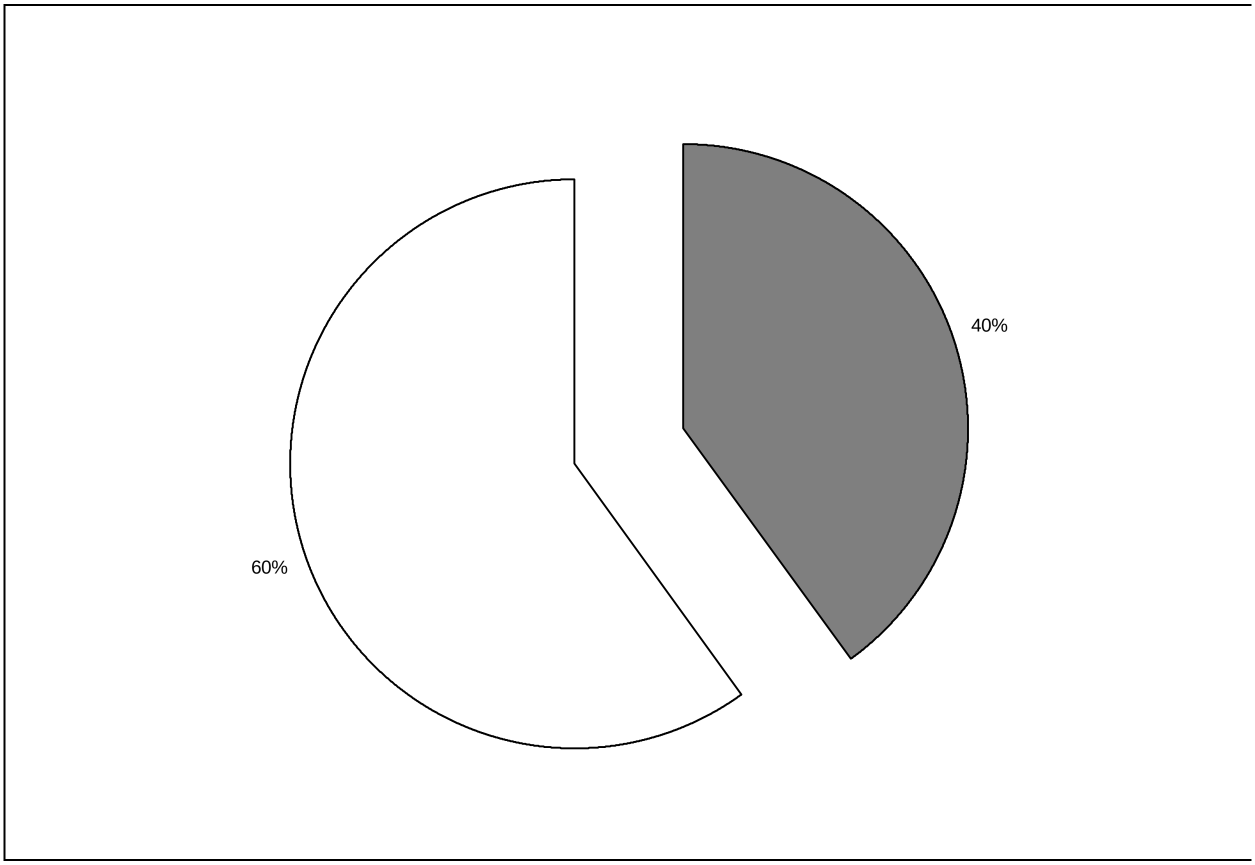


Figure 15 -- Criterion with .4 global priority

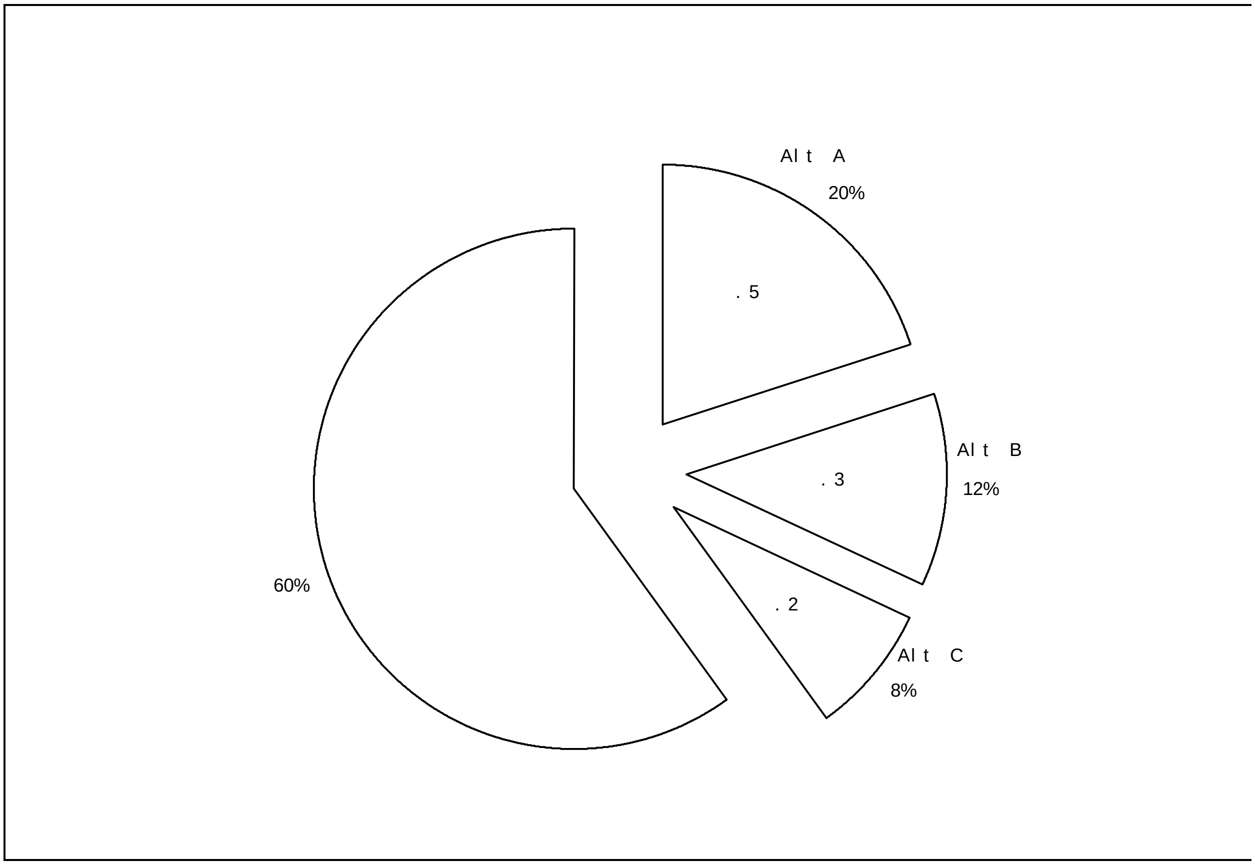


Figure 16 -- Criterion priority distributed to the alternatives

If a new alternative were added to (or removed from) the analysis, the existing alternatives would lose (or gain) priority under each criterion. For example, if a new alternative D, identical to the second best alternative B, were added under this criterion, the local priorities would change to 0.385, 0.231, 0.154, and 0.231. The distribution of the .4 priority of the criterion would be 0.154, 0.092, 0.062, and 0.092 as shown in Figure 17. The system is "closed" in that the total priority of the alternatives under each (sub)criterion will not change and the total priority for the alternatives under all (sub)criteria will always equal 1.0.

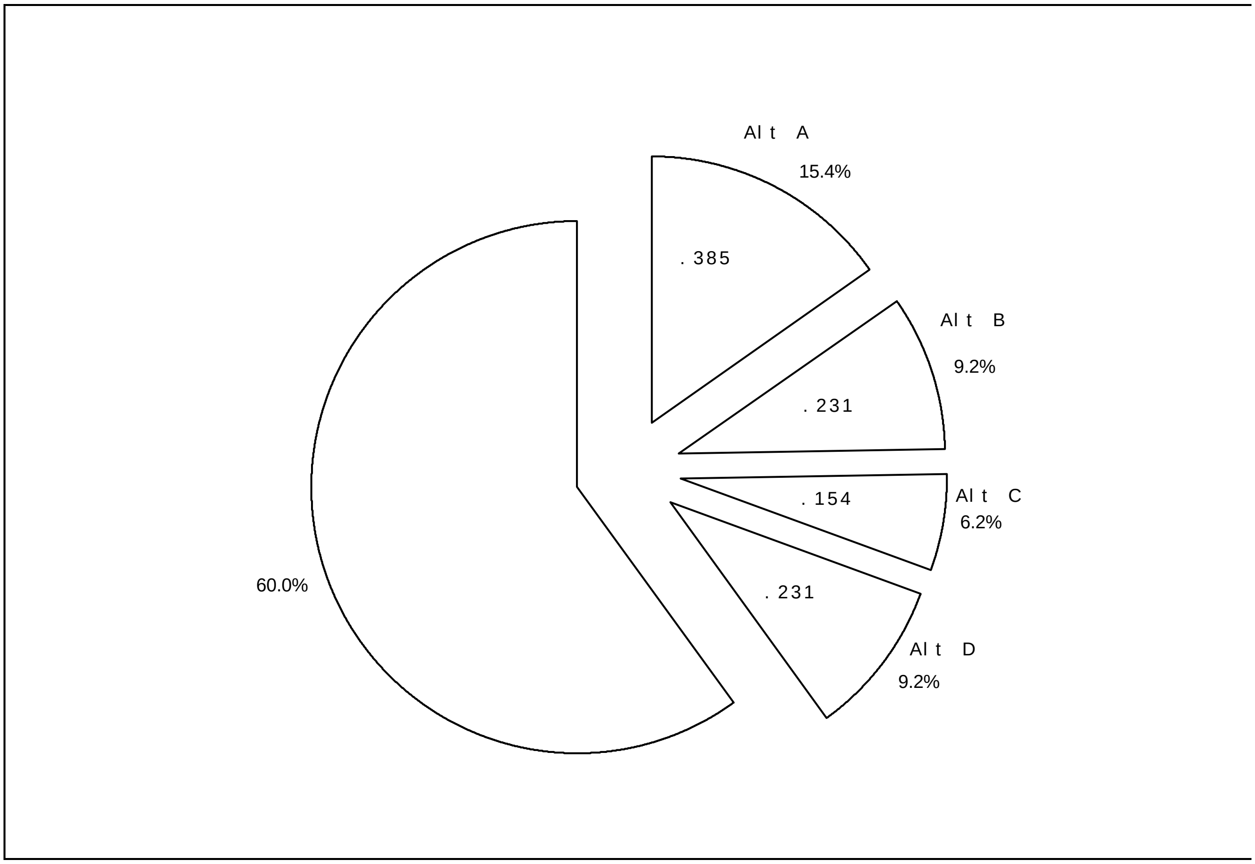


Figure 17 -- Distribution after adding a fourth alternative

8.3.5.2 Open System (Ideal Synthesis)

A simple extension has been made to AHP in order to model open systems. Instead of distributing each (sub) criterion's priority to the alternatives, the priority is allocated to the alternatives such that the most preferred alternative under each (sub)criterion receives the full priority of the (sub)criterion. This idea was first proposed by Belton and Gear as a replacement for, rather than an extension to AHP. Each of the other alternatives receives a priority *proportional to its preference relative to the most preferred alternative*. For example, if a criterion's priority were .4 (as shown in the right hand segment of the pie chart in Figure 1) and the local priority of three alternatives under the criterion were .5, .3 and .2 respectively, the three alternatives would receive global priorities of .4, .24 and .16 respectively as shown in Figure 18

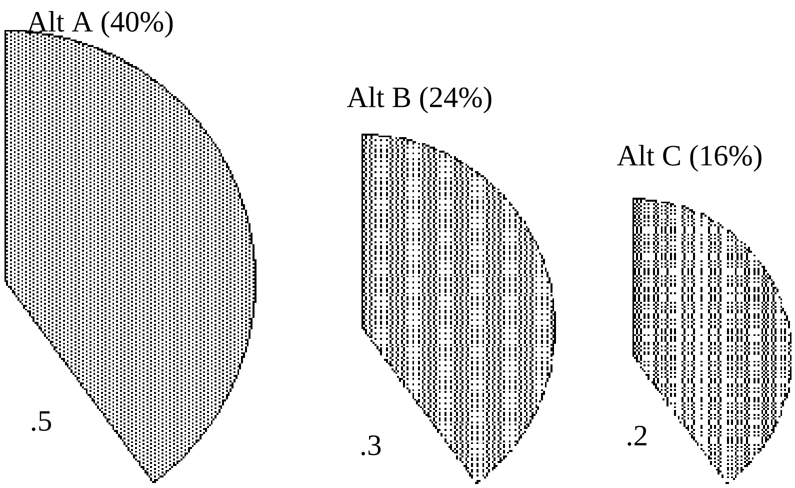


Figure 18 – Three alternatives under the .4 priority criterion

If, as above, a new alternative that is identical to the second best alternative under this criterion were added, the local priorities would again change to 0.385 0.231 0.154 and 0.231. However, the allocation of the .4 priority of the criterion using the open system (ideal synthesis) would be .4, .24, .16, and .24 as shown in Figure 19.

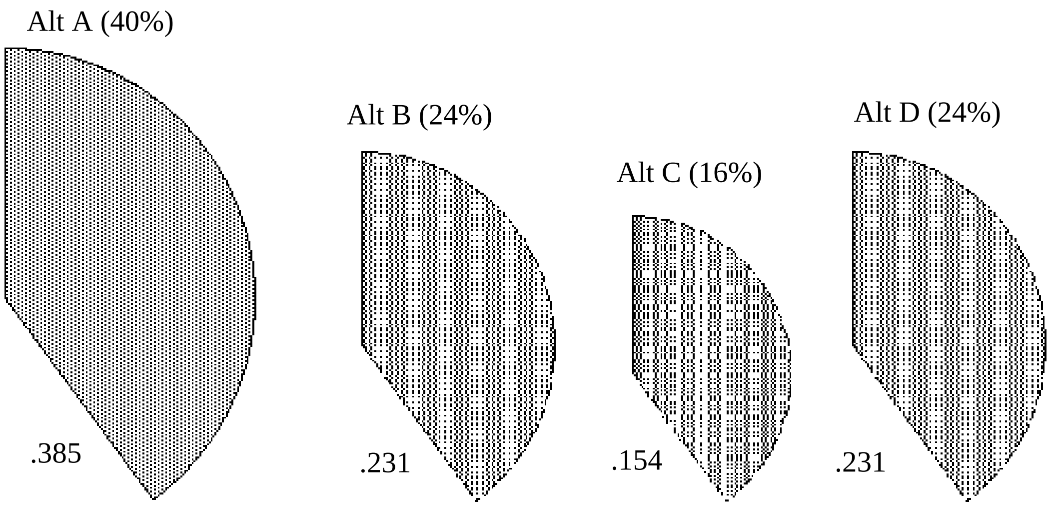


Figure 19 -- Ideal Mode: Criterion with .4 global priority and four alternatives

The rationale for this approach is that an "ideal" alternative (an alternative having the most preferred attribute value for every criterion) would serve as a reference and receive a total priority (before normalization) of 1.0, while each real alternative would have priorities proportionately less. If we think of 1.0 as representing a "standard", each real alternative receives some fraction of the "standard" depending on how well the alternative compares to the ideal on each criterion. Although, no alternative can receive a priority from a (sub)criterion greater than the (sub)criterion's priority, the sum of the alternatives' priorities under a (sub)criterion is not limited as in the "closed" system. If a new, irrelevant alternative is added (or an existing irrelevant alternative is removed), the priorities allocated to the existing alternatives under each criterion do not change because the alternative being added (removed) is, by definition, not better than the ideal under any criterion. Therefore, the ideal continues to receive the full priority of the respective criterion. Furthermore, the priorities allocated to the other alternatives, being proportional to the ideal, would not change either. However, the alternative being added (removed) would receive (relinquish) a priority in proportion to its preference with respect to the ideal alternative. Thus the total priority allocated increases (decreases) and the system can be said to be "open". After the alternatives receive priority from each of the lowest level (sub)criteria, a subsequent normalization is performed so that the alternative priorities sum to 1.0.

It is important to note that the only operational difference between the open and closed system occurs when a synthesis is performed. There is no difference in model structure or judgment process for closed or open systems. Also of importance is that both closed and open AHP systems produce *ratio scale* priorities. Ratio scale priorities have a higher level of measure than, and are preferred to interval scale priorities. If, in the open system (ideal synthesis), a transformation were made whereby the 'worst' alternative for each criterion received 0 priority (in addition to the transformation assigning all of a criterion's priority to the 'best' alternative), the mathematics would be analogous to that of MAUT but the resulting priorities would only be on an interval scaled rather than on a ratio scale. Not only are ratio scale priorities more preferable in general, but ratio scale priorities are *required* for many applications (such as resource allocation or systems with feedback) since the product of interval scaled measures is mathematically meaningless.

8.3.5.3 Illustrative Example

Consider the evaluation and ranking of employees in a small firm with a few employees. Suppose that Susan is as good or slightly better than John with respect all attributes except one -- John is the only employee who is proficient in application of personal computers in meeting the needs of the firm's clients. Suppose a multi-criteria evaluation is performed and the results indicate that John is the most valuable to the firm, with Susan a close second.

Subsequently, a new employee is hired, who is very knowledgeable about the use of PC's, but not quite as knowledgeable as John. John is superior with respect to the new employee in all other criteria as well. Since John dominates the new employee, the new alternative is "irrelevant", and according to MAUT practitioners, "should" not affect the ranking of the pre-existing employees. Is this necessarily reasonable? Since John's *relative* value to the firm has been diminished "should" John still be more valuable to the firm than Susan? We would conclude no!

To see that a *prohibition* of rank reversal in this evaluation is *not* reasonable, suppose more and more (similar) "irrelevant" alternatives are hired. Surely there would come a point where the value of John's ability with PC's would be diluted to the point where Susan would be considered to be the most valuable employee. This example, typical of many evaluations, leads us to conclude that *value* is *relative* in many evaluations, and that a methodology that allows for rank reversal is desirable in these situations. Conversely, methodologies, such as MAUT, which preclude rank reversal can produce flawed results for situations where worth *is* affected by relative abundance (above and beyond the impact of affecting the relative importance of the objectives.) This conclusion is not new! The need for a methodology to allow for rank reversal has long been recognized. For example, Huber and Puto (1983), in an article "Market Boundaries and Product Choice: Illustrating Attraction and Substitution Effects", state that:

> "Choice researchers have commonly used two general approaches to account for the way proximity of a new item affects choice. These approaches differ primarily in the way item similarity, as derived from the dimensional structure of the alternatives is assumed to affect the

> choice process. The first proposition (proportionality) assumes that the new item takes share from existing items in proportion to their original shares (i.e., no similarity effect)."

Proportionality would *preclude* rank reversal. Huber and Puto continue to say:

> "The second proposition (substitutability) assumes that the new item takes share disproportionately from more similar items -- i.e., the closer the added item is to existing items in the set, the more it "hurts" them (a negative similarity effect)."

Huber, Payne and Puto (1982) note that:

> "... the similarity hypothesis asserts that a new alternative takes disproportionate share from those with which it is most similar. Researchers have shown that the similarity effect is operant for individual or aggregate choice probabilities."

Substitutability requires that rank reversals be permitted. Decision makers must decide, and should not be told, which of these two approaches, proportionality (an open system -- ideal synthesis) or substitutability (a closed system -- distributive synthesis), is relevant to their evaluation. We believe that the substitution effect, is in general, more appropriate for multi-criteria evaluations. Huber and Puto argue that:

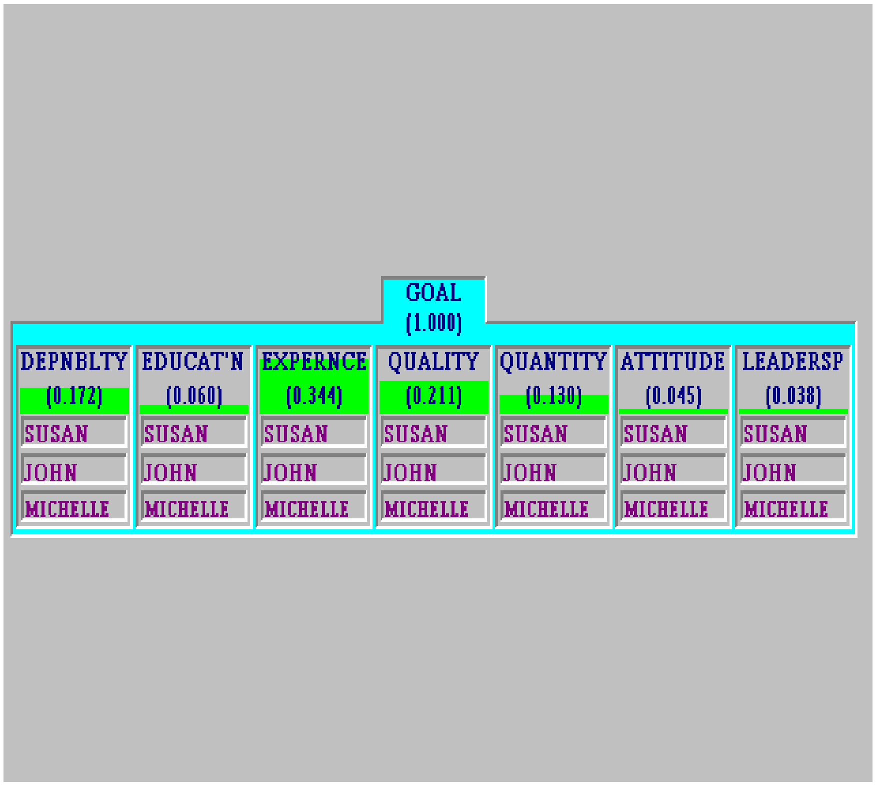
> "A substitution effect will be more salient where multi-attribute decision making occurs. It should, therefore, be most apparent in major purchases (where attribute-based processing is more cost effective) and in product classes for which a limited number of attributes emerge that permit easy comparisons across alternatives."

Since Multi Criteria Decision Making (MCDM) techniques like AHP are now facilitating comparisons across alternatives for more than just a limited number of attributes, the substitution effect should become even more common and the ability of a methodology to allow rank reversal should be welcomed.

Conversely, there are situations where a rank reversal would *not* coincide with the underlying preferences of the decision makers. Suppose, for example, that a decision maker, considering whether to buy an IBM PC compatible or an Apple MacIntosh, has decided on the IBM PC compatible. The introduction of another IBM PC compatible that is not as good on any dimension as the original PC compatible would not, for most decision makers, change the original ranking. For situations such as this, the AHP open system (ideal synthesis) should be used and will not allow a rank reversal. The following example illustrates the differences between the closed system (distributive synthesis) and open system (ideal synthesis).

8.2.5.3.1 Employee Evaluation using the AHP Closed System (Distributive Synthesis)

Employee Evaluation

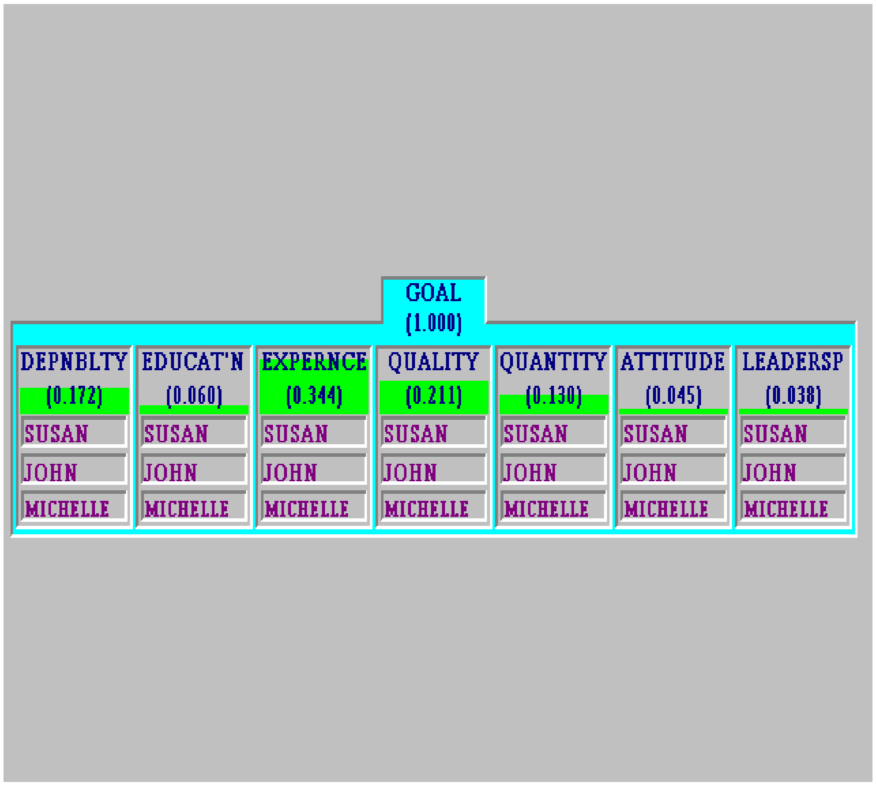


Abbreviation	Definition
ATTITUDE	ATTITUDE
DEPNBLTY	DEPENDABILITY
EDUCAT'N	EDUCATION
EXPERNCE	EXPERIENCE (INCLUDING PC HARDWARE AND SOFTWARE)
JOHN	Particularly good with computers
LEADERSP	LEADERSHIP
MICHELLE	Leadership her best attribute
QUALITY	QUALITY OF WORK
QUANTITY	QUANTITY OF WORK
SUSAN	Excellent in all categories

(Priorities shown are 'Local' -- relative to parent node.)

Figure 20 contains a model used in an AHP evaluation of three employees. With the closed system (distributive synthesis) the "global" priority of each alternative "node" is the product of the node's local priority with it's parent's global priority. The overall priority for each employee is the sum of the employee's global priorities throughout the model, as shown in Figure 21. In practice there may be several additional levels in an employee evaluation model. Overall, John is the most valuable employee, primarily because of his experience with personal computer hardware and software.

Employee Evaluation



Abbreviation	Definition
ATTITUDE	ATTITUDE
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EXPERNCE	EXPERIENCE (INCLUDING PC HARDWARE AND SOFTWARE)
JOHN	Particularly good with computers
LEADERSP	LEADERSHIP
MICHELLE	Leadership her best attribute
QUALITY	QUALITY OF WORK
QUANTITY	QUANTITY OF WORK
SUSAN	Excellent in all categories

(Priorities shown are 'Local' -- relative to parent node.)

Figure 20 -- Employee Evaluation with Three Alternatives

Employee Evaluation

Synthesis of Leaf Nodes with respect to GOAL

Distributive Mode

OVERALL INCONSISTENCY INDEX = 0.1

LEVEL 1	LEVEL 2	LEVEL 3	LEVEL 4	LEVEL 5
EXPERNCE=.344				
	JOHN =.163			
	SUSAN =.091			
	MICHELLE=.091			
QUALITY =.211				
	SUSAN =.089			
	JOHN =.067			
	MICHELLE=.055			
DEPNBLTY=.172				
	SUSAN =.074			
	JOHN =.057			
	MICHELLE=.041			
QUANTITY=.130				
	SUSAN =.051			
	JOHN =.040			
	MICHELLE=.040			
EDUCAT'N=.060				
	SUSAN =.025			
	JOHN =.018			
	MICHELLE=.018			
ATTITUDE=.045				
	SUSAN =.018			
	JOHN =.014			
	MICHELLE=.012			
LEADERSP=.038				
	SUSAN =.015			
	MICHELLE=.013			
	JOHN =.011			

Abbreviation	Definition
JOHN	Particularly good with computers
SUSAN	Excellent in all categories
MICHELLE	Leadership her best attribute

Figure 21 -- Closed System (Distributive Synthesis) and Overall Priorities

8.3.5.3.1.1 Adding An Irrelevant Alternative

Suppose an additional employee, Bernard, joins the company and suppose Bernard is an irrelevant alternative in that he is dominated on every criterion. However, Bernard also has experience with PC hardware and software. Since John's *relative* value to the firm has been diminished, "should" John still be more valuable to the firm than Susan? We would conclude no! This is the result in the model with Bernard added as is shown in Figure 22 and Figure 23.

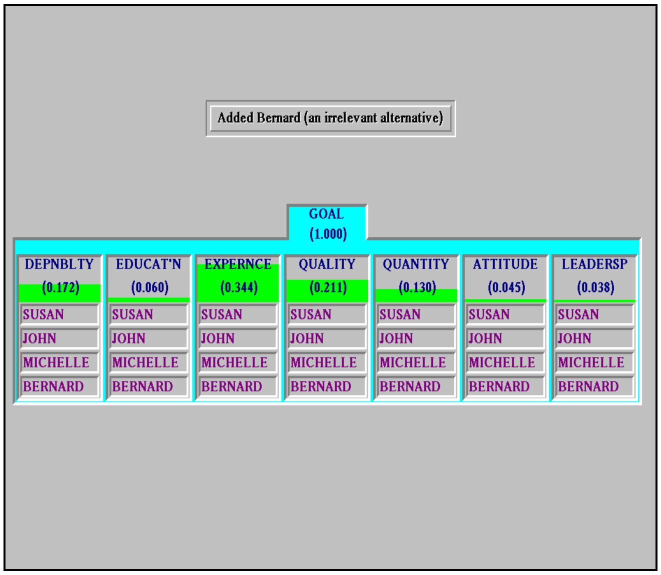

Figure 22 -- Added Bernard (an irrelevant alternative)

Added Bernard (an irrelevant alternative)

Synthesis of Leaf Nodes with respect to GOAL
Distributive Mode
OVERALL INCONSISTENCY INDEX = 0.04

LEVEL 1	LEVEL 2	LEVEL 3	LEVEL 4	LEVEL 5
EXPERNCE=.344				
	JOHN =.119			
	BERNARD =.093			
	SUSAN =.066			
	MICHELLE=.066			
QUALITY =.211				
	SUSAN =.080			
	JOHN =.060			
	MICHELLE=.050			
	BERNARD =.020			
DEPNBLTY=.172				
	SUSAN =.060			
	JOHN =.046			
	MICHELLE=.033			
	BERNARD =.033			
QUANTITY=.130				
	SUSAN =.047			
	JOHN =.036			
	MICHELLE=.036			
	BERNARD =.010			
EDUCAT'N=.060				
	SUSAN =.022			
	JOHN =.016			
	MICHELLE=.016			
	BERNARD =.006			
ATTITUDE=.045				
	SUSAN =.017			
	JOHN =.013			
	MICHELLE=.011			
	BERNARD =.004			
LEADERSP=.038				
	SUSAN =.013			
	MICHELLE=.011			
	JOHN =.009			
	BERNARD =.004			

Figure 23 -- Closed System (Distributive Synthesis) After Adding an Irrelevant Alternative.

8.3.5.3.2 Employee Evaluation using the AHP OPEN System (Ideal Synthesis)

In an open system (ideal synthesis), the most preferred alternative under each criterion receives the full priority of the criterion. Each of the other alternatives receives a priority proportional to its preference relative to the most preferred alternative. After the alternatives receive priority from each of the criteria, a subsequent normalization is performed so that sum of all of the alternatives' priorities is equal to 1.0 as can be seen in Figure 24.

Added Bernard (an irrelevant alternative)

Synthesis of Leaf Nodes with respect to GOAL
Ideal Mode
OVERALL INCONSISTENCY INDEX = 0.04

LEVEL 1	LEVEL 2	LEVEL 3	LEVEL 4	LEVEL 5
EXPERNCE=.344				
	JOHN =.344			
	BERNARD =.268			
	SUSAN =.191			
	MICHELLE=.191			
QUALITY =.211				
	SUSAN =.211			
	JOHN =.158			
	MICHELLE=.132			
	BERNARD =.053			
DEPNBLTY=.172				
	SUSAN =.172			
	JOHN =.134			
	MICHELLE=.096			
	BERNARD =.096			
QUANTITY=.130				
	SUSAN =.130			
	JOHN =.101			
	MICHELLE=.101			
	BERNARD =.029			
EDUCAT'N=.060				
	SUSAN =.060			
	JOHN =.043			
	MICHELLE=.043			
	BERNARD =.017			
ATTITUDE=.045				
	SUSAN =.045			
	JOHN =.035			
	MICHELLE=.030			
	BERNARD =.010			
LEADERSP=.038				
	SUSAN =.038			
	MICHELLE=.032			
	JOHN =.027			
	BERNARD =.011			

Figure 24 -- Open System (Ideal Synthesis) with Four Alternatives

The priorities in this example are such that the rank order of the four alternatives with this open system (Ideal Synthesis) are the same as the ranking of the four alternatives with the closed system (distributive synthesis) shown in Figure 9. However, if we now remove Bernard, the "irrelevant alternative", and again perform an open system (ideal synthesis), Susan remains the most valuable of the three employees (see Figure 25), a result different from the closed system (distributive synthesis) where John, because of his unique abilities with computers, is the most valuable among the three employees.

Employee Evaluation

Synthesis of Leaf Nodes with respect to GOAL
Ideal Mode
OVERALL INCONSISTENCY INDEX = 0.1

LEVEL 1	LEVEL 2	LEVEL 3	LEVEL 4	LEVEL 5
EXPERNCE=.344				
	JOHN =.344			
	SUSAN =.191			
	MICHELLE=.191			
QUALITY =.211				
	SUSAN =.211			
	JOHN =.158			
	MICHELLE=.132			
DEPNBLTY=.172				
	SUSAN =.172			
	JOHN =.134			
	MICHELLE=.096			
QUANTITY=.130				
	SUSAN =.130			
	JOHN =.101			
	MICHELLE=.101			
EDUCAT'N=.060				
	SUSAN =.060			
	JOHN =.043			
	MICHELLE=.043			
ATTITUDE=.045				
	SUSAN =.045			
	JOHN =.035			
	MICHELLE=.030			
LEADERSP=.038				
	SUSAN =.038			
	MICHELLE=.032			
	JOHN =.027			

Abbreviation	Definition
SUSAN	Excellent in all categories
JOHN	Particularly good with computers
MICHELLE	Leadership her best attribute

Figure 25 -- Open System Synthesis After Removing the Irrelevant Alternative

Summarizing, in this example (contrived for illustrative purposes), if there were only three alternatives, John would rank first using the closed system (distributive synthesis) while Susan would rank first using the open system (ideal synthesis). Since, in this illustration, the value of the employees is affected by relative abundance or scarcity of their talents (or in other words, one employee's talents can be *substituted* for another), the closed system (distributive synthesis) is more appropriate and *John should be the* *most valuable*!. Thus, the *lack* of rank reversal with the open system (ideal synthesis) produces less desirable results. While the rank order of the alternatives with the open system (ideal) synthesis is the same for three or four alternatives, the rank order of Susan and John is different with the closed system (distributive synthesis) depending on whether Bernard is or is not included. This is due to a dilution effect caused by the Bernard, an "irrelevant alternative". The removal of Bernard causes the priority of each criterion to be concentrated (the converse of a dilution of priorities when alternatives are added) under the closed system (ideal synthesis) because the total priority under each criterion does not change. Furthermore, the concentration is not the same for all criteria. For, according to the similarity effect discussed previously, a new alternative would take a disproportionate share from those with which it is most similar, so conversely, the removal of an alternative would give a disproportionate share to those with which it is most similar. Since Bernard was most similar to John on the experience criterion, John gains proportionately more priority if Bernard is removed and consequently John is the most preferred among the three alternatives. This makes intuitive sense since the value of John's experience with PC hardware and software has increased because it is more scarce if Bernard is not included.

8.3.6 When is scarcity germane?

When scarcity is germane a closed system (distributive synthesis) is appropriate and when it is not an open system (ideal synthesis) is appropriate. Yet, it may not always be obvious when scarcity is germane. The following questions can help determine whether to use the distributive synthesis or ideal synthesis:

Q: Is the purpose of the model to forecast, prioritize alternatives, or choose one alternative?
If the model purpose is to forecast or prioritize alternatives, then the closed system (distributive synthesis) is appropriate. If, however, the model purpose is to choose one alternative, then a subsequent question can be posed:
Q: Will alternatives not chosen still be relevant, i.e., will they still matter to you?
If the answer is yes, then the closed system (distributive synthesis) is appropriate. If not, then the open system (ideal synthesis) is appropriate.

How Significant is the Choice of Synthesis Mode in Practice? We investigated forty four applications of the Analytic Hierarchy Process, applying the above questions about scarcity to each. In our judgment, scarcity was relevant in sixteen of the forty four applications. Next, we compared the results of a distributive synthesis *and* an ideal synthesis for each application. Of the forty-four applications, thirty six had identical rankings of alternatives regardless of the synthesis mode. Of the remaining eight applications, six had the same first choice. The two applications for which the different synthesis modes produced different 'best' alternatives were each identified as 'closed' systems (for which the original AHP distributive synthesis was appropriate).

8.3.7 Summary of the Rank-Reversal when Adding Irrelevant Alternatives Debate

A multi-criteria modeling approach must be able to accommodate both "closed" systems -- with a fixed amount of resources and where scarcity is germane, and "open" systems -- where resources can be added or removed and where scarcity is not germane. The choice of an open or closed system (distributive synthesis or ideal synthesis) for a particular prioritization, choice, or resource allocation problem is one that must be made by the decision makers -- not prescribed by a methodology or its axioms. Recognizing that there are situations in which rank reversals are desirable and other situations in which they are not, a logical conclusion is that any decision methodology that always allows or always precludes rank reversals is inadequate. This paper has presented an enhanced framework for AHP that is capable of deriving ratio scale priorities for both types of situations.

8.4 Adding Relevant Alternatives and Rank Reversal

We looked at the introduction of 'irrelevant' alternatives in AHP in the preceding section. An irrelevant alternative is one that is dominated by one or more previously existing alternatives There we saw that the AHP ideal synthesis mode exhibits the same properties as MAUT – preventing the ranks of existing alternatives from changing when 'irrelevant' alternatives are introduced or removed. The AHP distributive mode allows modeling of real world applications where it is reasonable to expect ranks to reverse when irrelevant alternatives are added or removed. Here we will look at what can happen when *relevant* alternatives are added to AHP and MAUT models. We will see that with the AHP ideal synthesis mode, the introduction or removal of any alternative (relevant or irrelevant) will not affect ranking or ratios of existing alternatives, whereas the introduction of a relevant alternative in MAUT can change both ranks and ratios of existing alternatives.

Consider a decision involving three criteria and three alternatives with criteria weights and data as shown in

Table 2. We will assume linear utility for the sake of illustration. The minimum and maximum values used in an MAUT evaluation to construct the utility curve (which we will assume to be linear here) are shown for each column. Using this data, both MAUT and AHP (with ideal synthesis mode) produce the same ranking of the alternatives: A3 > A2 > A1. Notice that alternative A1 is irrelevant since it is dominated by Alternative A3. The ratio of the priorities of A2 to A3 are however different. The ratio is .989 for AHP and .778 for MAUT.

	Crit 1	Crit 2	Crit 3
	0.3	0.2	0.5
A1	85	70	50
A2	80	90	70
A3	90	80	70
Max	90	90	70
Min	80	70	50

Table 2 – Before Introducing a Relevant Alternative

Suppose we were to remove A1 and replace it by another alternative A1', where the values for A1' were the same for criteria 2 and 3, but differed for criterion 1. The relative ranking and ratios of priorities of the previously existing alternatives A2 and A3 remain unchanged with AHP no matter what value A1' has with respect to C1. This is not the case however for MAUT. If the value for A1' with respect to C1 is below 80 (still making it an irrelevant alternative), the ratios of the priorities of A2 to A3 *will* change. For example, if the value of A1' with respect to C1 is 70, the MAUT ratio of A2 to A3 changes from .778 to .994! If the value is 50, the ratio becomes 1.028, indicating a change in rank as well.!

Similarly, if the values of A1' with respect to C1 is changed to a value above 90, now making it a 'relevant' alternative, the ratio of priorities of the previously alternatives remain unchanged with AHP but not with MAUT.

MAUT practitioners might contend that this is not a problem and argue that the weights of the criteria should be changed when alternatives are added or removed such that the minimum or maximum value for any criterion is changed. We agree that in *some*, cases, the criteria weights might depend on the alternatives being considered and are capable of accommodating such dependence in a variety of ways, including the Analytic Network Process discussed below[7]. But there are many cases where we would not want to nor cannot conveniently change criteria weights each time an alternative value changes. MAUT can not produce the robust results that AHP does in such cases.

8.5 Measurement, Ratio Scales, and AHP

Measurement, along with structuring complexity and synthesis, is one of the three primary functions of AHP. Ratio scale measures, a cornerstone of AHP, convey more information than interval or ordinal measures and are required for some applications where interval measures are not adequate. Next we discuss why measurement is so important, and how and why AHP produces ratio scale measures of both objective and subjective information.

Stevens, when questioning why the measurement problem is often overlooked, observed that:

> "The typical scientist pays little attention to the theory of measurement, and with good reason, for the laboratory procedures for most measurements have been well worked out, and the scientist knows how to read his dials. Most of his variables are measured on well-defined, well-instrumented ratio scales. Among those whose interests center on variables that are not reducible to meter readings, however, the concern with measurement stays acute. How, for example shall we measure subjective value (what the economist calls utility), or perceived brightness or the seriousness of crimes?"[8]

In *The Theory of Social Cost Measurement*[9], Christopher A. Nash, observed that

[7] When the influence of alternatives on the importance of criteria is addressed by MAUT, the worst or best alternative with respect to each criterion can have an unrealistic extreme effect on the criteria importance. The Analytic Network Process, on the other hand, considers all alternative values, extreme or not, on each of the criteria.

[8]S.S. Stevens. "Measurement, Statistics and the Schemapiric View", *Science*, 30 August 1968, Vol 161, No 3844, pp 849-856.

[9] Christopher A. Nash, *The Theory of Social Cost Measurement*, pg 95.

"What is and what is not measurable is far from clear. Suffice it to say that in the historical process of developing measures, variables that were not measured at one point later came to be measured, and measures were constantly improved over the course of time."

Nash proposed that

"Rather than talk about intangible or unmeasurable effects of programs, we should be talking about how to develop improved measures of those things which we are already measuring and how to develop some measures of those program effects that we are currently not measuring."

AHP is such a development – a simple and improved way to measure objective and subjective factors, including subjective utility. AHP addresses problems such as that noted by Henry M. Levin:

"… we cannot assume that the same value on a utility scale has the same meaning to different raters. Some individuals will tend to rate even their lowest priorities with high values, while others will tend to rate even their highest priorities with low values. In a sense, this subjective process is inspired by different explicit reference points for what is high and what is low."[10]

Furthermore, AHP produces ratio scale measures, overcoming problems such as the following pointed out by Levin:

"a value of 8 on a utility scale does not necessarily carry twice the weight of 4. All that one can say is that 8 represents a higher level of utility than 4. Of course, many psychological scales have only ordinal rather than interval properties, so other measures of ... effectiveness may also be subject to this criticism."

AHP does this by eliciting pairwise relative comparisons that produce dimensionless ratio scale priorities. The decision-maker is asked for estimates of the relative importance, preference or likelihood (depending on whether objectives, alternatives, or scenarios are being evaluated). The estimates can be made numerically, graphically or verbally. Besides having the advantage of producing dimensionless ratio scale priorities in situations for which no scale exists (if there were a scale, the scale's dimension, whatever it might be, would cancel out when forming the relative ratio), relative judgments also tend to be more accurate[11] than absolute judgments. Without a ruler in hand, an absolute judgment that a board is about two feet long requires comparison to a mental image of a foot ruler. A relative judgment that a four foot board is about twice as long as a two foot board requires no real or mental standard for the comparison. Thus measurements need not be made according to agreed upon standards.

In discussing similarity and dimensional methods in biology, Walter Stahl[12] observed:

"Comparison of a small leaf with a large one, or of a child with its parents, leaves the conviction that a "similarity" of some sort is present."

Stall also observed that:

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[10]Henry M. Levin, *Cost-Effectiveness, A Primer* New Perspectives in Evaluation, Volume 4, Sage Publications, Beverly Hills, CA. p 121.

[11]Martin, James. *Design of Man-Computer Dialogues*. Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1973.

[12]Stahl, "Similarity and Dimensional Methods in Biology" (SCIENCE, 137, 20 July 1962) pp206-211.

"An outstanding feature of dimensionless similarity criteria is that they are *convenient* and embody *natural* physical properties of the system under study. They rely on internal rather than imposed standards of measurement."

Saaty recognized the importance of measurement and ratio scales to decision making:

"The problem of decision-making is concerned with weighting alternatives, all of which fulfill a set of desired objectives. The problem is to choose that alternative which most strongly fulfills the entire set of objectives. We are interested in deriving numerical weights for alternatives with respect to sub-objectives and for sub-objectives with respect to higher order objectives. We would like these weights to be meaningful for allocating resources. For example, if they are derived to represent the value of money or distance or whatever physical quantity is being considered, they should be the same, or close to, what an economist or a physicist may obtain using his methods of measurement. Thus our process of weighting should produce weights or priorities that are estimates of an underlying ratio scale."[13]

Ratio Scales, Pairwise Numerical and Pairwise Graphical Judgments

There have been some questions raised as to whether or not the priorities produced by AHP are, in fact, ratio scale measures. We examine these next.

Whereas an interval scale is defined to be a scale that is invariant under the transformation $y = ax + b$, a ratio scale is defined to be invariant under the transformation $y = Ax$. Because there is no b in the ratio scale transformation, the ratio scale is said to have 'true' zero. Some have questioned whether AHP produces a ratio scale because they do not see any zero in either the fundamental verbal judgment scale used for pairwise comparisons, or the resulting priorities. This misunderstanding is partly due to the misconception that 'fuzzy' verbal judgments are the only way to express relative judgments. We discuss next why using pairwise numerical or pairwise graphical judgments produces ratio scale priorities and then discuss how ratio scale priorities can often be produced with pairwise verbal judgments as well.

If asked for the relative weights or two rocks, an observer holding the rocks could estimate that the rocks are about the same weight or that the heavier of the two rocks is x times heavier than the lighter rock, where x is a number greater than 1.0. (There is nothing that explicitly limits the upper value of X, although the first axiom of AHP says that elements being compared are homogenous, which is often interpreted to mean within an order of magnitude). If we had N rocks, one could elicit judgments of this type for the N(N-1)/2 elements above the diagonal of a pairwise comparison matrix. AHP uses the normalized eigenvector associated with the largest eigenvalue of this matrix as the relative weights of the rocks. Since each pairwise comparison is already a ratio, the resulting priorities will be ratio scale measures as well. Experiments have shown that the resulting ratio scale priorities are more accurate than any of the individual comparisons.

Using a device such as a computer, an observer could represent the perceived ratio of the two weights by adjusting the length of two bars instead of providing a numerical estimate. The relative lengths of the two bars can then be used as entries in the pairwise comparison matrix and priorities derived in a similar fashion. Experiments have

[13]Saaty, T. L. 1980. *The Analytic Hierarchy Process*, McGraw Hill, New York., pg xi.

shown that the resulting ratio scale priorities are even more accurate with graphical judgments than with numerical judgments.

Pairwise numerical or pairwise graphical procedures can be used to elicit judgments about the relative size of geometric shapes, the relative brightness of objects, the relative importance of objectives, or the relative preference of alternatives with respect to a stated objective. While the judgments in each case would be subjective (i.e., depend on the subject), the results for the size and brightness judgments can be compared to objective measures; there are no such objective measures for importance or preference. Non-the-less, ratio scale measures of subjective importance and preference are essential for rational decision making and resource allocation and AHP can produce such measures.

Pairwise Verbal Judgments

The fundamental scale originally proposed by Saaty for AHP consisted of the words: Equal, Weak, Strong, Very Strong, and Absolute (Weak was subsequently changed to Moderate and Absolute changed to Extreme). Based on empirical research, Saaty proposed representing the intensity of these words with ratios of 1, 3, 5, 7 and 9 respectively, with even integers 2,4,6 and 8 being used for intermediate judgments such as 6 for between Strong and Very Strong. Unlike the numerical and graphical procedures discussed above, verbal judgments are not interval or ratio, but only of ordinal measure. This is *not* due to the fact that there is no zero in the scale, because a zero can be implied as well as explicit. (A line of zero length cannot be seen and absolute zero temperature cannot be achieved, but length and temperature can be measured on a ratio scale). The fundamental verbal scale is only ordinal because the intervals between the words on the scale are not necessarily equal.

Despite the fact that the fundamental verbal scale used to elicit judgments is only ordinal measure, Saaty's empirical research showed that the priorities *derived* from the principle eigenvector of a pairwise verbal judgment matrix, often does produce priorities that approximate the true priorities from ratio scales such as distance, area, and brightness. This happens because, as Saaty has shown mathematically, the eigenvector calculation has an averaging affect – it corresponds to finding the dominance of each alternative along all walks of length k, as k goes to infinity[14]. Therefore, if there is enough variety and redundancy, errors in judgments, such as those introduced by using an ordinal verbal scale, can be greatly reduced.

An experiment was conducted to demonstrate that redundancy is important in deriving accurate ratio level measures from imprecise pairwise verbal judgments. The experiment consisted of exercises in which an individual or a group of individuals made pairwise verbal judgments about the relative sizes of the geometric shapes. A wide variety of people participated in the exercises. In addition to participants from the business, government and educational communities in the United States, study participants also included Japanese business executives, Soviet scientists, and Chinese city planners. The subjects were given the following instructions:

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[14] Saaty, T.L., The Analytic Hierarchy Process, (New York: McGraw Hill, 1980), pp. 78-121.

Suppose you were allocating funds for environmental quality purposes and wanted to determine the relative need for funds for clean air, clean water, noise reduction, industrial dumps, and acid rain. As an analogy, suppose your insight about the relative needs coincide with the relative sizes (areas) of the five geometric shapes shown. Although you *could* look at these objects and estimate their relative sizes numerically, the experiment is designed to show how we can derive accurate ratio scale priorities for qualitative factors from "fuzzy" verbal judgments. The analogy with the geometric shapes is necessary in order to measure the accuracy of the priorities derived from your "fuzzy" verbal judgments.

In order to minimize numerical comparisons of the geometric shapes, subjects were not told the numerical values on the fundamental scale associated with each of the verbal judgments. They were told only that the meaning of "equal" was obvious, and that "extreme" meant an order of magnitude or more, but not necessarily that the largest shape was being compared to the smallest. Because the words were not precisely defined, some subjects or groups of subjects tended to use words higher up on the scale than did other subjects or groups.

FIGURE	Estimates from Verbal Judgments W/O Redundancy	Estimates from Verbal Judgments With Redundancy	Actual
A	.543	.514	.475
B	.078	.048	.049
C	.181	.242	.232
D	.109	.117	.151
E	.090	.078	.093

Table 3 – Comparison of Estimated vs. Actual Priorities for a Typical Set of Judgments

As can be seen from the results in Table 3, the pairwise verbal comparison process, used with redundancy as illustrated in this experiment[15], produces priorities that are "accurate" estimates of an underlying ratio scale. The average mean square error in the estimates derived from just the first row of judgments (no redundancy) was more than four times that of the estimates obtained with the full set of judgments. On an individual basis, the resulting priorities are often more accurate than those produced by asking an individual for direct numerical estimates of the relative sizes of the geometric shapes.

The preceding results are not guaranteed to occur for all situations. If there is not adequate redundancy or variety in the pairwise comparison matrix, the resulting priorities may not accurately reflect the underlying ratio scale. When comparing only two factors in a cluster of an AHP model, there is no redundancy and the pairwise graphical or numerical mode should be used instead of the pairwise verbal mode. If there are several factors in a cluster, all of which are identical with one being just slightly larger than the

[15]There are good reasons to feel confident that the results of this experiment extend to other applications. Other studies have shown that accurate priorities can be derived from pairwise judgments for applications such as estimating the brightness of light on chairs placed different distances from a light source, estimating the relative distances between cities, and estimating the number of people drinking coffee, tea, milk, etc.

others, the comparison matrix will consist of mostly 1's (for EQUAL) and some 2's (for EQUAL to MODERATE), resulting in inaccurate results that one factor is twice the others. Therefore, it is important that decision-makers examine the resulting priorities to assess whether they adequately represent their judgments. In cases where they do not, the pairwise numerical or graphical comparison modes can be relied on to produce accurate ratio scale measures as discussed above.

8.6 Prioritizing Objectives/Criteria

AHP has three judgment elicitation modes (verbal, numerical, or graphical) by which a decision maker can provide judgments about the relative importance of criteria or objectives. The judgments are made in a pairwise fashion. For example,: In the context of a specific decision, what is the relative importance of cost and performance? A verbal response would be something like: Performance is moderately more important to me than cost. A numerical judgment would be something like: Performance is 2.5 times more important to me than cost. A graphical response would involve moving two bars such that the ratio of their lengths represents the relative importance of performance and cost.

Some utility theory academics have questioned whether decision makers can meaningful make judgments about the relative importance of criteria or objectives. In over twenty years of application, we have not encountered *any* decision makers who have had difficulty in understanding such questions or in providing meaningful responses. We have, on occasion, had decision makers say they didn't feel capable of providing a verbal response, such as moderately more important. In such cases, the decision makers had no difficulty providing meaningful numerical or graphical judgments.

The ability for people to understand and make pairwise comparisons is one of AHP's strengths. To better understand this, we invite the reader to compare AHP's judgment process just described with that used by utility theory advocates, such as Kirkwood [1997], to derive weights for the objectives directly above the alternatives in a decision hierarchy.

> …First, the single dimensional value functions have been specified so that each of them is equal to zero for the least preferred level that is being considered for the corresponding evaluation measure. Similarly, each of the single dimensional value functions has been specified so that it is equal to one for the most preferred level that is being considered for the corresponding evaluation measure.
>
> From these properties of the single dimensional value functions, it follows that the weight for an evaluation measure is equal to the increment in value that is received from moving the score on that evaluation measure from its least preferred level to its most preferred level. This property provides a basis for a procedure to determine the weights. … Specifically these steps are as follows:
>
> 1. Consider the increments in value that would occur by increasing (or 'swinging") each of the evaluation measures from the least preferred end of its range to the most preferred end, and place these increments in order of successively increasing value increments.
> 2. Quantitatively scale each of these values as a multiple of the smallest value increment.
> 3. Set the smallest value increment so that the total of all the increments is 1.

4. Use the results of Step3 to determine the weights for all the evaluation measures.[16]

A paraphrased description of Kirkwood's application of these rules to his prototype example is:

> Suppose that the swing over the total range for Productivity Enhancement (Objective 1) has the smallest increment of value.… Suppose further that the swing over the total range for Cost Increase (Objective two) from 150 to 0 has 1.5 times as great a value increment as the swing over Productivity Enhancement from –1 to 2, and the swing over Security (Objective 3) from –2 to 1 has 1.25 times the value increment of swing over Cost increase.

An alternate approach to determining weights used by MAUT is even more obscure. It involves the consideration of hypothetical alternatives and asks the decision maker to determine intermediate levels for the alternative for which they would be indifferent between that alternative and one at its maximum level. Thus instead of the swing weight questions described above, the dialog might be something like:

> "Consider a hypothetical alternative that has the least preferred level for all the evaluation measures. Now suppose that you could move one and only one from its least preferred level to its most preferred level. Which would you move? Now suppose you could not move that one, which is the next one you would move? Now suppose that you could either move the second from its most least preferred level to its most preferred level, or the first from its least preferred level to some intermediate level. Select the intermediate level for which you would be indifferent between the two possibilities." (This question is usually easiest to answer by considering a specific intermediate level for Security, and then adjusting this level until indifference is established).[17]

8.6.1 Simplicity and Ease of Understanding

The MAUT judgment elicitation approaches described above are obscure enough that MAUT practitioners concede the need for a facilitator with years of training to help decision makers with the judgment process.[18] Compare either of the above approaches to the AHP pairwise comparison process:

Using numerical judgments, the decision maker would make judgments such as the following:

> Cost Increase is 1.5 times more important than Productivity Enhancement.
>
> Security is 1.25 times more important than Cost increase.

If specifying a numerical judgment is considered to be too arbitrary by the decision maker, the AHP verbal or graphical judgment modes can be used instead.

We argue, and many have agreed, that the AHP approach is much more straightforward and understandable. The MAUT approach requires that the decision maker construct a (sometimes artificial[19]) scale, make an absolute judgment about where each alternative lies on that scale, and then make a judgment about the ratio of swings

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[16] C. Kirkwood, "Strategic Decision Making – Multiobjective Decision Analysis with Spreadsheets", Duxbury Press, 1997, Belmont CA, p 68.

[17] Ibid, p 71.

[18] R. Howard – Statement made during panel discussion "Deciding on Multi-Criteria Decision Making Methods", Fall 96 Informs, New Orleans.

[19] Many of the objectives in a decision model are qualitative, meaning there is no scale. Even for those objectives, such as cost, for which there is a scale, we are concerned with the decision makers utility, not the absolute values on the scale.

over that scale. The AHP pairwise comparison approach does not require any 'scale'. Whereas scales are required for absolute measurement, the relative measurement of the AHP pairwise comparison process requires no scales since the process of forming ratios would produce the same results with or without a scale.

8.6.2 Flexibility

We also contend that the AHP approach is more flexible as well. Whereas the MAUT approach *requires* that the decision maker consider the swings in alternative values from the worst to the best case on each objective, such considerations are possible, but *not required* with AHP. There may be applications, such as strategic planning, where the importance of the objectives are the driving forces and are not dependent on the alternatives' values. On the other hand, there may be problems where the relative importance of the objectives are, in the decision makers mind, determined by the best value, or the worst value, or perhaps the average value of the alternatives under consideration. AHP, and AHP with feedback (or ANP) can accommodate any of these situations, as well as the not so uncommon situation where there *are no* alternative values for one or more objectives.

Finally, the MAUT approaches described above can *not* be used to prioritize objectives in the objectives hierarchy that are not directly above the alternatives. Practitioners of MAUT` "do not typically assess criteria weights for evaluation considerations that are not at the ends of branches in the evaluation tree, although these can be inferred from the assessed weights if desired."[20] Thus, the MAUT is bottom up, or alternative driven approach rather than an objectives driven approach. An AHP evaluation, on the other hand, can be top down, bottom up or a combination of the two.

8.6.3 Accuracy

Not only is the AHP approach more straightforward and understandable than the MAUT judgment approach, it is more accurate as well. By eliciting *redundant* pairwise comparisons (to fill in the upper diagonal of the pairwise comparison matrix) and deriving the priorities as the normalized principle eigenvector of the matrix, the priorities are more accurate than by computing them from a set of judgments without redundancy (as illustrated in Section 8.3). True, the redundant judgments take more time than making a minimal set of judgments, but this capacity to increase accuracy is an option with AHP that is not available with the MAUT approach. As discussed earlier, if a decision maker desires to make fuzzy verbal judgments, then redundancy is important in deriving accurate priorities. However, if the decision maker chooses to make numerical or graphical judgments, and has high confidence that each judgment is accurate, there is less need for redundancy.

Of course, MAUT advocates do not agree that AHP is more straightforward, flexible and accurate. Although Kirkwood concedes that:

> "the AHP is directed at a broader range of issues than just making decisions. It may have advantages with respect to these broader issues.."[21]

[20] Communication with C. Kirkwood, 2/24/98

[21] Kirkwood, p260

but continues on to say:

> "but I agree with Winkler's (1990) assessment that decision analysis methods are more appealing for aiding decision making. … the approach seems overly complex with its need for sometimes extensive pairwise comparisons of alternatives and extensive mathematical calculations to determine rankings. These characteristics seem to obscure, rather than illuminate, the tradeoffs involved in making decision with multiple objectives. … the separation of value assessment and scoring of alternatives that is characteristic of decision analysis methods makes it straightforward to determine whether the disagreements among stakeholders to a decision are with regard to values or the estimated performance of the alternatives."

To this we reply that (1) in practice, decision makers have found the AHP judgment process to be far more intuitive and appealing, (2) there is no need for extensive pairwise comparisons or any redundancy in judgments if decision makers are content to settle for the level of accuracy provided by the first of the two MAUT methods presented by Kirkwood , (3) the extensive mathematical calculations -- eigenvector calculations, are one of the most naturally occurring mathematical relationships in all of science and require minimal assumptions, (4) the calculation is performed in a fraction of a second by a personal computer, thus entailing no more burden on, or faith from, the decision maker than using a speadsheet to add a column of numbers, (5) there is as much separation from assessment of criteria/objectives and alternatives in AHP as there is in MAUT; the difference is that MAUT dictates that the latter be done using hypothetical scales and value curves whereas with AHP this can be done either with pairwise relative comparisons or, if one desires, using rating intensities with ratio scale priorities.

8.7 AHP with Feedback (ANP) and approximations

The third axiom of AHP states that judgments about, or the priorities of, the elements in a hierarchy do not depend on lower level elements. This axiom is not always consistent with real world decisions. In some decisions, not only is the preference of the alternatives dependent on which objective is being considered, but the importance of the objectives may also depend on the alternatives being considered. This dependence can be accommodated either with formal feedback calculations or, in most cases, intuitively by the decision maker(s). Consider the following example. Suppose you are the mayor of a medium size city. The city council has just approved funding for a bridge that will connect the eastern and southern districts– saving the residents 30 minutes in commuting time. You announce that the winning proposal will be chosen using a formal evaluation methodology in which the proposals will be evaluated on the basis of strength and aesthetics. In order to be fair, you will, before receiving any bids, specify which of the two objectives will be more important. It seems obvious[22] that strength is much more important than aesthetics and you publicly announce that strength will be the most important objective in choosing the winning proposal.

Subsequently, two alternative designs are proposed for the new bridge. Bridge A is extremely safe (as safe as any bridge yet built) and beautiful. Bridge B even safer than bridge A, but is UGLY!. Your hands are tied – you have announced that the most important objective is strength and your formal evaluation methodology forces you to choose the ugly bridge. Some decision makers, when confronted with such a dilemma, vow to never use a formal evaluation methodology again. The answer is not to avoid formal evaluation methodologies, but to those that are theoretically sound and use them in ways that make sense!

The 'top down' approach entails evaluating the importance of the objectives before evaluating the alternative preferences. A 'bottom up' approach, on the other hand, would consist of the evaluation of alternative preferences with respect to each objective before evaluating the relative importance of the objectives. If the decision maker had used a bottom up approach instead, he/she would have learned that although design B is stronger than design A, both designs far exceed all safety standards. Furthermore, the decision maker would have learned that design A is beautiful and while design B is ugly. Subsequently, while considering the relative importance of strength and aesthetics, the decision maker might reasonably decide that aesthetics is more important than strength and that Bridge A is more preferable, a result that is also intuitively appealing.

[22]In the abstract, it would be difficult to defend a position that the strength of the bridge is not more important than aesthetics.

Even if a top down approach is used, no harm will result provided the decision maker examines the tentative results and questions its reasonableness.[23] In this example, the Mayor would, after synthesizing the first time, realize that the choice of the ugly bridge is counter-intuitive. Now knowing that both bridges are more than adequately safe he or she should re-evaluate his or her judgments. Doing so will result in the judgment that aesthetics is more important than safety and that Bridge A is the preferred alternative.

8.7.1 The Analytic Hierarchy Process (ANP)

The need for such iteration is due to feedback – that is, contrary to the third axiom of AHP which says that influence only flows down in a decision hierarchy, there is feedback from the alternatives to the objectives in this example since the relative importance of the objectives depend in part on the alternatives. A more formal approach than intuitively iterating in order to incorporate feedback is to use the Analytic Hierarchy Process, or ANP[24],[25.] An ANP model for this bridge selection example would not ask the decision maker to compare the relative importance of safety and aesthetics with respect to the 'goal', but instead would ask for judgments about the relative importance of safety and aesthetics first with respect to Bridge A, and then with respect to Bridge B. The priority vectors of the objectives with respect to each alternative, as well as the priority vectors for the alternatives with respect to each objective are used to form a 'supermatrix', which, when raised to powers, will, under suitable conditions produce the limiting priorities of the alternatives and the objectives.[26] We have observed that for decisions involving only feedback from alternatives to objectives, it is possible to arrive at similar results by incorporating feedback through iteration with AHP as with the supermatrix approach of ANP. In general, however, the ANP makes it possible for us to deal systematically with all kinds of dependence and feedback. The ANP provides a framework of clusters of elements connected in any desired way to investigate the process of deriving ratio scales priorities form the distribution of influence among elements and among clusters. The distribution of influence is represented by interactions and feedback within clusters (inner dependence) and between clusters (outer dependence). The AHP is a special case of the ANP. Although some decision problems are best studied through the ANP, it is not true that forcing an ANP model always yields better results than using the hierarchies of the AHP. There are examples to justify the use of both.

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[23]In accordance with the forth axiom of AHP.

[24]Saaty, T.L., 1994. *Fundamentals of Decision Making and Priority Theory with The Analytic Hierarchy Process*, RWS Publications, Pittsburgh, PA., p38.

[25] Saaty, T.. L. *Decision Making with Dependence and Feedback, The Analytic Network Process*, 1996, RWS Publications, Pittsburgh, PA.

[26] Saaty, Thomas L.,1996. *Decision Making with Dependence and Feedback*, RWS Publications, Pittsburgh, PA, 1996.

8.7.2 Piecemeal attempts to approximate ANP with a modified AHP

Some academics, when examining the application of AHP to specific situations involving feedback from alternatives to objectives, have proposed different approaches to model this feedback[27],[28]. These approaches, known by such terms as referenced AHP, Linking Pins and Concordant AHP, are piecemeal approximations of ANP. They do not generalize well because they prescribe how the priorities of the objectives should be calculated based on the values of the alternatives and, in general, the importance of objectives are not determined, a-priori, by the values of the alternatives. We illustrate with an example given by Schenkerman (1997) involving the perimeter of four rectangular fields (the alternatives) each with a perimeter of 2,000 yards and each oriented so that its sides (the criteria/objectives) represent the length and width respectively. The four fields in are listed in Table 4:

Table 4

Field	Length	Width
A	1	9
B	2	8
C	3	7
D	4	6
Total	10	30

Schenkerman erroneously reasoned: "The focus (overall objective) is the perimeter, so both directions (the criteria) are equally preferred and the criteria weights are equal (0.5, 0.5)". Synthesizing using this reasoning produces priorities of .2, .233, .2667, and .3 for the perimeters of A, B, C, and D respectively (see Table 5). Since each field has the same perimeter, the priorities should each be .25.

Table 5

Field	Length	Relative Length	Width	Relative Width	Priorities
		0.5		0.5	
A	1	0.1	9	0.3	0.2
B	2	0.2	8	0.266666667	0.2333
C	3	0.3	7	0.233333333	0.2667
D	4	0.4	6	0.2	0.3

A correct application of AHP would not assume that length and width are of equal importance. Since the total width (30) is three times that of the total length, (10), the width should be three times more important than Length, not equal as Schenkerman erroneously assumed. A synthesis based on priorities of .25 and .75 for length and width respectively, does, in fact produce the correct priorities of .25 for each of the four fields.

[27] Schoner, B., & Wedley, W.C. (1989) Ambiguous criteria weights in AHP: Consequences and solutions. *Decision Sciences*, 20 (3), 462-475.

[28] Schenkerman, S. (1997), Inducement of Nonexistent Order by the Analytic Hierarchy Process, *Decision Sciences,* 28 (2), 475-482.

8.7.3 The fallacy of automatically linking criteria importance to alternative values

Suggestions, such as Schenkerman's, to modify AHP so that it *automatically* links the criteria importance to alternative values (in particular, the total for each criterion/objective) are short sighted. While they may work on some trivial examples, they can produce results that are counterintuitive and erroneous. As an illustration (one example such as this is sufficient to dismiss the approach), consider a decision to choose a means of transportation with two alternative vehicles and two criteria/objectives, based on the hypothetical information provided in Table 6.

Table 6 -- Choosing a vehicle for transportation

Vehicle	Miles per gallon	Safety (number of thousand miles per serious injury or death)
Vehicle A	5	800
Vehicle B	15	20
Total	20	820

Ignoring other factors such as comfort, most decision-makers would choose Vehicle A over Vehicle B because safety would be much more important than efficiency. Suppose this decision were modeled using Schenkerman's suggested modification to AHP and suppose that with some new technology, the manufactures of Vehicle B improved its safety to 780 thousand miles per serious injury or death as shown in Table 7. This should make Safety less important, and, for many decision-makers, Vehicle B would be preferred to Vehicle A. However, using Schenkerman's suggested modification to AHP, Safety would become *more* important, contrary to logic. Furthermore, Vehicle A would still be preferred to vehicle B, contrary to what many people would feel is the correct choice and contrary to what would be modeled with a straightforward application of AHP in its present form as described above, or with ANP.

Table 7 -- Choosing a vehicle for transportation

Vehicle	Miles per gallon	Safety (number of thousand miles per serious injury or death)
Vehicle A	5	800
Vehicle B	15	780
Total	20	1580

8.7.4 Impact of Scales

Another serious limitation with Schenkerman's suggested modification to AHP is evident when we change the scale in either dimension of the above example. Suppose that we measured safety in miles instead of thousands of miles. This would change the values of 800 and 780 to 800,000 and 780,000 (see Table 8) and would cause the priority of safety to further increase using Schenkerman's suggested modification. Clearly this is not correct. The results should *not* be dependent on the scale used in any dimension.

Table 8 -- Choosing a vehicle for transportation

Vehicle	Miles per gallon	Safety (number of miles per serious injury or death)
Vehicle A	5	800,000
Vehicle B	15	780,000
Total	20	1,580,000

Summary and Conclusion

We have examined the history and development of AHP. The three primary AHP functions of structuring complexity, measurement and synthesis make AHP applicable to a wide range of applications, not just choice problems. AHP's axioms are few, simple, and with the exception of the hierarchic composition axiom (that specifies that influence flows down but not up), in consonance with all real world situations we have encountered. For those situations where higher levels of a hierarchy are influenced by lower levels, we have described three ways to apply or modify the AHP process -- iteration, bottom up evaluation, and feedback with supermatrix calculations.

We have discussed why measurement is so important, why ratio scale measures, a cornerstone of AHP, convey more information than interval or ordinal measures and why ratio measures are required for some applications where interval measures are not adequate. We have discussed why AHP produces ratio scale measures of both objective and subjective information.. We have addressed academic debates and presented arguments for AHP's superiority in issues involving transitivity, rank reversal when adding irrelevant alternatives, rank reversal when adding relevant alternatives, and automatically linking criteria importance to alternative values. In comparing AHP's judgment elicitation process to that of MAUT, we have illustrated why we feel that AHP has significant advantage with respect to simplicity, ease of understanding, flexibility and accuracy. Substantiation of these arguments come from the thousands of applications of AHP around the world, as evidenced by numerous applications cited herein involving the choice of one alternative among many, prioritization/evaluation of a set of alternatives, resource allocation, benchmarking, quality management, public policy, health care, and strategic planning.

Although numerous organizations in both the private and public sectors have already benefited from the use of AHP, there are far more organizations still unaware of a process such as AHP that is theoretically sound, understandable, and matches their expectations. We hope that this exposition will help in making these organizations aware of a viable alternative to applying inferior common simplistic strategies to important decisions.

REFERENCES

Bell, D. E., H. Raiffa, and A. Tversky (eds.). 1988. *Decision Making: Descriptive, Normative, and Prescriptive Interactions*, Cambridge University Press, Cambridge, England.

Bell, D. E., R. L. Keeney, and H. Raiffa (eds.). 1977. *Conflicting Objectives in Decisions*, John Wiley and Sons, N.Y.

Belton, V. and Gear, T. 1982. On a Shortcoming of Saaty's Method of Analytic Hierarchies. *Omega* Vol. 11 No. 3, 226-230.

Chankong, V., and Y. Y. Haimes. 1983. *Multiobjective Decision Making*, North-Holland, N.Y.

Churchman, C.W. 1979, "Measurement for Management Decision: A Perspective", *California Management Review*, Vol 21, No 3 (Spring 1979), p14.

Corbin, R. and A. A. J. Marley. 1974. Random Utility Models with Equality: An Apparent, but not Actual, Generalization of Random Utility Models, *Journal of Mathematical Psychology*, 11, 274-293.

Cyert, R. M., H. A. Simon, and D. B. Trow. 1956. Observations of a Business Decision, *Journal of Business*, University of Chicago, 29, 237-248.

Dyer, J. S. 1990. Remarks on The Analytic Hierarchy Process, *Management Science*, Vol. 36, No. 3, 249-258.

Fishburn, P. C. 1991. Nontransitive Preferences in Decision Theory, Journal of Risk and Uncertainty, 4, 113-134.

Eyrich, H.G., "Benchmarking to Become the Best of Breed," Manufacturing Systems magazine, April 1991.

Fishman, G. S., and P. J. Kiviat. 1967. Digital Computer Simulation: Statistical Considerations, RM-5387-PR, The RAND Corp., Santa Monica, Calif. (Also published as: The Statistics of Discrete Event Simulation, *Simulation*, April 1968.)

Forman, E. H., 1987. Relative Vs. Absolute Worth, *Mathematical Modeling*, Vol. 9, No. 3-5, 195-202.

Forman, E. H., 1990. "AHP is Intended for More than Expected Value Calculations", *Decision Sciences*, Volume 21, Number 3, 670-672.

Forman, E. H., 1990. Deriving Ratio Level Measures from Verbal Judgments, *George Washington University Working Paper*.

Forman, E. H., 1993 "Ideal and Distributed Synthesis Modes for the Analytic Hierarchy Process", *George Wasington University Working Paper*

Forman, E. H., Saaty, T. L., Selly, M. A., Waldron, R., 1983. *Expert Choice*, Decision Support Software, McLean, VA.

Gass, S. I. 1983. Decision-Aiding Models: Validation, Assessment, and Related Issues for Policy Analysis, *Operations Research*, 31, 4, 603-631.

Gump, Forrest. 1994. *Forrest Gump--The Movie*.

Huber, J. and Puto, C., 1983. Market Boundaries and Product Choice: Illustrating Attraction and Substitution Effects, *Journal of Consumer Research* Vol. 10, June, 31-44.

Huber, J., Payne, J. W., and Puto, C., 1982. Adding Asymmetrically Dominated Alternatives: Violations of Regularity and the Similarity Hypothesis. *Journal of Consumer Research*. Vol. 9, June, 90-98.

Hwang, C.-L., and K. Yoon. 1981. *Multiple Attribute Decision Making*, Springer-Verlag, N.Y.

Keeney, R. L., and H. Raiffa, 1976. *Decisions with Multiple Objectives: Preference and Value Tradeoffs*, John Wiley & Sons, N.Y.

Kirkwood, C. “Strategic Decision Making – Multiobjective Decision Analysis with Spreadsheets”, Duxbury Press, 1997, Belmont CA,

Kuhn, Thomas S., 1962. *The Structure of Scientific Revolution*, University of Chicago Press.

Luce, R.D. and H. Raiffa, 1957, *Games and Decisions*. John Wiley and Sons, Inc., New York.

McCord, M., and R. de Neufville. 1983. Fundamental Deficiency of Expected Utility Decision Analysis, pp. 179-305 in *Multi-Objective Decision Making*, S. French, R. Hartley, L.C. Thomas, and D.J. White (eds.), Academic Press, N.Y.

Merkin, B. G. 1979. *Group Choice*, John Wiley & Sons, NY.

Milnor, J. 1954. Games Against Nature, pp. 49-60 in *Decision Processes*, R. M. Thrall, C. H. Coombs, and R. L. Davis (eds.), John Wiley & Sons, N.Y.

Osborne, M. J., and A. Rubinstein, 1994. *A Course in Game Theory,* M.I.T. Press, Cambridge, Mass.

Ozernoi, V. M. and M. G. Gaft. 1977. Multicriterion Decision Problems, pp. 17-39 in *Conflicting Objectives in Decisions*, Bell, D. E., R. L. Keeney, and H. Raiffa (eds.), John Wiley and Sons, N.Y.

Quade, E. S. 1989. *Analysis for Public Decisions*, North-Holland, N.Y.

Saaty, T. L. 1980. *The Analytic Hierarchy Process*, McGraw-Hill Book Co., N.Y.

Saaty, T. L. 1986. Axiomatic Foundation of the Analytic Hierarchy Process, *Management Science*, 32, 841-855.

Saaty, T. L. 1990. An Exposition of the AHP in Reply to the Paper "Remarks on the Analytic Hierarchy Process", *Management Science*, Vol. 36, No. 3, 259-268.

Saaty, T. L. 1991a. How to Make a Decision: The Analytic Hierarchy Process, *European Journal of Operations Research,* Vol. 48, 9-26.

Saaty, T. L. 1991b. Rank and the Controversy About the Axioms of Utility Theory -- A Comparison of AHP and MAUT, *Proceedings of the 2nd International Symposium of The Analytic Hierarchy Process*, Pittsburgh, PA, 87-111.

Saaty, T. L. 1994a. How to Make a Decision: The Analytic Hierarchy Process, *Interfaces*, 24, 19-43.

Saaty, T. L. 1994b. *Fundamentals of Decision Making*, RWS Publications, Pittsburgh, PA

Saaty, Thomas L.,1996. *Decision Making with Dependence and Feedback,* RWS Publications, Pittsburgh, PA, 1996.

Schenkerman, S. 1997, Inducement of Nonexistent Order by the Analytic Hierarchy Process, *Decision Sciences*, 28 (2), 475-482.

Schoner, B. S. & Wedley, B. W, 1989, "Ambiguous Criteria Weights in AHP: Consequences and Solutions", Decision Sciences, 20, 462-475.

Simon, H., 1972. Theories of Bounded Rationality, in *Decision and Organization*, C. B. Radner and R. Radner, (eds.), North-Holland, Amsterdam, 161-176,

Straffin, P. D. 1993. *Game Theory and Strategy*, The Mathematical Association of America, Washington, DC.

Stevens, S.S., 1946), "On the Theory of Scales of Measurement", *Science*, (103, 1946), pp. 677-680.

Tversky, A. 1969. Intransitivity of Preferences, *Psychological Review*, 76, 31-48.

Tversky, A., and D. Kahneman. 1988. Rational Choice and the Framing of Decisions, in *Decision Making: Descriptive, Normative, and Prescriptive Interactions*, Bell, D. E., H. Raiffa, and A. Tversky (eds.), pp. 167-192, Cambridge University Press, Cambridge, England.

United States Department of Commerce, 1996,"The Malcom Baldridge National Quality Award", Technology Administration, Gaithersberg, MD.

Vazsonyi, A. 1995. Multicriteria Decision Making, *Decision Line*, December/January, 13-14.

von Neumann, J., and O. Morgenstern. 1947. *Theory of Games and Economic Behavior*, 2nd. ed., Princeton University Press, Princeton, N.J.

Watson, S.R., and D. M. Beude. 1987. *Decision Synthesis*, Cambridge University Press, Cambridge, England.

Whyte, LL, 1969,*Hierarchical Structures* , American Elsevier, New York, N.Y.

Zeleny, M. 1982. *Multiple Criteria Decision Making*, McGraw-Hill Book Co., N.Y.