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The Limits and Possibilities of Decision Models
for Army Research and Development Project Selection

by

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The case is made for applying Multicriteria Decision Models (MCDM) to the Army's research and development (R&D) project selection process. Given the recent changes in the international strategic environment and the resulting congressional emphasis on applied research short of production, the need for improved efficiency in selecting Army R&D projects is increasing. R&D project selection choices are non-trivial, with many stakeholders and multiple criteria for evaluating the alternatives to meet the organization's various objectives. Research on human cognition has revealed that typical decision making processes are inefficient for dealing with multi-criteria decision problems. MCDM such as the Analytic Hierarchy Process, Multiattribute Utility Theory, Goal Programming, and Graphical Techniques are designed to support these decisions by formulating logically supportable choices. Each of these four models is described and a summary of their strengths and weaknesses is presented.

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The Limits and Possibilities of Decision Models for Army Research and Development Project Selection

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of the requirements for the degree of

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ABSTRACT

The case is made for applying Multicriteria Decision Models (MCDM) to the Army's research and development (R&D) project selection process. Given the recent changes in the international strategic environment and the resulting congressional emphasis on applied research short of production, the need for improved efficiency in selecting Army R&D project alternatives is increasing. R&D project selection problems are non-trivial, with many stakeholders and multiple criteria for evaluating the alternatives to meet the organization's various objectives. Research on human cognition has revealed that typical notions about decision making are inefficient for dealing with multi-criteria decision problems. MCDM such as the Analytic Hierarchy Process, Multiattribute Utility Theory, Goal Programming, and Graphical Techniques are designed to support these decisions by formulating logically supportable choices. Each of these four models is described and a summary of their strengths and weaknesses is presented.

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I. INTRODUCTION AND BACKGROUND

> The quality of American technology has enabled us to successfully deal with difficult military conditions and help minimize the precious loss of life. We have given our men and women the very best. And they deserve it.
>
> President George H. Bush,
> State of the Union address, January 1991

A. INTRODUCTION

The President's moving words of gratitude reflect the enormous success of America's armed forces against Iraq, largely wrought from our overwhelmingly superior application of technologies to defeat naked aggression. His stirring emotion had to fill those responsible with quiet assurance that their efforts over the past several decades had been vital.

At the same time, many in Congress were and are calling for deep cuts in military spending. Yet no one in the administration or Congress wants to dull America's technological edge. How can the U.S. maintain, much less improve its lead in the race for defense technological superiority under these circumstances? Whatever the answer, it will be multi-faceted and at least as complex as the bureaucracy from which it is born.

Critical decisions in complex organizations are rarely easy, especially those involving the expenditure of significant public funds and with potential consequences affecting the very lives of the men and women of our nation's armed forces. The decisions about which technologies are to comprise the Department of the Army's technology base investment strategy are central to this serious issue.

Given these changes in U.S. budget priorities as well as national and global political and economic realities, there is certain to be a call for heightened oversight and accountability of the technology investment process. Thus, in spite of defense management cries to reduce micromanagement, scrutiny is sure to be more strenuous as the reverse is less politically attractive or rewarding.

With increased scrutiny of the decision process will come greater need for clear logic, consistency, and credibility in technology investment decisions without stifling creativity from heightened risk aversion. Analytic decision models (ADM), designed to support the multidimensional decision environment of defense technology investment, can fill this need.

Over the past 30 years there has been something of a silent explosion in model development. Yet decision models are not widely used by the very managers they are designed to support [Ref. 1]. The purpose of this study is to introduce Army R&D managers and their support staffs to the virtues and limitations of some important project selection analytic decision models (ADM). Given the need and their effectiveness, ADM's will have an ever increasing role in obtaining logical solutions to problems of competing priorities, goals and objectives.

B. DISCUSSION

Analytic decision models such as the Decision Matrix, Hurwicz criterion, and Analytical Hierarchy Process are used to structure decision making under risk and uncertainty and may offer some support for the Army's research and development (R&D)/technology base investment strategy decision process. First of all, formal decision models help to formulate a structure for all issues bearing on the problem. They offer a rational process for assigning values to the important factors on the basis of current priorities and policy. Environmental factors such as the likely international political climate may also weigh into the problem and a "best" solution may be deduced from the relevant, possible alternatives.

Research into the psychology of human judgment over the past several decades reveals that, while the environment in which decisions are made has become increasingly more complex, the intuitive judgmental skills of the decision makers has not kept pace. Rather than clarifying the choices, ever increasing amounts of information often lead to selectively "seeing only what we want to see." Filtering information in this way, basing decisions predominately on past experience, can adversely skew results. [Ref. 2]

Memory is another weak point in human judgment. Since many decisions are constructed from the data, based upon a reconstruction of past similar situations, limited memory is a source of potential human error. Additionally, people do not have good success judging probabilistic outcomes regarding risk and uncertainty. People do not have innate intuitive abilities to assess probable outcomes from random input data. Formalized decision models can provide a framework to organize input data which exposes these and other sources of potential error, systematically minimizing risk to improve results. [Ref. 3]

Perhaps the most important reason for incorporating ADMs into the Army technology investment process is money. The Department of Defense (DoD) annual budget will shrink each year as a result of the President's agreement with the Congress at the close of 1990. This trend is accelerating as the apparent international military threat continues to diminish and domestic economic needs mount. The Army will have fewer dollars to spread around and R&D investment decisions will undoubtedly become more critical in terms of choosing "the right" programs. The current budget climate is likely to intensify congressional scrutiny and program manager accountability.

Steps to formalize the Army's technology investment decision making could be taken at any point in the systems research, development and acquisition (RD&A) process, but should first be applied to the initial R&D investment decisions to realize the greatest benefit. Given that the Army's Fiscal Year (FY) 1992 investment in basic and applied R&D will represent 14.4 percent of the Department of Defense's $40 billion research and development budget, even small improvements in effectiveness will yield substantial expenditure results. [Ref. 4]

A formalized decision process using ADMs can structure the decision process to reveal the logical steps used to arrive at an investment choice. Such procedures do not replace the decision maker. They provide a record of the reasoning used to arrive at a decision. ADMs can incorporate current priorities and readily adapt to ever changing priorities, both planned and unplanned, funding decisions, lessons learned, and shared experience from other programs related to the current decision. This can ensure that no single factor or factors are unduly weighted or ignored in the decision and that decision maker bias is minimized.

Employing a formal decision procedure using decision models may add stability and continuity, thus reassuring the decision maker and his superiors. One of the findings of the 1986 Packard Commission and others assessing the failures of the defense acquisition process has been the continual turnover in defense programs, resulting in inconsistent management and program turmoil. In his 1988 book, The Defense Management Challenge: Weapons Acquisition, Ronald Fox states that,

> In the late 1980's, military rotation and individual military career considerations caused program managers to be assigned to programs for an average period of only thirty months, and the turnover is often higher one or two levels below the program manager. [Ref. 5, pp.177-178]

Use of ADMs could help to minimize the turmoil caused by personnel turnover by giving incoming managers awareness of the logical progression of the choices that brought the program office to its present position.

Once incorporated in the overall decision process, ADMs could also lower the management learning curve aiding continuity and further diminishing turmoil and confusion. As a potential source of increased efficiency, ADMs might reduce the perceived need for micromanagement by increasing management confidence at all levels to which it was applied.

These are only some of the inefficiencies that ADMs were designed to address. If resolving these inefficiencies is truly a central goal of the present defense acquisition process reform, formalizing the investment decision procedures using analytic or economic decision models may be one small step toward accomplishing a major part of that goal. In any case, helping the Army's R&D investment managers consistently minimize the risk and uncertainty of their program choices may prove incentive enough for the adoption of ADMs.

C. SCOPE OF THE THESIS

The aim of the study is to develop a basic understanding of what decision support models are supposed to do for the decision maker, their usefulness, and limitations for research and development project selection decisions. The research study will begin by describing the basic process of initiating research and development projects and programs in the buying commands of the Department of the Army (DA). Rather than examining how the decisions get approved in the budget submission and Program Objective Memorandum process, this work looks at how the new program initiation decisions are made at the lowest level, where operational concerns have some degree of priority over budgets and bureaucracy.

The focus is on the application of ADMs for project selection decisions in the area of basic and applied research. It is hoped that the work will provide a single reference point for the beginning user on the availability, usefulness, application, and limitations of proven decision support models for project selection problems.

The goal is to assess currently successful applied economic and analytical decision models for use by the Army's RD&A community. It is designed to aid those within the Department of the Army (DA) charged with seeking technology initiatives and promising, innovative, high payoff opportunities to support the transition from theory to application.

Currently the Army's technology investment program decisions are predominantly made on the basis of the Army's Staff Study procedure, whereby all viable alternatives are presented to the decision maker with their apparent advantages and disadvantages, based upon stated or implied criteria, with a recommendation for the "best" possible choice. The techniques introduced in this research provide those who must prepare such studies with a model for structuring each alternative's advantages, disadvantages and criteria in order to assess probable outcomes upon which the decision maker can logically evaluate the choices with more than intuition alone.

D. METHODOLOGY

This study presents information collected through a search of the current literature regarding DA policies for program/project initiation procedures to describe the current technology investment decision process in the context of the Department of the Army's overall research, development, and acquisition cycle. This information is supplemented by telephone or personal interviews with the authors of the Army Technology Base Master Plan; the Deputy for Technology and Assessment, Office of the Assistant

Secretary of the Army (R,D&A), and follow up with representatives of the specific buying commands within the Army Materiel Command, such as, the U.S. Army Missile Command (MICOM), Tank and Automotive Command (TACOM), Aviation Systems Command (AVSCOM) and others. [Ref. 6]

The literature search provided some of the background for an analysis of the application of analytic decision models based on the types of decisions being made and the factors typically bearing on relevant decision issues. Subsequent analysis then details four prevalent analytic decision models for multiple criteria problems that have a significant record as effective aids to decision-making in fields closely if not directly related to Army research, development and acquisition (RD&A) program/project selection activities.

The data for this analysis will be derived from a review of the works on the subject as well as personal interviews with professors at the Naval Postgraduate School and other experts in the field of operations research. This report is not a lengthy scientific investigation into the worthiness, efficiency, or absolute effectiveness of each analytic decision model uncovered in the course of this research. Instead, it presents scholarly opinion and advocacy of a particular model's usefulness, situation applicability, limitations, pitfalls, and/or any assumptions of those experts who have used and/or developed subject models based on both their written works as well as personal or telephone interviews.

The aim is to develop clear and sufficient evidence and examples to allow managers of the Army's research and development investment strategy and their staffs to decide with reasonable confidence the usefulness of a particular decision model to their circumstances. Each model catalogued will be sufficiently detailed to permit the user to examine and articulate the logic of the model's structure and application.

II. THE ARMY RESEARCH AND DEVELOPMENT INVESTMENT STRATEGY

> ...with limited resources, an ever widening range of technology opportunities, rising international technological competition, and an increasingly more capable third world threat, the Army must invest where the warfighting requirements and potential improvements are greatest. [Ref. 6]

A. INTRODUCTION

There are certainly many reasons to consider improving the efficiency and effectiveness of Army R&D investment decisions. This chapter will explore the two central to our discussion thus far. First, with reductions in the perceived threat to American security abroad and the accompanying reduction in defense spending, some in Congress have expressed serious concerns about assuring America's international preeminence in advanced defense technologies development and assuring the maintenance of the defense industrial base. The opening quotation serves to sum up the Army's understanding of these concerns.

Beginning with Public Law 101-189, November 29, 1989, Congress directed the Secretary of Defense (SecDef) to submit an annual plan for developing those technologies considered most critical to U.S. defense qualitative superiority. This in turn led to the Army's development of its annual Technology Base Master Plan (TBMP) to incorporate the guidance from the Secretary's Defense Critical Technologies Plan. The Army TBMP provides the basis for the way in which R&D decisions are to be made in the Army in light of these congressional concerns. [Ref. 7]

Secondly, as described in the opening background discussion, decision theory provides a sound basis for using decision models in support of multiple criteria decision problems such as those posed by the Army's R&D investment process. These models may provide a logical foundation for structuring the analysis by incorporating ADMs for specific decision alternative choices. Thus, this chapter describes the Army's research and development investment decision process, followed in Chapter III by an explanation of basic decision making theory.

B. THE TECHNOLOGY BASE INVESTMENT STRATEGY

The decision process whereby the Department of the Army (DA) determines which key emerging technologies will be funded for possible concept development is a critical step in shaping the material warfighting capabilities of the future Army. The decision to fund or shelve an emerging technology can have far reaching implications for those firms focused on defense applications as well as society at large if the technology had proven useful in civilian applications. Another concern is that a critical link in our nation's chain of defense might be chopped from the Defense

Program Objective Memorandum (POM) because of the budget cutter's ax.

The hard choices of what flies and what dies is sure to leave many defense contractors gasping their final breath in the 1990s. Should DA's decisions to fund certain development programs be based solely on the needs of our ground forces to overcome a foreign threat? Or, should the Army's leadership seek to include the broader goals of supporting a strong industrial base ready and able to deliver the American-made war goods needed for the next theater of conflict as well as the broad socioeconomic legislation all government procurement is pledged to support. The issue of supporting the technology base has already been partially addressed in Congress and the Army Acquisition Executive, Stephen K. Conver has acknowledged that goal. [Ref. 8]

One thing is certain: as long as the Army's Procurement budget continues to shrink from $14.2 billion in 1991, down to $11.6 billion in 1992, and projected under $9.5 billion for 1993, the choices will become more difficult and the consequences of an inefficient choice more severe. For, in strictly economic terms, less Defense Procurement spending means less diversification over fewer systems and less private research and development spending by contractors strapped by reductions in Defense Procurement spending. [Ref. 9]

The shrinking Army budget for fiscal years '92 and '93 will have a serious impact on Army R&D investment. While the Army's investment in basic and exploratory research is growing in response to Congressional concerns, compared to the rest of DoD, the Army's share is declining. For example, while the Army's share of the total defense budget for Fiscal Year '93 is projected to be just under 25 percent, the Army share of the total DoD RDT&E program is projected to decline from 15.5 to 14.3 percent. A credible technology research investment strategy will be essential to assure a viable technology base for future Army systems and could be a catalyst to reverse this trend. These factors increase the Army's technology risk in several ways. [Ref. 4]

One risk is the shrinking industrial and technology base. With declining defense spending spread over fewer program new-starts, defense contractor funded basic research is expected to fall. Fewer choices between contractors and programs will mean that some key prime contractors may leave the field and with them may go critical expertise. This concern is perhaps even more acute for the lower tiered sub-contractors who support the primes with precision science and engineering skills. [Ref. 10]

We learned in the 70s and 80s that limited deployment times meant "come-as-you-are-war" with no time to gear up industry to overcome our material shortcomings. The alternative may be to rely on the capabilities of allies for support in those areas in which we fall behind. Obviously this is in part what Congress hopes to avoid by supporting the Defense Critical Technologies Plan.

In sum, there may not be time to recover in a crisis. There may not be the expertise to recover. We may not have the resources to commit or divert to such a recovery effort in time to meet the need. Reliance on allies leaves us vulnerable in other ways. There is, as there has always been, the potential that some important breakthroughs will be overlooked entirely in the decision process, but this risk increases as fewer dollars are spent on fewer programs.

Before suggesting some ways to minimize these potential risks in the decision process, it is appropriate to review the way in which the Army selects research technologies in which to invest will be presented. Although the entire process is fairly complicated with many decision makers at various levels, the following is a basic summary.

C. THE ARMY RESEARCH AND DEVELOPMENT INVESTMENT PROCESS

The Army has divided its research program into four commands: the Army Materiel Command (AMC), the Deputy Chief of Staff for Personnel (DCSPER), the Surgeon General, and the U.S. Army Corps of Engineers. Each has responsibility for developing technologies critical to their area of expertise and each has a structure for managing various aspects of the technology base to meet the needs of their user community. [Ref. 11]

For example, AMC includes Laboratory Systems Command (LABCOM) with leadership over seven Army Research, Development and Engineering Centers (RDEC) and the Army Research Office (ARO). The Army laboratory structure includes 42 laboratories and RDECs, complicating communication and technology transfer. A LABCOM plan for restructuring the Army laboratory system, called LAB-21, has been included in the 1990 Base Closure and Realignment Act. It is a six year program designed to streamline and increase the productivity and efficiency of the Army's research and development organizations. [Ref. 12]

The ARO on the other hand, interacts with the nation's research universities, funding basic research in university laboratories throughout the country. Any of these actors can play a part in the process that determines which technologies should be funded for further development in this highly decentralized management structure.

The formal decision process also includes the "user community" represented by the Army's Training and Doctrine Command (TRADOC) which has leadership over each of the Army combat training branches, from Artillery, Aviation, Armor, to the Ordnance Corps, the Signal Corps, and Medical Corps. Each of TRADOC's combat and combat support training schools publishes their annual Mission Area Analysis (MAA) in which they identify their greatest combat survivability and offensive capabilities needs based on TRADOC's warfighting doctrine for the Army and the threat capabilities assessment.

TRADOC then consolidates and prioritizes these needs and hands them off to the Secretary of the Army. The Army's Joint Requirements Oversight Council, chaired by Army Acquisition Executive, Steven Conver, Assistant Secretary of the Army (Research, Development, and Acquisition) marries requirements with capabilities and funding. The result is the Army's Technology Base Master Plan (TBMP) which includes their Technology Base Investment Strategy. [Ref. 13]

According to the 1990 Army TBMP, thirteen areas are considered critical to the Army's future warfighting capabilities. They are called the Army's key emerging technologies. The list includes directed energy weapons, biotechnology, artificial intelligence, neuroscience, robotics, and others. Each of the thirteen "were reviewed by Army technical managers, scientists, and engineers. Then Army leadership approved the final list." [Ref. 5]

D. THE ARMY TECHNOLOGY BASE MASTER PLAN

The Army TBMP represents the Army leadership's top down guidance, objectives, and goals and includes the Technology Base Investment Strategy. It is intended to

> ...create an atmosphere that fosters technology initiatives and the pursuit of promising innovative opportunities while providing sufficient flexibility and funding to laboratory and RDEC Directors to seize local, high payoff opportunities. [Ref. 6, p. I-10]

The process of review and approval of the future technology investment needs, from the MAAs to the TBMP, is based on the experience, judgment, and intuition of the decision makers involved. It is an annual process, beginning with the RDEC Directors and their supporting staffs, up to the Assistant Secretary of the Army for Research, Development, and Acquisition (RD&A). How the exact process actually works is not clearly spelled out, but one source summarizes it this way:

In the case of advanced technology transition demonstrations, the Army employs a Senior Advisory Group (SAG) co-chaired by the Deputy Assistant Secretary for Research and Technology, DASA (RDA), and the Assistant Deputy Chief of Staff for Operations and Plans, Force Development, HQDA. Submissions are made to a working group that is co-chaired by the Army Materiel Command Deputy Chief of Staff for Technology Planning and Management, and the Assistant Deputy Chief of Staff for Combat Developments, TRADOC. The working group reviews candidate proposals and provides recommendations to the SAG for new start approval. This procedure began in April 1990 in response to the Office of the

Secretary of Defense (OSD) Critical Technologies Plan (CTP) guidance. [Ref. 14]

In addition to its internal process of approval, all Army programs have to be funded in the annual Program Objectives Memorandum (POM) approved by the Secretary of Defence and the Joint Chiefs of Staff. This step, POM approval, is the juncture where a perceived need becomes a budgeted requirement. It is possible that a critical Army need (in the eyes of the users) could go unbudgeted in the Army POM, conceivably leaving our forces vulnerable in a critical combat area.

In addition to the POM, OSD publishes its annual Critical Technologies Plan for Congress. The Services are expected to follow it in designing their TBMP's. The CTP represents the Defense Department's judgment of the 20 most important weapons-related technologies of the 200 or so technologies recommended by the Services. Multiple criteria are used to determine which technologies make the CTP.

Finally, priorities are assigned based on the judgments of a working group with inputs from a number of defense industry contractors. The final decision is made by a senior committee representing individuals in the DoD and the Department of Energy with management responsibility over the National Science and Technology program. [Ref. 7]

This is a decision process steeped in the give and take of group dynamics, political coalition building, consensus and compromise among key stakeholders, their advocates and adversaries. There are many actors and plenty of room for inefficiency, if not outright error. The next chapter will discuss additional sources of potential error in decision making that can introduce inefficiencies of their own.

III. BASIC DECISION THEORY CONCEPTS

A. INTRODUCTION

Our goal thus far in reviewing the Department of the Army technology investment strategy has been to demonstrate that the process is not immune to the risks of human decision making and their resulting inefficiencies. This chapter will be a presentation of basic decision theory fundamental to an understanding of the importance of decision model application. The discussion will conclude with an evaluation of the applicability of incorporating analytic decision models into the DA process for potential improvements in efficiency and effectiveness.

It should be noted that although there are many human dynamics theories and models (such as the rational policy model, the organizational process model, the bureaucratic politics model, among others) affecting the process thus described, their assessment is outside the scope of this current work. While these human dynamics models may be essential to the implementation of organizational decisions, they have little to do with analyzing and achieving economic efficiency.

B. THE ROOTS OF ANALYTIC DECISION THEORY

The study of decision making under uncertainty has a long past. Beginning in the 1600's with the founders of modern probability theory, Fermat and Pascal, it was shown that outcomes over time could be quantified by the likelihood of their occurrence. This probability of occurrence times its known payoff can be summed to support a choice on the basis of the outcome's expected value, which is the average of all the potential payoffs. This idea led to the belief that if we can quantify the payoffs and their likelihood of occurrence, rational decision makers could use this information in judgments involving uncertainty. [Ref.15]

Decision making, however, is much more complex. The complexity of rational decision making under uncertainty is supported by a vast field of research on the psychological profile of decision makers and spans the topics of heuristics and biases, prediction theory, inductive reasoning, causal schemata, conservatism, and risk perceptions, to name just some of the broad categories.

Probably the most important work regarding the way managers make decisions is being done by Dr. Herbert A. Simon, professor of Computer Science and Psychology at Carnegie-Mellon University. Professor Simon's work on how we make decisions in organizations spans more than 40 years and earned him the Nobel Prize in 1978 for his concepts of "objective, subjective, and bounded rationality." [Ref. 16]

Basically, Professor Simon logically developed the notions of rational decision making and pointed out many important shortcomings in human cognitive abilities that limit our ability to make rational decisions. For example, according to Professor Simon, people;

- tend to limit the scope of the decision problem, the factors impacting the choices, the alternative pros and cons, and objective criteria in some way to 'bound' the issue within their capacity and experience, discounting data that doesn't conform to closely held beliefs.

- do not seek to optimize in their decision-making process but, rather seek to select solutions that are good enough.

- attempt to construct means-ends (or cause-effect) chains to solve complex problems in a series of steps to achieve the ultimate ends in a hierarchical fashion. However, the conscious integration of weighing values against alternatives often becomes an increasingly complex chain and is seldom attained in actual behavior.

- judge alternative strategies based on their experience and prior opinions about the consequences that follow on their choice of action. Obviously, no one can directly know the consequences of all behaviors. So, the quality of any decision depends on how close their experience corresponds to the choice problem.

- often weigh information received initially and lastly more heavily than information received in the middle of a discussion on alternatives about which they must formulate a decision.

- tend to classify problems as programmed and non-programmed. In organizations the former tends to drive out the latter. Non-programmed decisions are generally solved by reducing them to a series of programmed decisions. [Ref. 17]

One distinguished source on Simon's work made the following observation:

> ... it is essentially impossible to attain objective rationality. To do so the decision-maker must know all alternatives, construct all appropriate means-ends chains, assess expectations for all uncertain consequences, etc. It is here that Simon's notion of bounded rationality takes form. The decision-maker can know these important aspects of a decision only within the limits imposed by experience, knowledge, time and effort available to search and study the decision environment. [Ref 16, p. 39]

So where, one might ask, does that leave the rest of us mere mortals? The answer lies in Simon's notion of subjective rationality. For a decision to be subjectively rational, it must:

- be the best choice dictated by the current state of knowledge using all available data
- be congruent with the values, goals, and objectives of the organization with regard to the decision criteria
- conform to the organization's subject experts' collective judgment regarding alternative consequence outcomes. [Ref. 16, p. 40]

None of this may be particularly earth shattering to today's manager, but Professor Simon's 1977 book, The New Science of Management Decision [Ref. 17], brought many of these interdisciplinary concepts of decision theory together for the first time. It not only identified the basic human decision process and its foibles, but also provided some exceptional direction for resolving non-programmed decisions in organizations. It's an exceptionally positive book, in that regard. It should be required reading for any manager preparing to confront multiple criteria decision problems. Its 168 pages offer extensive management insight that might otherwise take years of experience to attain.

C. RISK CONCEPTS IN DECISION MAKING

No discussion of the basics of decision theory is complete without a comment regarding risk. After all, no choice among competing alternatives would be difficult if everyone knew with certainty the outcomes of each alternative. The decision maker (DM) would choose the alternative whose outcome best achieved the organization's goals, assuming the DM were rational. The above discussion of objective and subjective rationality sheds light on the ways in which DMs deal with uncertainty in complex problems given human cognitive limits. Risk management is another important aspect of the R&D project selection decisions.

The concept of risk is closely related to the notion of uncertainty. In terms of decision making, risk is the degree of certainty that an undesirable outcome will occur as the result of an action or event. To clarify this from the common notion of risk, think of it this way. We could say, for example that the risk of cancer among white males in the U.S. is 25 percent, meaning that roughly 25 percent of all white males will contract cancer in their lifetime. The degree of uncertainty determines the level of risk. If we know an outcome is certain to result from an action, there is no risk associated with the decision.

The confusion comes when we think of the popular notion of taking action which reduces the uncertainty of a negative outcome as placing us at a "higher risk." To continue the cancer analogy, those who smoke all their lives actually lower the uncertainty that they will become cancer victims, yet we say they are at higher risk. In fact, we can predict with reasonable certainty that they will indeed contract cancer. This popular notion of risk actually shifts from an event uncertainty to a timing and security uncertainty involved with perception and fear. [Ref. 18]

In project selection, the risk of an alternative is weighed against a subjective appraisal that its payoff will exceed the resources needed to achieve the anticipated result. The appraisal must include the concept of opportunity cost (the payoffs foregone from the most promising alternative opportunities) to be valid. The greater the potential payoff of an alternative, the greater the acceptable risk, within the resource limits imposed. [Ref. 19]

Even the novice DM is basically familiar with this concept of risk in choosing among alternatives. Nevertheless, the impact of risks and their effects on choice cannot be dismissed. Particularly in austere budget climates when risk aversion is likely to increase.

Risk averse behavior is a judgment bias that can severely limit innovation in the technology investment process and must be guarded against as any bias should be in rational decision making. Some of the decision models that will be examined in the upcoming chapters are specifically designed to highlight risk levels to help the DM avoid the inefficiency resulting from risk averse behaviors.

D. THE DECISION ENVIRONMENT

One final concept regarding complex decisions is the notion of the decision environment encompassing the organization making the decision. Fundamental changes in an organization's internal and/or external environment can dramatically alter the organization's mandates, goals and objectives-the basis on which important decisions rest. In the case of the Army's R&D technology investment decisions, environment refers to the national and international strategic, economic, and geo-political setting. As one research scientist pointed out in this regard, "The decision space is Markovian: Given today, the past and future are independent [Ref. 20]."

The point is, as the Russian statistician, Markov, theorized, the future state of nature depends only on the present environment and cannot be accurately ascertained from the past because the future is independent of past events. They are connected only by a sequence of events in time. Because the outcome payoff of a course of action is directly linked to the environment in which it results, the DM's payoff assessment must incorporate his belief of the future state of nature at the time that the program achieves maturity. [Ref.20]

This notion is especially pertinent to a development cycle conservatively estimated to take 20 years from concept to fielding. It is this notion of Markovian independence that has given operations research its broad footing and support for the development of decision models. No other discipline copes with this concept in a decision context.

E. DECISION THEORY SUMMARY

Risk, payoff, uncertainty, rationality, opportunity cost, judgment, all relate to statistical probabilities in choosing among outcomes, which can leave all but the operations research analyst more than a little nauseous. The point in providing decision theory is to help Army R&D managers make better, informed choices supported by technical analysis in their organizations, not to be better statisticians.

Even if no decision models are used to aid the decision process, keeping human cognitive errors in mind can improve decision quality. Models were never developed to replace human judgment but to enhance its capacity. The following judgment biases and pitfalls are discussed in chapter I:

- filtering bias
- experience bias
- to give priority to information by order received
- memory capacity limitation
- conformity to prior beliefs
- causal chains of likely outcomes limitation
- risk preference bias
- independence of the future from the present

IV. INTRODUCTION TO ANALYTIC DECISION MODELS

> ... when asked to advise companies on the acquisition of a computer, my advice was, before any commitment, make a careful determination of its need and how they would use it. I soon realized that this was poor advice-a company only acquired the ability to make sound decisions about computers by hands-on experience with them. The first investment in a computer was not to be judged by its cost saving potential-it might have none-but by its contribution to intelligence capabilities and subsequent decisions.
>
> Dr. Herbert A. Simon, 1977
> The New Science of Management Decision, p. 43

Dr. Simon's comment regarding his early advice to companies' attainment of increased "intelligence capabilities" can apply equally well today to multi-criteria decision support models. These two powerful management tools, decision models and computers, have a nearly parallel development history. Decision support models of any complexity are almost completely reliant upon computers for their often lengthy computations. This can at once serve to enhance a model's considerable utility and further shroud its seemingly mystical results.

Multicriteria decision models (MCDM) can confound the manager confronted with dealing with the models' results and the analysts' technical interpretation. Although they offer the manager improved leverage in enhanced decision making capabilities, it has been widely documented that management places minimal emphasis on their use in actual decision making [Ref. 1 and 21]. Yet, as one important source put it:

> Whether a modeler's recommendations are accepted or rejected, they must be questioned and understood. If they are rejected, equally quantitative arguments may be required to contradict the analysis.... The planner who uses computers and formulas must be reckoned with. [Ref. 22, p.1]

A. BACKGROUND ON GENERAL DECISION SUPPORT MODELS

Although many decision support models have been developed since management science got its start after World War II, many are not well suited for R&D project selection problems with multiple objectives. For example, Professor William Souder of the University of Alabama, Huntsville, in his 1984 book, Project Selection and Economic Appraisal [Ref. 23], summarizes nearly the entire field in 150 pages. However, the models he presents are those which primarily focus on one objective-the project's economic benefit or payoff.

Economic decision models such as cost/benefit analysis, break-even point, make or buy, return on investment, payback period, and internal rate of return are all excellent and may be absolutely essential to business decisions where profits determine performance (if not out right survival). Others, like the Simplex method and Dynamic Programming, use a sequential approach to optimize resource allocation. By allocating the scarce resource in question (personnel, space, machine time, funding, etc.) to the candidate projects, as many of the candidate projects (or jobs) are completed as the resource allows.

Both single objective and sequential decision support models require that alternative action outcomes be known with mathematical certainty and measurable in terms of the subject resource (usually in dollars). In the public sector, this is frequently not the case. Many other factors weigh into the problem in a free and democratic society from many quarters and competing stakeholders. From benefits to the local community to the nation's technology base, in terms of jobs and welfare, to effects on the environment, to issues of keeping annual program budgets fully committed - many issues must be simultaneously addressed for a decision model to be completely beneficial to the user. (See, References 17, 22, 23 and 24, if need be, for an excellent development of the economic and analytic decision models mentioned here).

Obviously, if the choices between alternatives were trivial there would be no need for detailed modeling of the decision problem. If the DM is reasonably certain of the outcome of each alternative project available and suitable to comprise his R&D program in a future fiscal period, the individual's intuition and judgment alone are sufficient. However, most R&D project selection decisions are complex for several reasons.

They often involve a host of interrelated elements with varying degrees of impact on the decision. Furthermore, the experts upon whose judgments the DM may have to rely, will often be stakeholders in the decision's outcome, with their own varied priorities weighing in their decision criteria [Ref. 26].

Expert input is valued, but may need to be standardized or quantified to weigh considerations on a level basis, to avoid lending undue credence to any particular point of view [Ref. 26]. Essentially, if the trusted experts disagree on the criteria and approach for weighing the value of alternatives, and the outcome is critical, the decision is non-trivial and the need to quantify qualitative considerations and factors to structure the decision problem should be apparent.

B. THE MULTI-OBJECTIVE ENVIRONMENT OF R&D PROJECT SELECTION

Consider for a moment the Army's Research, Development and Engineering Center (RDEC) directors who are expected to balance the many objectives listed in Table 4.1 [Ref. 6] from Congress, Office of the Secretary of Defense (OSD), on down to Army Materiel Command priorities. In addition, there are a number of technology investment objectives that conflict or complement these stated goals. Some current examples include minimizing development time, life-cycle cost, damage to the environment, while at the same time maximizing dual use technologies, performance capability,

TABLE 4.1 THE ARMY TECHNOLOGY BASE STRATEGIES; Source: 1990 Army Technology Base Master Plan [Ref. 6, pp. I-9 - I-10]

*Enhance warfighting
*Balance R&D between near, mid, and far-term needs
*Balance between next generation, emerging technologies, systemic issues, and support capabilities
*Seize technology initiatives
*Leverage R&D outside the Army
*Reduce concept risk and development times
*Foster innovation and seek high payoff opportunities

and protecting the industrial and technology bases, all within a projected budget limitation essentially beyond his or her immediate control.

This is the decision environment multicriteria decision models (MCDM) were developed to handle and support. It is an environment in which the decision maker (DM) must achieve multiple goals with a given budget over a broad range of continually changing R&D project alternative opportunities, each with its own expected returns for achieving at least some of the required objectives.

How can project alternatives be compared to determine which ones best satisfy program decision criteria? Where a considerable budget is involved with frequently changing goals, objectives, criteria and priorities, the decision process will hardly be routine. As mentioned previously, with increased scrutiny and oversight, expert opinion alone may no longer suffice.

The basic answer to our "How to compare" question lies in quantifying subjective judgments from experts in a systematic, formal analysis of alternatives and objectives. Some might conclude that complex issues in the public sector should be left to subjective evaluations, but for many of the reasons stated in the second chapter, it is quite often inefficient to do so.

For example, although we may not be able to directly quantify the value of several aircraft designs of near equal cost- some offering improved performance, others increased efficiency, and still others technological advantages- we could ask experts to judge which design(s) is preferred over the other and use the preferences to develop a rank ordering. Quantifying the rankings and comparing them against priorities and constraints can lead to a logical choice among alternatives. [Ref. 27]

In conclusion, several important multi-criteria decision models (MCDM) have been developed to support the kinds of decisions facing the Army in its R&D project selection process. These are non-trivial decisions involving extensive cost, payoff data, and opinion as well as many competing goals, objectives, criteria and priorities. By organizing the input data, quantifying expert judgments, and forcing choices among competing criteria, MCDM can help the decision maker (DM) overcome many of the inefficiencies inherent to human decision making- namely, biases and error- discussed in chapter III.

C. PURPOSE AND STRUCTURE OF THE UPCOMING FOUR CHAPTERS

The next four chapters are designed for the management DM who may not be aware of the potential of MCDM applications for supporting R&D project selection decisions in the public sector. The models chosen for presentation are those MCDMs that predominate the literature of management, management science and operations research. As such, they are considered the most useful and widely recognized for R&D project selection and other resource allocation problems of this kind. These are the MCDMs which the management DM in the public sector is most likely to encounter and for which some knowledge of applications will be increasingly important.

We begin with a summary of some of the graphical techniques for multi-criteria decision support developed from several sources. We will then move to a development of the Analytic Hierarchy Process (AHP). Next, the

Multiattribute Utility Theory (MAUT) will be detailed. Finally, chapter VIII will present a development of the Goal Programming (GP) method for solving problems of choice with multiple criteria.

It is important to keep in mind that this is not a technical development or analytical assessment. As a management student curious about the power and limitations of MCDMs, my goal is to spark the curiosity and inform my peers about what management science is contributing to this specific decision environment. As in an explanation of the value and power of application software, the point is what these tools can do for us, not the bits and bytes of how it's done. A deeper understanding can and should be sought from the primary sources listed as the references.

Throughout the discussion so far, several terms central to decision support modeling have been used, the meanings of which may be becoming somewhat blurred. To alleviate confusion, the following definitions are offered to assist the reader in keeping each term in focus:

- **criteria**: the measures of effectiveness against which alternatives are evaluated.
- **attributes**: the variable outcomes contributing to program objectives.
- **objectives/goals**: stated and implied R&D program mandates and priorities.

- **constraints**: the physical and economic limitations to program optimization.

- **alternatives**: candidate projects for selection.

V. GRAPHICAL APPROACHES TO MULTI-CRITERIA DECISION PROBLEMS

We begin our discussion of multicriteria decision models with a development of some graphical approaches to solving the Army R&D selection problem. These techniques are adequately covered in the literature of management science for solving choice dilemmas with conflicting attributes. But more significant is their flexibility. These models can incorporate data from simple cost/benefit analysis to sophisticated risk and utility functions if desired by the DM.

First, the model will be presented through a discussion of the development process to present some idea of how the model works to turn input data into output recommendations. This will be followed by a discussion of the technique's strengths and weaknesses identified through research or actual applications where available. The chapter will conclude with further analysis of the limitations, pitfalls, and strengths of this technique. Some comparisons between graphical models and models to be developed in later chapters will also be provided.

A. GRAPHICAL MODEL STRUCTURE AND FORMULATION

Graphical techniques are a symbolic depiction of the expected outcome for each alternative with respect to each attribute. Subject matter experts establish the measures of effectiveness criteria upon which each alternative is to be judged and establish some effectiveness rating scale for scoring the alternatives. For example, some objectives for an R&D program might be to:

- Maximize utility and effectiveness (coverage such as dual use technologies, interoperability, etc.)
- Maximize research personnel utilization
- Minimize development time
- Minimize resource consumption (funding, overhead, and support costs, for example)
- Maximize "critical technologies" state-of-the-art
- Minimize development risk (such as outcome suitability and contractor experience/ability to deliver)

Next, some measures of effectiveness (MOE) for each objective would have to be established and agreed to by the subject experts/stakeholders. Determining the program objectives and adequate MOE for evaluating each alternative project under consideration is the first step in applying graphical techniques. [Ref. 28]

Some of these measures, such as costs, are hard criteria for which reasonable data figures may be available. Some of the others are soft criteria that would have to be based on expert judgment, experience and intuitions of those involved. These soft criteria must be quantified so that measures can be compared on an equivalent basis. [Ref. 29]

One way to do this is to establish "scoring functions" or graphs which depict ratings for the predicted alternative attributes (outcomes) for each of the selected criteria, such as those shown in Figure 5.1. Both quantitative and qualitative results can thus be shown. [Ref. 30]

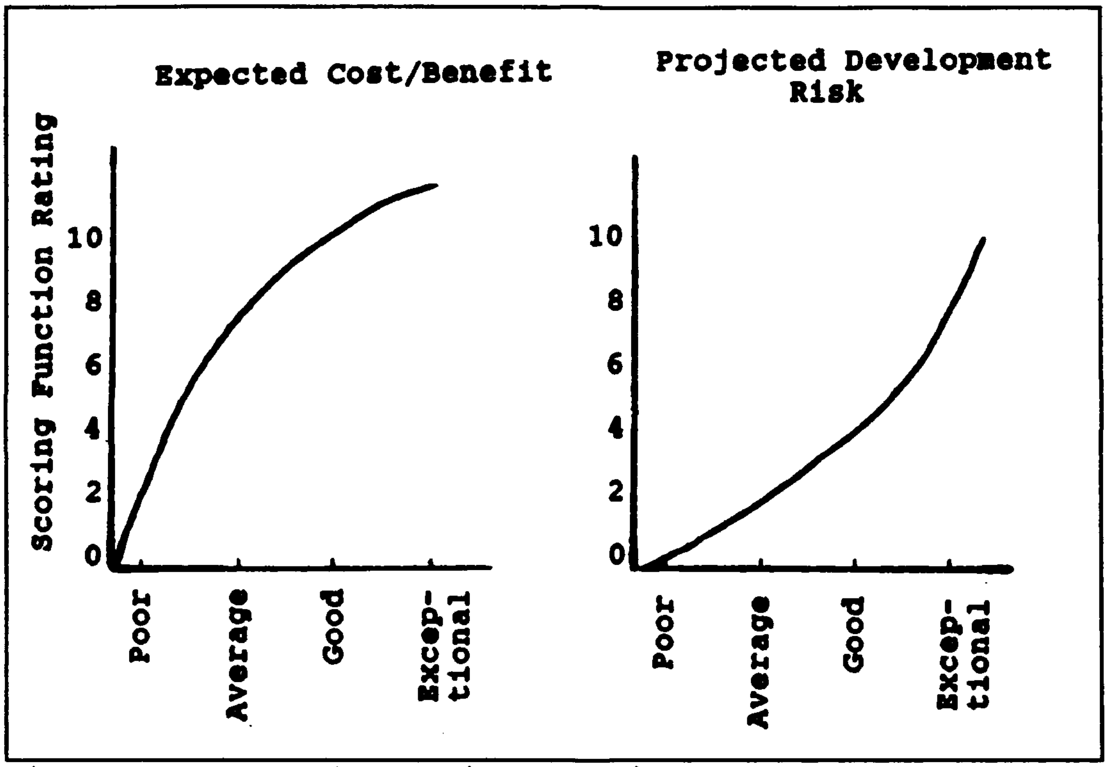

Figure 5.1 Example Scoring Function Graphs

One graphic technique for multiattribute decision analysis presented by Zeleney, Canada and Sullivan, and others, [Ref. 29, 30 and 31], is called Polar Graphing. This method consolidates the results from scoring function graphs to visually demonstrate relative contributions of each alternative's attributes. Two example presentations of the model's output are shown in Figure 5.2 [Ref. 29 and 30].

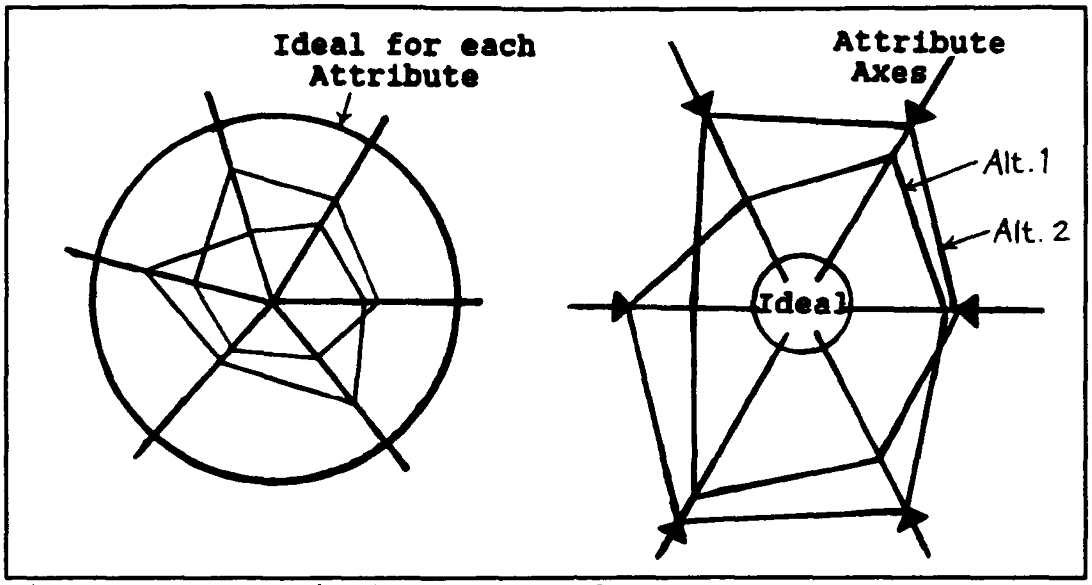

Figure 5.2 Typical Polar Graphs

Polar graphs can facilitate decision making by revealing those projects that make the greatest contribution to the RDEC research and development program objectives. As with many graphs, however, the axis, scale values can be manipulated to represent the data in different ways for a variety of interpretations.

One criticism of the polar graphing technique is that in structuring this method of multicriteria decision modeling, no author has formulated a specific way to weight the criteria (represented by the "spokes" in Figure 5.2) for evaluating the attributes (depicted as the "spider web" linear values around the spokes) of the various alternatives in a consistent way. Although general "utility values" can be chosen and assigned using the scoring function graphs, this is considered highly subjective. While the model analyst and DM may develop agreement on consistent MOE, their interpretation and the resulting axis, scale values might not hold up under close scrutiny. [Ref. 32]

This issue of MOE validity for the selected utilities and their representation of the true values is dependent, at least in part, upon the specific program objectives and how closely the utility values and scores represent them. If the scale values are accurately represented, the graphs may reveal relative desirability between alternatives. Then, as long as all experts and stakeholders agree which attributes should dominate the selection criteria, a valid choice can be made. [Ref. 26]

Looking at the example in Figure 5.2, another shortcoming is evident. Clearly, with more than five or six criteria and three to five alternatives, the aid this presentation provides is rather dubious. It would do little to clarify the choice considerations. On the other hand, consider the inadequacy of traditional models, such as cost-benefit ratios, that simplify the problem by limiting the analysis of alternatives to a comparison of only two criteria. A polar graph analysis could demonstrate the need for greater clarity among alternatives. [Ref. 29]

Another graphical method that at least partially overcomes this visual complexity problem is suggested in Keeney and Raiffa's Decision with Multiple Objectives [Ref. 27]. Their approach depicts the attribute scores of each alternative in a "performance profile," like that shown in Figure 5.3. In this technique, the vertical lines depicting the attribute scales are not standardized to an evaluation rating or scoring function as with polar graphing.

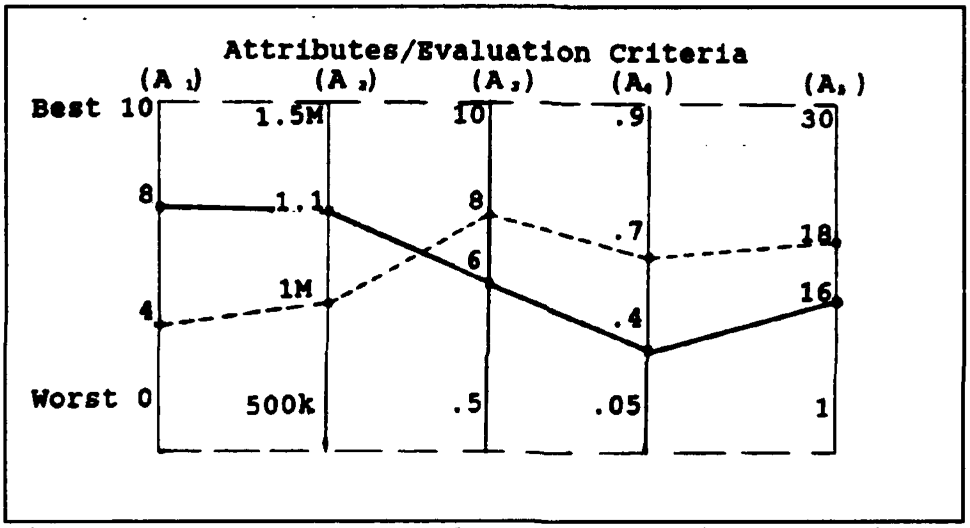

Figure 5.3 Example Performance Profile Graphic

However, the authors indicate that this can be done if it clarifies the problem. In addition, Keeney and Raiffa's work covers the development of weighted value functions for determining preferences between criteria. [Ref. 27]

Graphic techniques used to support multi-criteria decision problems are useful because they are intuitive by design. The information presented can be used much as in a traditional trade-off analysis assessing more than two criteria. The support staff officer can show a lot of the information quickly and clearly without a lot of fanfare or technical jargon to explain the approach. The results or output supporting the decision at hand can be largely self explanatory. This is particularly true for comparing self-evaluation and cross-evaluation of alternatives, as seen in the examples [Ref. 26].

B. ASSESSMENT OF THE STRENGTHS, LIMITATIONS, AND WEAKNESSES OF THE GRAPHICAL TECHNIQUES

The first comment heard regarding the value of the polar graphs or the performance profiles is what scale values are to be used and how are these values determined? In both cases, Keeney and Raiffa's development of value functions and utility functions can be used [Ref. 27]. In addition, more familiar decision aids can also be incorporated, such as net present value, internal rate of return, cost-benefit analysis, and many of the other financial and economic assessment techniques. Some authors suggest adjusting these traditional value equations for risk and time factors to further enhance their usefulness and accuracy [Ref. 33].

This is actually an important strength of multicriteria graphical techniques. That is, they are extremely flexible as mentioned at the outset. Many of the other MCDM that will be developed in the upcoming chapters do not incorporate the traditional economic analysis formulas which may in part account for the lack of use of MCDM in American business and industry.

In the often cited surveys by Matthew Liberatore and George Titus regarding MCDM for R&D project applications, none of the 40 respondents from 29 "Fortune 500" firms queried in 1983 used MCDM in their R&D project selection process. However, net present value and cost-benefit analysis were reportedly used 74 percent and 62 percent of the time, respectively. Clearly, for a model to be seen as effective, it must first be regarded as important and reliable by the intended user. On this basis, the graphical approaches must be given high marks for user confidence. [Ref. 21]

Another shortcoming cited by Vickers and Belton in their 1988 study on graphical techniques (which they refer to as "visual interactive models") is the time and difficulty of formulating these models and their accompanying displays for real problems. However, the authors suggest the use of several commercially available software packages to assist DMs and analysts with formulations. They recommend Symphony and Framework for the novice and Why, Hocus, Witness, and Genetik for more advanced formulations by analysts. The authors also present a complete model development with results from input by 60 student evaluators. Their work is exceptionally informative and helpful for the beginner.[Ref. 31]

Dr. Milan Zeleny of the Graduate School of Business, Fordam University argues effectively that polar graphs and other graphic techniques are more than mere visual displays because they serve to improve decision making. He points out that most MCDM ease the decision process by separating the problem into its sub-parts and guiding the DM to state his preferences in a piecemeal fashion.

Zeleny argues that this only reorganizes the problem rather than resolving the inefficiencies resulting from bounded rationality. He explains that this is primarily because such methods disrupt the holistic view of the problem. It is the holistic view that is essential to good decision making and the essence of human cognitive skills. Graphical techniques, on the other hand, fit all the essential pieces of conflicting information together to diminish the role of the analyst/facilitator and increase that of the decision maker. [Ref. 29]

In conducting this research it appeared that another important weakness of graphical techniques for multicriteria decision problems is the lack of data from users conducting actual problem analysis. The only data found were from hypothetical modeling of simple problems. This might be a result of the fact that no particular author or group claims ownership of these methods to champion the research efforts necessary. Additional field work needs to be done to prove the theory and reassure potential users of the benefits obtainable.

VI. THE ANALYTIC HIERARCHY PROCESS

Chapter VI will familiarize the reader with the Analytic Hierarchy Process (AHP) for aiding the DM in determining the optimum mix of R&D projects to comprise the program within a limited budget environment. Much has been written about the strengths and weaknesses of AHP and its applicability to this particular problem. This chapter will present an overview and description of how the model is formulated followed by some assessments of AHP from users of the technique.

A. INTRODUCTION TO AHP

The Analytic Hierarchy Process was developed and introduced by Professor Thomas L. Saaty of the Wharton School, University of Pennsylvania and documented in his 1980 book of the same name [Ref. 34]. This technique is quite possibly the most important for quantifying qualitative expert opinion and judgment for decision support, at least in terms of its ease of use, its parallel to actual decision making processes, and its broad applicability. AHP enjoys the widest acceptance among managers of all the multi-criteria decision models that will be presented in this work.

This technique requires the DM to construct a hierarchy with the organization's top objective, broadest goal, or mandate at the top. Subsequent levels of the hierarchy include more specific objectives, activities, or effects necessary to achieve the top goal, such as those listed up in Table 4.1, from the Army's Technology Base Master Plan [Ref. 6]. The lower levels are the attributes of specific alternative project choices (courses of action) that contribute to the organization's objectives. The final level is comprised of the specific projects themselves. An example three tiered hierarchy is shown below in Figure 6.1. [Ref. 30]

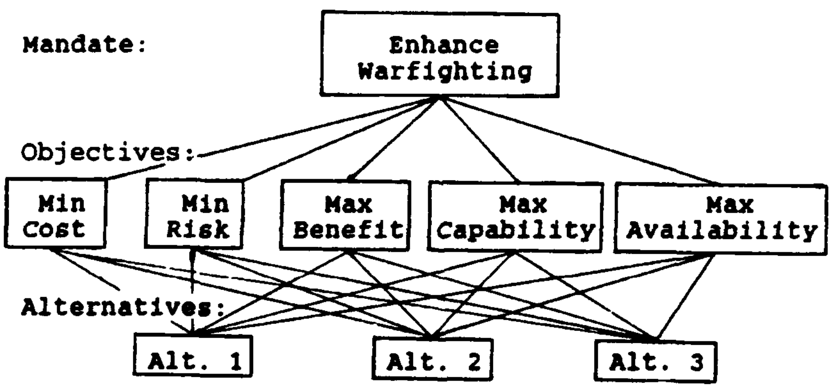

Figure 6.1 Sample Decision Hierarchy

The process of developing this decision hierarchy breaks the decision down into its sub-elements and is designed to get the organization to concentrate on where its resources need to be focused to achieve their ultimate goals. There is little room for hidden agendas, nest feathering, or the "underling problem" (wherein a subordinate seeks to maximize personal aspirations regardless of their impact on the organization's goals) when priorities are examined in this process. [Ref. 22, p.43]

The hierarchy development process can also disclose relations and overlap of goals and projects. It is also hoped that the process will help to examine justifications in terms of "virtues" or planning criteria of future returns on R&D. The hierarchy can help clarify what has been omitted, where boundaries have been drawn sub-optimally narrow, and where principles and programs extraneous to the organization's basic mission are being used to justify expenditures. [Ref. 35]

The hierarchical structuring of the decision problem is to be developed to deal with three issues in the R&D investment problem:

- How do we plan for research and development under a multitude of uncertainties?
- How can we design and implement our R&D program so that, if successful in its separate parts, it will aggregate to a coherent system a quarter century hence?
- How can the organization, given a quality selection of projects that emerge from our analysis of the above questions, allocate our budget cost effectively so that benefits of investments in technologies today will accrue on schedule? [Ref. 35]

Within the hierarchy itself, each element at a given level, called "virtues" (or attributes), may also be assessed as obstacles. As the hierarchy is developed, the experts can evaluate the severity of the challenges posed to operations if a given attribute were inadequately resourced. The intent is for the subject experts to identify areas where future funding will be needed to stave off potential lags in capability. This is to orient the exercise toward anticipating growth needs rather than simply extrapolating trends. [Ref. 35]

The sub-objectives of the hierarchy can also be established as priorities broken out by the organization's divisions. The DM can use the hierarchy to assess the relative merits of alternative programs, projects and technologies. What emerges is a hierarchy of benefits that can be expected to accrue to each program area. The potential benefits can be discounted and thus used to plan current investment over the organization's planning horizon-one, five, or more years out. But this is just the first step in the AHP analysis.[Ref. 35]

Once the hierarchy has been designed, the next step is to elicit expert opinion to compare the attributes on each level to one another to determine and establish the relative merit of each attribute in terms of its contribution to achieving the next higher level goal. The experts assign a number value from a scale like the one shown in Table 6.1. These scores (called preference factors) are recorded and organized into a separate matrix for each level's elements.

TABLE 6.1
SAMPLE PREFERENCE SCALE

IF attribute **1** is... preferred to attribute **2**		
"Equally", then rank is		1
"Slightly"	=	3
"Slightly more"	=	5
"Strongly"	=	7
"Always"	=	9

The scores are then aggregated and standardized using the formal theorems of matrix algebra to derive relative weights for the projects at the lowest level of the hierarchy. The experts' preferences are thus translated into a project selection ranking of the alternatives with respect to the attributes by revealing which projects are most adequate for achieving the overall goal. [Ref. 25]

Although the matrix algebra calculations can get fairly extensive with only a few levels of attributes and experts scoring, software is commercially available to conduct the calculations. The use of a computer software package is essential for quantifying the preference value judgments of several experts from different departments or divisions. [Ref. 25] [1]

Each expert with input to the decision process must make 1/2n x (n-1) paired comparisons (where n is the number of elements on a level of the hierarchy). This means that a hierarchy with ten alternatives, eight attributes, five objects, and a primary goal would require 83 paired comparisons from each expert. Because of this need for extensive input data as well as the limits of human cognition for making these comparisons, Professor Saaty and others have recommended keeping the number of elements in any level at no more than nine and the number of levels to between three and five. [Ref. 25 and 36]

B. ASSESSMENT OF THE STRENGTHS, LIMITATIONS, AND WEAKNESSES OF THE AHP MODEL

In 1984, researchers conducted a multi-year study of an actual application of the AHP method to the R&D selection process of a pharmaceuticals manufacturing firm in England. The application was conducted to assess the strengths and weaknesses of AHP against those of other multiattribute decision methods for an actual case. The study was not an

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[1] For additional information, contact Decision Support, Inc. about "Expert Choice" at 4922 Ellsworth Ave., Pittsburgh, PA 15213 or call (412) 682-3844.

experiment but rather an application of AHP in the public sector. The problem required ranking ten alternative projects against eight criteria attributes selected by the firm's DM and his project managers. [Ref. 37]

The study is a good example demonstrating the formulation process, model output, and user reactions. The decision maker and his staff in this case regarded the process of using the preference factor ranking scale confusing and the extensive paired comparisons, described earlier, as tedious. Even after explaining the preference factor to the users, the authors reported many still made errors and found that they could not remember how they had ranked earlier alternatives to attribute comparisons the further they got into the procedure.

The researchers were able to work the participants through these formulation problems to obtain output the participants found reliable. In spite of the shortcomings they had cited, all of the participants found the process of structuring the decision in an analytic hierarchy useful for gaining insight and understanding of the important factors in research planning. In fact, the authors report in their conclusion that the R&D division of the firm has incorporated AHP, with some recommended modifications, into its routine R&D selection procedures.

In a 1987 follow up to this original research work, Geoff Lockett and Mike Stratford found the R&D division at

ICI Pharmaceuticals continued using AHP without the technical advisors to guide them. The DM was utilizing and acting on the numerical results obtained from the model. The section managers and project manager found that formulating the decision problem with AHP was helpful and the output was useful. [Ref. 38]

However, Lockett and Stratford also stated that some of the respondents (including the project manager himself) were continuing to misuse the preference factor scale and changed their input choices once they had additional clarification on its correct use. The authors indicated that this was a significant drawback to AHP since, in their opinion, "In practice, judgmental models will have to be used without technical advisors if they are to become accepted [Ref. 38, p. 399]." In addition, after conducting a comparison, they recommended incorporating multiatribute utility theory (MAUT) methods for choices among similar attributes to improve results.

Several other improvements have also been suggested by researchers working with the AHP technique for the R&D selection problem [Ref. 39, p. 305 and p. 345] In addition, Professor Saaty has responded to the criticisms regarding the data from value comparisons using his original preference scale in a 1987 article in Decision Sciences. He suggests ranking alternatives with a relative proportion method rather than his original scale values of 1-9. [Ref. 40]

There literally seems to be no end to the controversies surrounding the value and weaknesses of AHP in assisting decision makers to evaluate multiple alternatives with multiple conflicting criteria. While one source would find the hierarchic structure development awkward, others said that it helped their understanding. Some decried the lengthy comparison process as unnecessarily tedious, while others argued this was a strength of AHP through its development of a kind of "average preference" value. In any case, the overwhelming consensus in the literature is that applying AHP to the decision process improved the quality of decision making for the DM. But the method is not without its critics, many of whom advocate alternative MCDM methods of their own (see, for example, Ref. 25, 26, and 28.)

VII. MULTIATTRIBUTE UTILITY THEORY

Another multicriteria decision model which has proven useful for supporting the evaluation of projects for R&D selection is multiattribute utility theory or MAUT. As has been the pattern thus far, the chapter is organized in two parts. The first will introduce the basic elements of the model and its formulation and the second will review the important literature regarding the model's strengths and limitations. The goal is to allow the reader to garner some notion of the value of this technique for supporting decision problems with multiple objectives.

A. INTRODUCTION TO MULTIATTRIBUTE UTILITY THEORY

This important multicriteria decision model uses theories from mathematics and economics regarding utilities to quantify DM preferences. The first and dominate example of this technique was presented by Ralph Keeney of Woodward-Clyde consultants and Dr. Howard Raiffa of Harvard University in their 1976 book, Decisions with Multiple Objectives: Preferences and Value Tradeoffs. [Ref. 27]

The Keeney-Raiffa MAUT decision model uses fairly advanced mathematical development and economics manipulation to evaluate alternatives against multiple criteria and arrive at the optimal course of action to achieve the desired outcome, goal or objective. Although its application to the R&D project selection problem is not as well documented as that of AHP, it has been widely applied to many types of selection problems with multiple qualitative and quantitative criteria. It must therefore be included in any serious discussion of this class of MCDM.

Like AHP, Multiattribute Utility Theory (MAUT) begins by determining the overall program goal, objectives, attributes, criteria, and project alternatives and organizing them into a hierarchy. The notion is to divide the multicriteria problem into its basic component parts, determine the DM's preferences on each component, and derive the alternative that best fulfills those preferences. The process can become fairly complicated. The following is a narrative explanation of the steps in the MAUT procedure.

Once objectives, attributes, and alternatives are determined, subjective measures of effectiveness are derived and assigned to each attribute. Objective data are used for this whenever available and applicable. The DM's quantified values and/or expected values are thus established for each attribute. Value functions are then derived by summing the attribute values that represent the DM's preference structure by assigning a weighting constant, an exponent, or both to each attribute element of the function for each alternative [Ref. 41]. Several example value functions adapted from those presented by Keeney and Raiffa are shown in Figure 7.1 [Ref. 27, p.81].

$$v(X) = c_1x_1 + c_2x_2 + c_3x_3$$
$$v(Y) = y_1^2 y_2^4 y_3^2$$
$$v(Z) = c_1z_1 + c_2z_2 + c_3(z_1 - b_1)^2 (z_2 - b_2)^4$$

Figure 7.1 Sample Value Functions for Hypothetical Alternatives X, Y, and Z

Next, value tradeoffs are conducted systematically in which the DM must decide how much of one objective he is willing to give up to improve his chances of achieving one of the other objectives. Outcome probabilities are used to determine expected values where uncertainties are involved. The tradeoff analyses are conducted between the alternative value functions using marginal analysis as in classical economics. The basis for this approach is that the utility of any course of action under risk equals the expected value of its payoff.

Multiatribute utility theory relies heavily on economic principles of Pareto optimal analysis. A fundamental assumption of this analysis is that for each act there is an outcome, and the set of all the available alternative outcomes which are most efficient comprises an efficiency frontier for a particular decision maker. If we, as that DM, knew which acts (alternative programs) led to the most efficient outcomes, and we were rational, we would choose to do those acts to obtain the maximum benefits. That is, we would choose the Pareto optimal set of alternatives. With MAUT, the analysts use probability and DM preferences to derive the DM's Pareto optimal outcome set. [Ref. 27]

The value functions and the outcome probabilities are combined to obtain a utility function for each alternative. The alternatives with the greatest utility for the DM are those that should comprise his R&D program. Numeric values can be determined for the attributes comprising the utility functions so that a utility value can be calculated. Thus the alternative projects can be rank ordered from greatest to least utility for achieving the organization's goals. [Ref. 42]

Obviously, the mathematical expressions get rather lengthy with only a few attributes for each alternative. Not only that, but the utility functions involve the integration of the area under the theoretical Pareto optimal curve and the curves can be monotonically decreasing or nonmonotonic increasing in three space with additive or multiplicative risk values! This is not the kind of analysis the typical management decision maker is comfortable with. The tradeoff analysis process for just three alternatives takes the authors nine pages to explain. [Ref. 27]

Utility theory says that the DM must assign a utility to a course of action (project alternative) based on his perception of the risk of the probable outcome for each alternative. For example, if the most desired outcome were only half as likely to occur at the conclusion of project A, but a less desired outcome were sure to occur with alternative B, the DM should assign a higher utility to project B, and fund B accordingly. The point is, the DM should act to maximize his expected utility. The DM's perception of risk is factored in as well. If the DM is risk prone or risk averse, he will naturally adjust his utility for each alternative. [Ref. 22]

With MAUT the assumption is that DM preferences are consistent and independent of each other. The idea of decomposing a problem implies that there will be less error from random judgments when the DM can focus on single components of a decision problem. The central assumptions are that the DM will make rational choices that optimize his utility and that a decision is rational if it maximizes the DM's expected utility.

One other point unique to MAUT is that the technique allows for only one DM instead of inputs from multiple experts. Utilities of multiple stakeholders are not aggregated and factored in mathematically, but their opinions should be weighed into the DM's utility function for each alternative. The DM could call for subject experts to provide input to set attribute values and assist with utility tradeoffs preferences. It would then be up to the DM how he would use their input to weigh on his own judgments. [Ref. 41]

B. ASSESSMENT OF THE STRENGTHS, LIMITATIONS, AND WEAKNESSES OF THE MAUT MODEL

First of all, do not feel intimidated if, having read the above explanation, you're not sure what you read. This seems to be a frequent response to utility theory in general and MAUT in particular. In many instances this was the typical user response. In comparisons with other techniques such as AHP and goal programming, the outcomes for optimal alternative ranking were strikingly similar. This often reassured users of the method's value. However, the concern remained that this model may be difficult to use without the assistance of a competent analyst to work the DM through the process (see, for example, Ref. 37 and 41).

This lack of understanding of how the MAUT quantifies qualitative preference "data" and probable outcome functions to obtain its rank order solution is the complaint most common in application analyses uncovered in this research. Many of the researchers have questioned the value of MAUT on the basis of this concern, pointing out that the formulation itself- the way value and preference questions are themselves presented- may too strongly influence the optimal outcome results. More study should be done in this regard, but some research has already shown that this point does not negate the value of MAUT to decision makers in actual practice. [Ref. 43]

One of the other common complaints about MAUT is the lack of a means for sensitivity analysis. The value functions and probability analysis leading to the utility functions that comprise the model and determine the output are not easily manipulated to answer DM's various "what if" questions. In addition, if the value functions developed do not accurately reflect the actual Pareto optimal efficiency frontier, the output results will reflect the inaccuracy but without the knowledge of the DM. As one author has remarked, "For all its outward appearance of mathematical precision, MAUT is highly subjective, is not intuitive, and presents many difficulties in practice." [Ref. 30, pp.256-257]

VIII. THE GOAL PROGRAMMING MODEL

With this chapter the introduction to the primary, important multicriteria decision models for R&D project selection is completed. The goal programming (GP) method will be explained here through a description of the formulation procedures. This will be followed, as in the preceding three chapters with a summary of the strengths and limitations of GP for solving multicriteria problems such as those facing the Army's R&D community.

A. INTRODUCTION TO GOAL PROGRAMMING

The Goal Programming (GP) technique for supporting multiattribute decision making is a modification of linear programming, using mathematics to spread limited resources (time, manpower, funding, etc.) over multiple objectives. Abraham Charnes and William Cooper are frequently credited with first introducing this method in 1961. [Ref. 30]

Because of its longevity, many complete formulations of the GP model for solving the R&D selection problem in the public sector are available for further study (see, for example, References 36, 44, and 45). Nevertheless, in their 1983 survey of 29 major "Fortune 500" industrial firms, Liberatore and Titus found only four of the 40 respondents indicated that they were even aware of GP and none indicated that they used the technique to support their R&D project selection decisions. [Ref. 21]

B. GOAL PROGRAMMING MODEL DESCRIPTION

With linear programming the DM seeks to optimize a single objective given the constraints imposed by the environment in which the decision is made. It is very widely used, for example, in scheduling machine operating hours for various jobs. This is a well known example, where the constraints might be time and materials with the objective of maximizing production output to meet demand.

With GP on the other hand, the object is to satisfy a number of competing objectives as completely as possible with the given resource constraints. As in our production example, we might set maximum production output as a goal along with say, minimizing operator overtime (accounting for worker safety and fatigue as well as expenses), minimize machine set-up times (caused by switching from one type of job to another), and minimize finished goods inventory stack-up at the next work station. [Ref. 22]

Each of these goals competes for the critical resources of time and materials which must be conserved while filling each of the competing demands as completely as possible.

This is a classic GP problem. Because of this capacity for handling multiple objectives, GP has been established as one of the dominate, if not the predominate MCDM.

C. THE GOAL PROGRAMMING MODEL FORMULATION PROCESS

The goal programming technique is powerful because once the problem is formulated into its linear objectives and constraints, a sound feasible solution can be obtained for the DM which is intuitive and logically supportable. The model is also appealing because it is flexible.

Goals may be stated as absolute priorities, as objectives to be sought in some ranking by priority, or interval goal constraints can be specified with over or under achievement boundaries. Although the DM may state preferences between competing objectives as with AHP or MAUT, there is no requirement to do so. [Ref. 22]

Weighting constants are not used in GP. Instead the objective functions contain plus and/or minus deviation variables, which represent surplus or slack resources that can be applied to competing objectives in the formulation. A negative deviation variable represents a floor limit set by the DM, while a positive deviation variable is a ceiling. Both plus and minus deviation variables (the d_j^{+-} factors in equation 7-3, of Figure 8.1) in one objective function designate an interval for required fulfillment. If the objective is absolute, no deviation variables are included in that objective function. [Ref. 44]

If absolute priorities are established for more than one objective in the formulation, the goals must be ranked in the DM's order of importance. Preferences can be expressed in many ways, but AHP is often recommended if a number of tradeoff comparisons must be determined. [Ref. 22]

Once linear objective functions are constructed from the DM preferences, the GP technique uses a preemptive goal algorithm to maximize each objective. This means that lower importance goals are only considered after all higher objectives are fulfilled. Priority coefficients (the P_k factor in equation 7-2 in Figure 8.1) can also be established to indicate priorities where slack or surplus resources should be assigned by DM preference.

$$\mathit{Find}\ldots X=(x_1, x_2, x_i \ldots, x_n)\ (7\text{-}1)$$
$$\mathit{Maximize}\ldots Q=\sum P_k \cdot f(d_j^+, d_j^-)\ (7\text{-}2)$$
$$s.t.\ldots \sum a_{ij}x_j + d_j^+ - d_j^- = c_j\ (7\text{-}3)$$

Figure 8.1 Example Goal Programming Formulation

Figure 8.1 contains a generic GP formulation that includes each of the elements discussed so far. In this example formulation, the x_j factors are the project alternatives, the a_{ij} is a coefficient value associated with a particular project (a quantity of resource j for alternative i, for example), and c_j is the goal or objective value for constraint j. [Ref. 30, pp.289-290]

As this explanation may indicate, formulation of a multiple objective decision problem with competing priorities, and constraints into a mathematical model is no simple task. Goal programming is a recipe for transforming a problem, such as R&D project selection, into a model from which a solution can be derived.

To summarize, there are three basic steps in the formulation process:

- Determining the <u>aspiration</u> levels for goal constraints
- Determining the slack or surplus allowed for each objective and the priority (if any) by which each is to be allotted to competing objectives, and
- Development of the objective functions.

D. ASSESSMENT OF THE STRENGTHS, LIMITATIONS, AND WEAKNESSES GOAL PROGRAMMING MODEL

Although formulation of the specific GP model itself can be formidable when each step is straight forward, there are two assumptions that must be dealt with even before formulation can begin. First, each objective function derived will be linear and second, all goal constraints must be quantifiable for mathematical formulation.

Both of these assumptions must be understood and agreed to by the DM before the objectives can be quantified and formulated into a value function. Take for example an objective, "to minimize program risk."

Development risk should decrease over time, as complications are worked out of the design approach. Schedule risk, on the other hand, may increase or decrease several times as the project continues, but it will most certainly not remain linear. In either case assumed linearity of the risk factor may or may not be significant enough to invalidate the model's output. After all, it is only a model. But generalizations of this kind can adversely effect DM confidence in the output reliability, thereby virtually invalidating the entire modelling effort. [Ref. 45]

As for quantification, quantifying constraints like time, funding levels, personnel and materials is fairly routine in a GP formulation. If, however the DM's objectives are to "maximize benefit, capabilities, or value of the research efforts", GP alone will not suffice. [Ref. 46]

One way to quantify the intangibles is to employ other techniques, such as AHP, to quantify qualitative factors and use the output as input to GP so that the problem can be formulated. An example of combining the two procedures was conducted for the U.S. Army Strategic Defense Command in 1987 to determine R&D project selection given the program's multiple goals and constraints. [Ref. 36]

One important strength of this model is its ability to handle a vast number of constraints and objectives to evaluate numerous alternatives. In Dr. James Ignizio's work for the Army on R&D project selection, his goal programming code handled problems with over 100 variables, over 20 constraints, and from three to five objectives [Ref. 44, p. 271]. Captain Anderson obtained reliable output for the Army Strategic Defense Command using his formulation of five objectives and 35 constraints to evaluate 35 alternative projects [Ref. 36, pp.49-59]. However, there is a limit.

In their GP work, Choo, Wedley and Lam reported that their model "exploded" (a computer term for an endless loop which yields no feasible solution) with any evaluation of over 53 alternatives. The authors also pointed out however, that this figure was a matter of the software program used, the number of priority coefficients used in the objectives, and the extensive outcome probabilities used for each alternative. [Ref. 47]

Finally, some researchers have argued effectively that the assessment of the DM preferences, priorities, and deviation variables in the GP formulation process is actually a search for the Pareto optimal alternative, as described in chapter VII. They point out that ignoring this fact can lead to suboptimal results. Halme and Korhonen, for example, develop the theory (with proofs) for incorporating utility theory into the GP analysis in their 1988 work on multiple objective optimization problems. [Ref. 48]

These references to research on the integration of several models is added to alert the reader. Overlap between the dominate MCDMs may be encountered in actual decision applications. This research effort indicated that successful applications blended the strengths of at least two models. Although this strategy may increase formulation time, the results have been encouraging.

Goal programming is considered the first true MCDM. It has been evaluated and assessed widely, particularly overseas, over the past three decades. Almost without exception, the response to its results for improving the quality of decisions is overwhelmingly positive. However, the results of Titus and Liberatore's survey of top management from 29 "Fortune 500" companies in 1983 revealed that not only did American business not use this technique for R&D management, over 85 percent indicated that they were unaware of it. This indicates a clear disconnect between the management science model developers and the managers who are the users of these techniques. [Ref. 21]

IX. CONCLUSION AND SUMMARY

> There are many quantitative techniques available to aid the decisionmaker (sic) in arriving at a choice that has a high probability of meeting his objective.... The military decisionmaker must consider the ideas and approaches that decision technology has to offer. [Ref. 49] U.S. Army War College, Army Command and Management, August 1991

A. CONCLUSION

The decision models presented in the last four chapters represent the state-of-the-art in American management science efforts to assist decision makers solve multicriteria decision problems. None of them will replace a decision maker or diminish the responsibility for the decision made. Each of them is after all, a representation, a model of a non-trivial decision process. They help to expand the bounds of rationality for those involved in the decision by prompting an analysis of as much of the available information as the decision maker desires.

Each of the four modeling techniques represents a slightly different view of how complex decisions are structured to get a handle on and resolve the critical issues. For the Army Research, Development, and Engineering Centers, the problem is how to allocate limited resources over an ever widening range of technological opportunities to achieve each of their goals to the greatest extent possible. This is a common problem that many of the authors and researchers identified herein have been working on for business, industry, and government for several decades.

These models are not static, but are continually being reshaped to meet the needs of the user community. The users are international in scope, from Europe to the Pacific Rim and Australia. In fact, the models introduced in this thesis seem to be enjoying their greatest acceptance and application in Europe and Japan, according to the work at the International Conference on Multiple Criteria Decision Making [Ref. 39].

Decision theory in general and MCDM in particular will grow increasingly important to decision makers as the models become more sophisticated and user oriented. In 1983, The Harvard Business Review quoted Robert Newman of General Electric:

> Within 10 years, decision theory, should occupy the same role for the manager as calculus does for the engineer today. The engineer of Roman times was unaware of calculus, but he could make perfectly good bridges. However, he could not compete today, even in bridge building, let alone in astro-engineering. Management today is at the stage of Roman engineering. Needless to say, managers will still use specialists, just as engineers use heat transfer experts. [Ref. 50, p.149]

This was not exceedingly prophetic, but rather a statement of the obvious. Decision models may not be as important as calculus yet, but their potential benefits for improving decision quality are enormous.

B. SUMMARY

For the Army research and development project selection problem, MCDM hold a great deal of promise. With increased pressure from Congress for the Department of Defense to assure America's technological defense superiority in the face of dramatically reduced defense spending, there will be increased scrutiny and accountability for the Army's R&D resource commitment decisions. Multicriteria decision models offer a means to develop logically supportable solutions to this issue.

The Army decision maker will rarely know with absolute certainty which R&D alternatives hold the greatest promise for achieving the Army investment strategy objectives. The final choice will likely be something of a compromise, a tradeoff among judgments based on quantitative and qualitative factors and valued expert opinion on potential benefits, risks, costs, and payoffs.

These intuitions from competing stakeholders must be assessed on a level basis, as free as possible from human biases, and in keeping with organizational values. Multicriteria decision models can incorporate these elements, organize the decision criteria, and quantify subjective opinion regarding alternatives' relative merits so that the DM can make a rational choice on the basis of available data.

Furthermore, the limits of human cognitive skills introduce additional inefficiencies of their own. Multicriteria decision models can bring structure to these non-trivial decisions and systematically aid the decision maker to overcome the random errors common to multicriteria problems of choice. Clearly if a decision problem can be effectively modeled, then the quality of the decision can be improved.

In sum, the quality and efficiency of the Army R&D resource commitment must increase. The decisions to commit resources to achieve organizational goals and execute mandates are perhaps the single most important function of any leader. Nevertheless, precious little time can be dedicated to a comprehensive analysis of all of the factors that support these decisions. Multicriteria Decision Models clearly offer an attractive means for resolving this dilemma.

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