CRIME PREVENTION THROUGH ENVIRONMENTAL DESIGN

Technical Guideline 6: Decision Aids and CPTED Evaluative Criteria

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PREFACE

This guideline has been prepared to assist decisionmakers in identifying among alternative program proposals the most attractive one for implementation. The decision aids for systematically determining this preference are drawn from the rapidly expanding literature on multiobjective decisionmaking. Their relevance for crime prevention through environmental design (CPTED) stems from the multiple and conflicting operational, economic, social, and political objectives typical of CPTED-based programs.

Not surprisingly, methodologies which attempt to tackle an inherently complex subject, such as multiobjective decisionmaking, may themselves be complex, but more manageably so. Although knowledge of probability theory and linear algebra, and prior exposure to the precepts of systems analysis, are considered minimum audience attributes by the author, those lacking in these skills are not discouraged from reading this material. Short of simplism, an attempt has been made to keep the language and illustrations simple to permit greater readership. Although formal mathematical notation and definitions are used to provide clarity, rigor, and conciseness beyond that given in the verbal descriptions of the methodologies, almost all of these have been relegated to a mathematical appendix. The reader who is unacquainted with the mathematics involved or does not find the formalities helpful can skip these with little loss in conceptual understanding. While this will undoubtedly strain the patience of some readers, the persevering will be rewarded by an expanded repertoire of decisionmaking aids and a deeper, more formalized comprehension of techniques they may have been using intuitively for some time.

To further aid in assimilating the material, the order of presentation of the background material and the methodologies is from least to most complex. Accordingly, certain sections or subsections can be omitted, depending on the reader's experience and interests. The following summary of section topics provides additional guidance in this regard.

The introductory section states the purpose of this technical guideline and briefly discusses its underlying philosophy, particularly with respect to the benefits and limitations of systematic analysis of complex urban problems. The second section attempts to relate this report to the companion issues addressed by the CPTED Program Manual and to the systems approach generally. Although the definitions and broad overview will be familiar to the professional analyst, some of the difficulties of problem definition, goal setting, and suboptimization in the context of CPTED may not. For the nonspecialist, this section serves as a briefing on the systems approach and articulates where the decisionmaking task emerges in the systems analysis process.

The third section presents guidelines for eliciting program goals and performance criteria. Here, the nature of the complexity which inheres in selecting alternative courses of program action is carefully developed as the precursor to the decision methodologies treated in the remaining sections. Both the nontechnical reader and systems specialist will find useful the guidelines on structuring objectives and developing program performance measures in a CPTED context. These are accompanied by an overview of the basic nature of security systems.

The core of the guideline is Section 4. Following a recapitulation of the decisionmaking problem in formal CPTED and systems terms, nine decisionmaking techniques are elaborated and illustrated. Albeit simplified to decisionmaking situations in which only four program alternatives are being compared on only five security system attributes, the illustrations serve as excellent pedagogic vehicles. Despite this dimensional simplicity, the illustrations still afford realism through the conflicting objectives and disparate performance scores incorporated in the examples. With the mathematical notation held to a minimum throughout the discussion, the nontechnical reader should have no trouble reconciling the results of the illustrations and thereby reinforcing his understanding of the basic methodology. To provide added perspective, Section 4 also develops a simple typology of available decision aids. This is used to break the otherwise unwieldy section down according to this dimensionally based typology. The section ends with guidelines on how uncertainties regarding individual program performance scores can be incorporated into all nine schemes. Again, with little loss, this subsection can be skipped by the nontechnical reader.

The final section presents a case study in which one of the unidimensional schemes, a linear performance index, is used to decide which of 15 synthesized program alternatives, judged with respect to 8 performance measures on 2 crime types, should be implemented. The design context involves the improvement of security in New York City public housing. Although somewhat dated, the study is one of the few well documented attempts at comprehensive, interdisciplinary analysis of such problems. The material thus obviates the substantial resources necessary to demonstrate fully another methodology, or the same technique in a different setting. Unlike the Section 4 illustrations, moreover, the data are not contrived, but stem from a real application in which significant resources were at stake.

A mathematical synopsis of the decision aids presented in Section 4 is provided in a separate technical appendix. The intended audience for this appendix is the operations research/management science specialist. Programmers assigned the task of implementing the decision algorithms on a computer will find this appendix of direct use as well.

Nontechnical readers wishing to enhance their knowledge of systems analysis and decision methodology will find the concluding reference and bibliographic sections helpful. Operations researchers whose specializations lie outside multiobjective decisionmaking may also find the extensive bibliography valuable in reviewing the state of the art.

1. Introduction: Purpose and Philosophy

Faced with an array of CPTED program alternatives, how does the decisionmaker identify the most attractive design for implementation? At the heart of this issue is the need to express a final preference, despite disparate performance measures. There are two components to this problem. The first entails constructing an acceptable basis for assessing the absolute or relative merits of a set of proposed programs. This framework must be broad enough to factor in key attributes of an operational, economic, social, and political nature. The second involves establishing a methodology for accomplishing the multidimensional trade-offs, ultimately collapsing the individual program assessments into a unidimensional ranking of preferences, a step which, despite the inherent complexity of choice, decisionmakers ultimately do complete. The methodology itself must suit the state of the art in CPTED practice, especially with respect to theoretically validated relationships, the expected level of measurement, and the availability of data.

This guideline attempts to provide assistance in both these matters, in different degrees for the nontechnical reader and systems specialist, as noted in the Preface. Before delving into methodological details or systematically linking the present effort to the issues addressed in the other segments of the CPTED Program Manual, however, some discussion of the philosophy behind the approach is in order. First, implicit in this presentation is the belief that with regard to complex choices involving the allocation of scarce resources, we can do better than muddle through (1, 2, 3).* That is, it is better to explicate objectives and performance measures to identify where one is aiming than to proceed aimlessly. While maintaining an appropriate balance between rigor and relevance, it is better to have systematic decisionmaking and evaluation than to leave a legacy of no audit trails to capitalize on, nor any idea of how much or why goals were missed.

Second, it is not our intention here to overstate the case for systematic analysis via the eclectic techniques of operations research, cost-benefit / cost-effectiveness analysis, or the planning-programming-budgeting-system paradigm. Even the strongest advocates of these methods have widely acknowledged the often severe impacts of externalities (4, 5, 6, 7, 8). These uncontrollable forces outside the system's scope can influence and sometimes dominate the system's behavior. Moreover, the problems of systems analysis do not end with either unrecognized or uncontrollable exogenous events, such as political pressures. It may be presumptuous, especially in a criminal justice context, to talk meaningfully in system terms. True, one can identify components such as police, prosecution, courts, probation, corrections, and parole. One can also cite or hypothesize common objectives such as improvement of public safety and equity in the

*See list of references following text.

legitimized role of inflicting punishment. However, on an operational level, the fact is that actual behavior of these components is hardly systematic. They behave more as a loose organizational confederation, linked incidentally by law, with individually conflicting objectives and interacting operations, and little explicit or certain feedback regarding the attainment of goals (9). Thus, in part, police strive to maximize the probability of detection and apprehension of criminals; prosecutors to heighten likelihood of conviction; courts to improve assurance of a fair trial and equitable punishment; corrections to minimize escape, maximize control, provide humane containment, reduce recidivism through rehabilitation; and so on. While the latter goals are patently conflicting, and within one system component at that, the others become so through their operational manifestations. Further exacerbating the meaningfulness of system and the tractability of analysis, one might argue that the scope of the system, such as it is, should include educational, social, religious, economic development, and other organizations since causal linkages can be reasonably hypothesized or demonstrated vis-à-vis criminal justice goals. Even if the systems paradigm were applied, and at the proper scope, there would be substantial difficulties in attempting to quantify the nature of relationships. These stem from uncertainties about basic crime characteristics (e.g., level, rate, spatial and temporal trends, displacement and/or escalation, morbidity or mortality, demographic factors, tactics, and even type), from insufficient knowledge of causative factors and the extent to which they operate, as well as from the grossly inadequate information on the way in which criminals, victims, and anticrime elements interact. The analyst's task is thus complicated not only by the primitiveness of the state of the art, but by the diversity of crime types, offender methods, victim characteristics, and the profusion of conditions under which crimes occur (10).

Our third point, then, is that in the face of such obstacles, subjective judgments regarding CPTED strategies obviously will not be displaced by any purely objective, mechanistic algorithm for program choice, a naive aspiration in itself since value judgments inhere in the selection of objectives, criteria, thresholds of acceptability, model, scope, and methodology (11). What we can offer and what such complexity as CPTED demands but has seldom received, is a systematic approach; that is, an approach which defines objectives and goals, identifies functions to be accomplished, translates those functions into detailed social-system requirements and specifications for component performance, and evaluates actual performance, dynamically amending any of the aforementioned in regard to unacceptable disparities in achievement. Such an approach can provide a framework which makes the decision question explicit, identifies the relevant data, indicates how it is to be collected, and presents a method for bringing the information to bear on the decision, a framework which, in short, imposes a plan and a structure to complement the subjective elements of decisionmaking. No doubt, final preferences will be predicated on less than an exhaustive consideration of all the variables involved and will represent a suboptimization at best. For the foreseeable future, however, we will have to face the disturbing realities that optimal allocation of resources to crime prevention programs will depend in part on nonquantifiable, and sometimes even unknowable, considerations, and that short-term optimal or, simply satisfactory, designs may quickly become irrelevant as environmental circumstances shift and objectives change. The undue quest for precision is not only unrealistic and perhaps self-defeating, it may come at the expense of timely decisionmaking and more social experimentation supported by sound longitudinal evaluation; it may also overemphasize the quantifiable elements of a problem at the sacrifice of other salient factors (12). Very likely therefore, systematic analysis will wind up revealing more about the true dimensions of complexity and choice in a given CPTED situation than substantially reducing the decisionmaking chore. Our contention is that this provides a firm basis for progress and that, in any case, the alternatives to this mode of rational decisionmaking share most of its shortcomings, but few of its advantages.

Our concluding point amalgamates the preceding concerns regarding the state of the art in CPTED theory and practice and the benefits and concomitant limitations in applying systems methodology to problems as challenging as crime control. The point is that the analytical aids which we present must avoid simplism on the one hand and a paralysis of complexity on the other. Our selections and presentations of various decision aids are guided by this and the practical wisdom that decisionmakers will not vote for what they do not understand.

2. Relation to Systems Approach and CPTED Program Manual

The systems approach provides direct assistance in relating the decisionmaking concern of this document to the companion issues addressed throughout the CPTED Program Manual. In a somewhat simplified manner, Figure 1 depicts the major tasks entailed in conducting a systems analysis (13). Before turning to the subtask labelled "selecting best program," the focus of this section, some system concepts and terminology will be described which will enable us to appreciate the unifying framework which this figure presents.

A *system* is a set of resources organized to perform designated functions in order to fulfill desired ends. The system's life cycle begins with the perception of needs and terminates when it is deactivated or scrapped, the overall life span being divisible into periods of planning, acquisition, and usage. During these phases, the system consumes limited, valuable resources such as personnel, facilities, materiel, and information. The fact that these resources are valuable and could be allocated for attainment of other human needs emphasizes the importance of the problems of design and choice of alternative system configurations, particularly in complex social systems which draw upon significant quantities of such resources.

A hierarchy of elements can be identified in any system. If two or more systems are interrelated, they can be considered jointly as yet another system or *supersystem*. In this broader context, the original systems may be viewed now as *subsystems*. In turn, each of

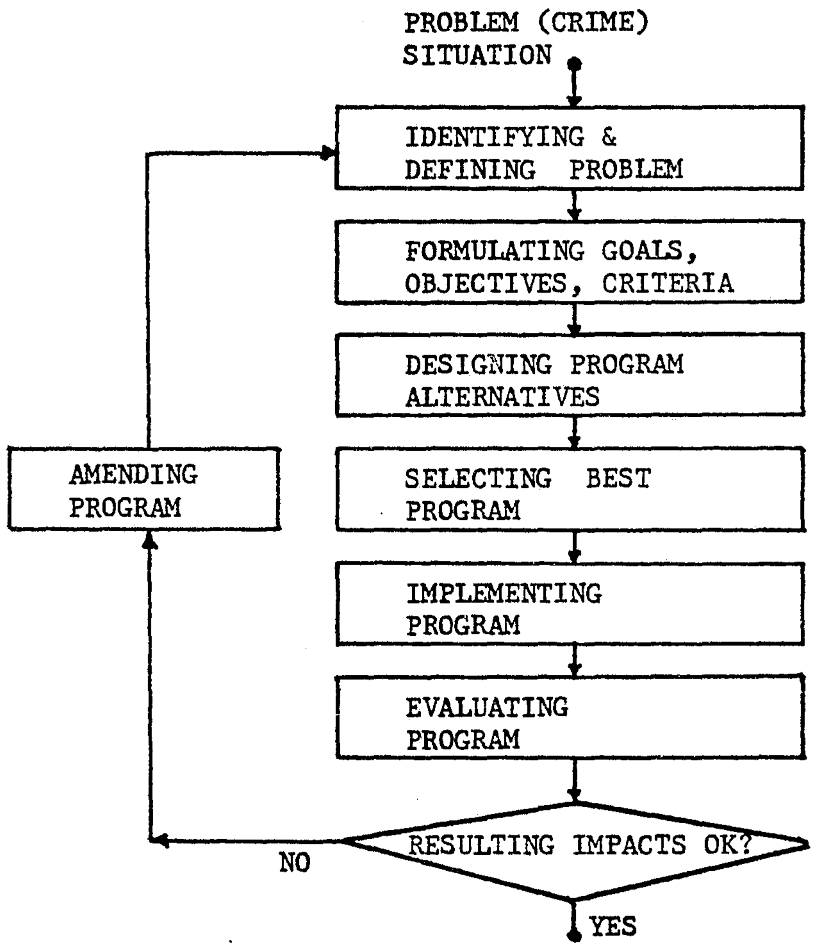

Figure 1. Overview of the Systems Approach:
Major Steps and Iterative Processes

the subsystems may comprise other subsystems. The lowest level of these, beyond which decomposition is not necessary or useful, is called a *component*. Clearly, systems will always be embedded in what CPTED theory refers to as broad-sense environmental systems, including those of a legal, political, social, and economic, as well as physical nature. Systems about which design and implementation questions must be made will often have significant interactions with these environmental systems, usually being much more influenced by such interactions than vice versa.

The systems approach recognizes the interdependencies and constraints which bind a system together and requires that the scope of the system be sufficiently extended to encompass those interrelationships most relevant to the design problem. In order to maintain meaningfulness and tractability (since it can be argued that everything is somehow connected to everything else in the world), the analyst must make difficult judgments regarding proper scope and level of detail. Despite the present inevitability of component rather than whole system treatment, and of suboptimum or acceptable designs rather than optimum programs, the astute analyst can strive to discover those key components whose performance measures are consonant with the overall system, and whose increases are followed by improvements at the system level as well. Inevitably, then, we should recognize that for analysis of social systems to be a manageable process and to provide timely policy inputs, some considerations will always have to be left out. The point is that although such judgments will be unavoidable, we can at least begin by considering the whole problem and then, as the modeling and analysis proceed, we can deliberately and judiciously decide what to retain and what to set aside. In so doing however, it is crucial that the objectives and performance criteria which we apply to the suboptimization be consistent with those applicable to the fuller problem.

As Figure 1 suggests, the novelty of the systems approach to providing advice and selecting a course of action lies in its emphasis on articulating the whole problem, in attempting to clarify objectives and assumptions, in searching for alternative solutions, in explicitly recognizing performance criteria and uncertainties in their validity and values, and in systematically applying quantitative methods, judgment, and intuition to cull out the predicted best alternative for implementation. This choice of best, in turn, consciously factors in implementation or realizability concerns. While there are many opportunities for repeating and refining portions of this analytical process, Figure 1 indicates that overall iteration, closure, or feedback arises through longitudinal evaluation of the chosen option. In the course of such comparison of actual performance with objectives, amendments may be suggested in the program, the program's goals, or both, with the new objectives and program alternatives potentially necessitating repetition of the entire analytical process. These changes may be triggered by the desire to fine tune a successful program, to fix or scrap a failing one, or to accomodate new needs or heightened levels of aspiration.

The first step in the systems approach entails problem definition, a deceptively difficult but crucial step. Working on the wrong problem is not only a clear waste of analytical resources, but improper problem formulation can lead to exacerbation of the situation and further waste of precious implementation resources. In the present context, designing programs to ameliorate crime conditions and fear of crime, we know that dimensioning the problem is no mean task. The difficulties are hardly eliminated by gathering victimization data to complement archival UCR* statistics, nor are the difficulties limited to this obvious need. Community values and representativeness of community interest groups will also affect problem identification, since their views and opinions concerning needs will be normally solicited during the CPTED preplanning phase. The problem identification stage should end with a high degree of articulation, specificity, and realistic scope to keep the problem limited to manageable proportions and to keep the remaining design steps relevant.

Once the problem is adequately dimensioned, the next step can be taken: eliciting and refining goals, objectives, and performance criteria. Incorrect or imprecise specification of these prevents the development of meaningful solutions on the one hand and identification of the superior, inferior, or unacceptable alternatives on the other.

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* FBI Uniform Crime Reports

The problem here is that in creating public systems, there are often multiple, conflicting, unclear, and even latent objectives. Moreover, the objectives, goals, and evaluative criteria employed are, in part, reflections of the values held by the decisionmaker, the decisionmaker being a single person or perhaps an elected body presumably acting on behalf of the community towards which the prospective program is aimed.

Assuming there is consensus of interests, commonality of goals and priorities, and agreement on criteria, one may yet be faced with the knotty problems of conflicting objectives (a frequent public sector phenomenon) and the necessity of using proxy criteria and surrogate measures. For example, in the usual circumstance of a broadscale crime problem, an appropriate top-level goal may be to improve public safety (i.e., below the goal of improved quality of life, of course). Appropriate subgoals may be the reduction of violent acts such as robbery and nonviolent property crimes such as burglary. Accordingly, specific objectives may be to reduce the rate of each of these by 5 and 10 percent, respectively, in the year following program implementation and with minimum inconvenience to the community served by the program. Even in this modest statement, many of the aforementioned problems lurk. First, assuming that these goals or objectives would be agreeable to the majority (i.e., that felony assaults might be deemed more important than burglaries), it is not clear that such reductions in burglaries might not exacerbate the robbery situation in the target community (setting aside the still more difficult displacement problem and the suboptimization issue which it engenders). Second, the objective, "with minimum inconvenience," is not clear. If it means restricted usage of certain facilities or increased taxes, this would be understandable, although not completely so, and may even admit of quantitative measurement. If it means little loss of privacy (e.g., following the use of surveillance measures or patrols in semiprivate spaces), the objective is still far less clear and perhaps not amenable to measurement. Third, although the two crime objectives are relatively clear and the performance measures of robberies and burglaries per thousand population during the given year seem to be suitable criteria, the actual measurement of the numerators and denominators of these terms are well known to suffer unreliability, instability, incomparability, and costliness problems. Fourth, assuming that reduction of fear or maintenance of current police force sizes and visibility were important, but latent objectives, the decisionmaker might well opt for an alternative that was not best with regard to the explicit objectives and performance criteria which guided the synthesis of program alternatives.

Having completed problem formulation, elaboration of goals, objectives, and performance criteria (processes which are assisted by the planning guidelines set forth elsewhere in the CPTED Program Manual), the CPTED specialists are then in a position to enter the third and most creative stage, that of designing program alternatives for the decisionmaker to consider. This array of alternatives may comprise radically different approaches, variations on a basic strategy, or both. During these synthesis activities, the specialist can draw upon CPTED theory, the strategies and specific directives described in the CPTED Program Manual, as well as the general literature on crime prevention. As Figure 1 indicates, this synthesis phase is followed by analysis and comparison of alternatives with respect to the agreed upon performance criteria. Once the performance estimates have been accomplished, a decision must be made as to which alternative to implement, the primary task which the remainder of this guideline addresses. Before illuminating the complexities of multiobjective decisionmaking and describing specific decision aids and their limitations, the reader's attention is drawn to the last two tasks identified in Figure 1: program implementation and program evaluation. Here too, a large body of material has been provided in the CPTED Program Manual to assist in these tasks, tasks which are individually crucial to success not only in immediate program terms, but in the broad sense of building CPTED theory and improving its practice.

3. Guidelines for Erecting CPTED Goals and Performance Criteria

3.1 Introduction

Decisionmaking centers on the element of choice, selecting alternative courses of action. It is a process which is routinely carried on by individual decisionmakers at any level of an organization. The need for decisionmaking arises because of actual or perceived discrepancies between an existing or anticipated situation and the organizational goals toward which a decisionmaker is mandated to direct his efforts. As our discussion of the systems approach has emphasized, system or policy alternatives are normally characterized by several features by which their relative desirability is to be judged. The attributes are directly related to a set of performance criteria which are derived from specific program objectives. The multiattributive decision situations which such complex alternatives engender are themselves complicated by the fact that some alternatives will appear preferable when certain goals and their associated attributes are examined, while others will become so as other attributes are considered. As the number of relevant attributes and proposed alternatives grows, the decisionmaking problem becomes increasingly less tractable for the decisionmaker: there are too many comparisons to make, and the dimensions or attributes of comparison are incommensurable.

Section 4 explores these matters more deeply and relates them to several decision methodologies which vary in their informational needs, assumptions, and abilities to preserve the multidimensionality which inheres in such decision problems. Detailed illustrations of the methodologies as well as the issues raised in this section are also deferred to Section 4. The remainder of this section focuses on what an appropriate set of goals might look like in the context of crime prevention and, in turn, what might constitute a reasonably comprehensive set of CPTED program attributes by which to compare alternatives. As a precursor to that discussion, a brief digression will be made to clarify the terms "goals," "attributes," etc.

3.2 Definitions of Terms

Throughout our discussion we shall define a *goal* as a general direction that enhances a societal group's welfare or quality of life. While we will often use the terms goal and objective interchangeably, *objective* has the connotation of being a targeted level of a particular goal. A *policy* or *policy alternative*, or simply *alternative*, is a specific course of action designed to accomplish an overall goal. How the benefits of the policy's implementation are distributed requires a specification of different *interest groups* in society. These are groups of individuals or organizations which share common views about an alternative's consequences. Typically, these might be further classified as to whether they are program users, operators, affected socio-economic classes of society, or implementing agencies with control over resources and with regulatory powers, an obviously nonmutually exclusive set of categories.

At this point, we also need clarification of the term "attribute."

General goals or policies can be translated into program or system performance objectives. These objectives, in turn, can be subdivided into individual performance subobjectives. These subobjectives and the appropriate physical units for measuring their performance are called *attributes* (interchangeably referred to in the literature as program features, characteristics, properties, dimensions, factors, performance measures, performance parameters, or figures of merit) (14). These all signify dimensions of benefit that are expected to be provided at varying *levels* (the actual value of an attribute) by the program alternatives on the one hand, and desired by users, operators, societal groups, and agencies on the other. The crucial point is that once attributes and units of measure are identified, it becomes possible to characterize system demands and impacts as well as to specify system and subsystem performance objectives designed to satisfy such demand and accomplish such impacts. It also becomes possible to evaluate proposed alternatives in specific performance terms, the necessary precursor to determining which alternative is best.

3.3 Structuring Objectives and Attributes

Initially, goals or objectives should be stated in very broad terms. The idea is to be comprehensive at first and then, through a process of successive elaboration, to narrow these objectives down into a highly articulated statement of desired performance. This specification forms the basis for eventual evaluation of alternatives. In the context of crime prevention, for example, the initial overall goal might be to improve public safety, itself subsumed by enhanced qualify of life. This higher level goal, which might encompass criminal victimization, injury due to fires, transportation vehicles, and environmental hazards, might be confined to security improvement vis-à-vis crime only. This, in turn, could be further divided into subobjectives concerned with increased risks of criminal detection, apprehension, and conviction. These could be further divided into increased surveillance and police response capacity, and so forth. By this point, if not earlier, conflicting objectives might start to emerge in the form of preservation of privacy, low cost, and high system durability.

Before suggesting a specific evaluative framework which incorporates such concerns, it should be noted that the list of overall performance objectives should possess the following properties. First, it should be *comprehensive* in the sense that no major performance objective is omitted. Second, to the extent possible, the listed objectives should be *independent*. As we shall see in the discussion of decision methodologies, this independence is very important to establishing trade-offs and minimizing double accounting of system benefits in assessing the total worth or performance of an alternative. Third, the initial list should contain only performance objectives of *top-level importance* in order to provide a sound basis from which to derive lower-level objectives and their attributes.

Once the list of top-level objectives is completed, we can proceed to the next task, operationalizing the key objectives. This is accomplished by subdividing each objective into a treelike structure of lower-level objectives and attributes. At this stage we have consciously defined each objective's intent and have evolved a utility or worth structure in the form of a set of attributes by which to judge the merits of any set of proposed alternatives. The final step in devising the set of key attributes is to select a physical unit of measure for each attribute. This provides a concrete physical interpretation for the performance characteristics and thereby establishes a link between the real world of physical or procedural alternatives and the subjective preferences of decisionmakers. That is, attributes provide a tangible, observable measure of what alternatives can deliver (or are delivering, as in post-implementation program evaluation), as opposed to the stated subobjectives which simply reflect what a decisionmaker subjectively desires.

Selection of physical performance measures requires informed judgment. Well-defined attributes and readily measurable units should be chosen which reflect the intended meaning of the lowest level objective being considered; i.e., they should have face validity and admit of easy measurement. The process for obtaining a final list of such measures will usually be iterative and follow steps along the following lines (15).

(1) Locate an objective or attribute in the list without an attached measure (i.e., find an incomplete branch on the hierarchical tree of objectives).

(2) In the context of the application (e.g., CPTED), determine whether a given objective is to be interpreted directly by a physical performance measure or to be further subdivided (if the latter, go to step 3, otherwise skip to step 5).

(3) With respect to the applications context, subdivide the given objective into 2 or more subobjectives and attributes (together with the other objectives and attributes of the list, these now constitute an expanded master list).

(4) Select any of the new attributes which emerged in step 3 and return to step 1.

(5) In the context of application, select a physical performance measure relevant to the subobjective being considered.

(6) Move backwards up the current branch of the hierarchical tree of objectives until encountering the first level containing an uncompleted branch. If not at a top-level objective, select the incompleted branch and return to step 1; otherwise go to step 7.

(7) If all major performance objectives and their associated attributes have been completed at the top level of the tree, the process terminates; otherwise select any incomplete branch and return to step 1.

3.4 Security System Concepts and a Preliminary Attribute Framework

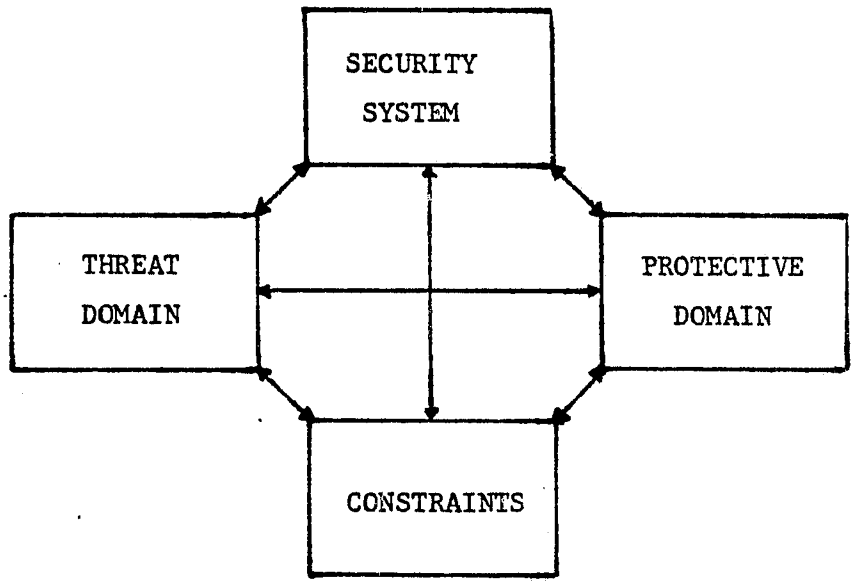
As a precursor to scoping out an attribute framework to use as a basis for assessing and comparing CPTED alternatives, we shall introduce several security system concepts (16). The term *security system* will be used to denote an entity which interacts under external constraints with specific threats and protective elements to accomplish criminal deterrence and apprehension. *Threat domain* will denote the specific criminal activities to be curtailed by the security system; its description includes such factors as forcefulness, frequency, scale, modus operandi, etc., and their translation into physical characteristics. *Protective domain* will signify the specific property and persons to be safeguarded as well as the precise locations and times involved. Finally, the *constraint set* will include the technical descriptors of the relevant social, political, economic, technical, environmental, etc., factors that circumscribe the threats, the protected personnel and property, and the security system itself (i.e., to the extent such technical representations are possible).

This definition leads to a broad operational view of a security system and includes the notions of security held by several agencies. The property owner, for example, considers a security system as a conglomeration of components which jointly act to reduce personal loss. The police would add the notion that a security system should enable the apprehension of offenders. An insurance underwriter would view a security system in terms of its ability to facilitate recovery of stolen goods; an attorney, in terms of providing evidence for conviction; a social worker, in terms of deterring or denying antisocial behavior. Despite the variety of viewpoints, one can attempt to state broadly what a security system is in a way that considers all these dimensions.

Fundamentally, the measure of effectiveness for a security system should be the degree to which throughts of crime are not translated into actual deeds, and, failing this, the extent to which attempted crime is not successful. To be effective, then, a security system must act as a deterrent, provide resistance, and afford apprehension capability. Two strategies are commonly employed to deter or resist criminal acts and to make them self-defeating: (1) Decreasing the real or apparent opportunities for crime; and (2) increasing the perceived risk of apprehension and penalty. Since these deterrents and denials do not always suffice, an ability to apprehand and penalize must be actually present, generally in the form of the capabilities summarized in Figure 2. Security effectiveness is reflected in the successful, collective accomplishment of all the enumerated objectives. In order to apply numerical or judgmental ratings to alternative security proposals, however, these objectives must be translated into effectiveness measures, or security system attributes, as discussed earlier.

Figure 3 is a preliminary attempt to generate and partially operationalize a set of security system attributes. Although not exhaustive, the list should suffice to evaluate most aspects of security design commonly of interest. As will become apparent in the definitions which follow, the proposed security criteria lack complete independence, a feature which will hamper further analysis as explained earlier and elaborated more fully in Section 4. Once operationalized, it is clear that the numerical or qualitative assignments which are ascribed to the attributes will depend heavily on the applications context, varying with the specific threat category, the protective domain, and the operational constraints.

Some of the attributes described in Figure 3 require additional definition. We have previously described *deterrence* as the capacity to prevent threat initiation and to make criminal activity self-defeating. A deterrent capability can consist of real physical barriers as well as



OBJECTIVES AND FUNCTIONS

- Detect and Discriminate the Crime
- Actuate and Transmit an Alarm Condition
- Annunciate and Decode the Alarm
- Command and Control Forces
- Transport Forces to the Crime Area
- Search and Examine the Crime Area
- Identify, Locate, and Arrest the Criminal
- Provide Evidence to Aid in Conviction
- Recovery Property and Reduce Morbidity and Mortality

Figure 2. Security System Interactions and Objectives

ATTRIBUTES

- Security-Effectiveness
  Deterrent Probability
  Detection Probability (sensitivity, spatial & temporal coverage)
  Discrimination & Identification Capacity (false alarm/dismissal rates)
  Alarm Transmissibility (probability of reception)
  Response Capacity (response time and manpower/force level)
  Reliability (system failure rates)
  Survivability (susceptibility/likelihood of destruction)
  Adaptability (probability of accomodation to changing threats and countermeasures)

- Implementability
  Availability (for purchase and use by target date)
  Installation Feasibility
  Public Acceptance

- Compatibility
  Convenience of Use
  Privacy Incursions
  Aesthetic Appeal

- Operability
  Management Requirements
  Dependence on User Cooperation
  Modularity (ease of system expansion)
  Safety
  Repairability (ease of maintenance)

- Cost-Benefit
  Research & Development Cost (equipment,maintenance,administration before production)
  Capital Cost (equipment,maintenance,administrative costs during production)
  Operating Cost (equipment,maintenance,administrative costs during use)
  Scrap Value (residual value at end of use)
  Expected Total Benefit (value of reduced crimes: morbidity,mortality,property,etc.)

Figure 3. Illustrative Security System Performance Measures and Units

suggested ones. The combination of these physical and psychological obstacles should heighten the potential perpetrator's imagined and actual chances of apprehension and conviction.

By *detection*, we mean discovery of the existence of characteristics indicative of a threat. By this definition, detection differs from the usual connotation of entrapment, identification, or verification. Detectability is linked instead to system sensitivity and to spatial and temporal coverage.

Closely related to detectability is the capacity for *discrimination*, i.e., the ability to distinquish real threats (the desired signals) from innocent activity (noise) and to classify uniquely each threat signature. It is discrimination capacity which makes the human an indispensible element of high security systems. Humans are more readily adaptable to elusive threats and are far better at real-time pattern recognition than currently available physical mechanisms. Because random noise introduces uncertainty into all real security systems, an obvious trade-off exists between these detection and discrimination functions or attributes. By accepting a sufficiently high false alarm rate, the false dismissal probability can be made arbitrarily close to zero (17). Thus, the level at which a detection threshold is set always results in a compromise between mistakenly announcing or ignoring an alarm. Both types of error can be simultaneously reduced, or course, if one is willing to wait for more information about the possible criminal act in progress. The selection of the proper threshold for a given amount of information will depend on the relative importance or costs associated with the two types of errors.

The *alarm* process requires only intelligible annunciation, usually after transmission to a command and control center removed from the crime site. The alarm can be based on detection alone, discriminated detection, or both. Once an alarm is made, the system must *respond* forcefully enough to abort the threat if the net gain from doing so exceeds some preassigned criterion or threshold. Since it may be necessary to do this repeatedly, the system's duty cycle must match the highest anticipated threat repetition frequency to minimize failures due to spoofing or repeated real attack. Moreover, the system's response time must be less than the total crime duration if on-site arrest is to be made. The response mode itself might be any of a number of forms: from no action, to a simple electromechanical or chemical trap, to an elaborate security guard or police contingent. In any case, the forcefulness or manpower level associated with the response should be commensurate with the threat.

System *reliability* is an attribute which pertains to the assurance of meeting a prescribed confidence level for system operability, usually expressed in probabilistic terms. Reliability is also closely related to the requirements of *repairability* and *maintainability*, perhaps even the capacity for self-diagnosis and fault indication, if not for self-repair. These attributes are broken out separately under the major attribute heading, *operability*.

The system must also fulfill a specified probability of satisfactory functioning in the face of numerous countermeasures and evasive tactics: sabotage, vandalism, unintentional and purposeful jamming, etc. This is what is meant by *survivability*. We distinquish this from *adaptability* which connotes the ability of a system to cope with changing or elusive threats for which it was not specifically designed. For simplicity, the features we have called reliability, survivability, and adaptability might be crystallized into one attribute called *durability*.

When these criteria of performance are further coupled with implementability, compatibility, operability, and cost-benefit characteristics, we then obtain a fairly comprehensive attribute set from which to judge the merits of proposed design alternatives. The next section addresses the issue of how a decisionmaker decides which alternative is best considering all the relevant attributes and estimated levels which have been assigned to all of them. All of the methodologies will be illustrated in terms of the five major attributes we just considered: Security-effectiveness, implementability, compatibility, operability, and cost.

4. Decision Aids and Treatment of Uncertainty

4.1 Introduction

The primary concern of this section is how to select from an array of candidate CPTED alternatives the best one for implementation. We assume, therefore, the satisfactory completion of the precursory stages of problem definition, identification of goals, objectives, and performance criteria, as well as synthesis of suitable options. To answer the question of "best," the decisionmaker must refer to the goals and criteria explicated earlier in the systems analysis process. Despite this rationality and systematicness, the decisionmaker's task will be hampered by two factors present in every significant social design problem. The first of these has to do with uncertainty, the second, with limitations associated with our capacity to process information (18-19).

Often we do not know precisely an alternative's outcome before its implementation. There may even be problems in accurately assessing a program's impact after it has been put into operation, as elaborated elsewhere in the CPTED Program Manual. The reason for the uncertainty stems from the fact that the program's outcome may depend upon events and conditions beyond the decisionmaker's control (exogenous events or externalities). Another form of uncertainty relates to the actual levels, as opposed to the predicted or estimated levels, associated with the performance measures by which a program is judged. That is, either because of ignorance regarding certain variables and their interactions, or because of their inherent randomness, we may not know the exact outcomes, but only a distribution of possible outcomes and their associated probabilities. The term decisionmaking under risk is given to the latter circumstance. When even the probabilities are unknown, the term decisionmaking under uncertainty is applicable (20). Figure 4 illustrates this hierarchy of certainty-to-uncertainty (21). The expressions of varying certainty apply generally to any aspect of program performance or outcome variable of interest.

Because of our limited ability to assimilate and process information relating to complex systems, even when high levels of uncertainty are present and computers are available to assist, decisionmaking can still be very difficult. As we have seen in the previous section, a common type of complexity which frequently occurs in social systems and public policy problems stems from the multiple objectives and therefore multiattributive nature of such systems and issues. That is, system or policy alternatives are normally characterized by several attributes by which their relative desirability will be judged. As Figure 5 illustrates, such complexity forces us to construct and manipulate some simplified model of the problem situation in order to assess the relative merits of proposed policy or program alternatives. Choice is then guided by estimated values of the performance criteria, the criteria having been established from an elicited set of desired objectives. While this is not the only path open to the decisionmaker, it is the only practical one. Choice could

STATEMENT	LEVEL OF UNCERTAINTY & SPECIFICITY	DECISION CONTEXT
Program alternative A is estimated to cost $1.5M.	Complete uncertainty; no expression of likelihood is provided.	UNCERTAINTY
Program A is estimated to cost $1.5M; however, analyst is not certain about the figure.	Nearly complete uncertainty; a vague caveat regarding uncertainty of the estimate is provided however.	RISK
Program A is estimated to cost between $1.1M and $1.9M.	Uncertainty is made more explicit and a range (interval estimate) is provided to express the magnitude of uncertainty. However, no probability or confidence measure accompanies the interval estimate. It remains uncertain whether the analyst believes the true cost has a 1%, 50%, or 100% chance of falling in the range. Nor is it clear whether the true cost is more likely to be nearer $1.1M than $1.9M.	
Program A's cost has a strong probability of costing $1.1M - $1.5M -$1.9M where $1.1M and $1.9M are the estimated lower and upper cost limits and $1.5M is some central measure.	Uncertainty is made still more explicit by adding a qualitative probability measure to indicate degree of confidence associated with the interval estimate. It is not clear what measure of centrality (mean, median, mode, etc.) is conveyed vis-a-vis the $1.5M figure.	
Program A's cost is estimated to be in the interval $1.1M to $1.9M with probability 0.90 and with $1.5M being the estimated modal value.	Uncertainty regarding the interval estimate is now given a quantitative expression, and the sense of centrality is made precise (in this case, the most likely or modal cost). The probabilities associated with other ranges of cost remain unknown however.	
Program A's cost follows the following probability distribution (density function) with parameters. .	Uncertainty is completely characterized by providing the entire probability distribution (density function) for cost. Probabilities corresponding to any cost estimate can be derived from the graph or the analytical expression for the cost density function by computing (integrating) the area under the appropriate portion of the function. Presumably, the function is known exactly.	
Program A's cost is known to be exactly $1,405,671.15.	Cost is known with complete certainty to the nearest penny.	CERTAINTY

Figure 4. Hierarchy of Uncertainty: Forms of Expression and Specificity

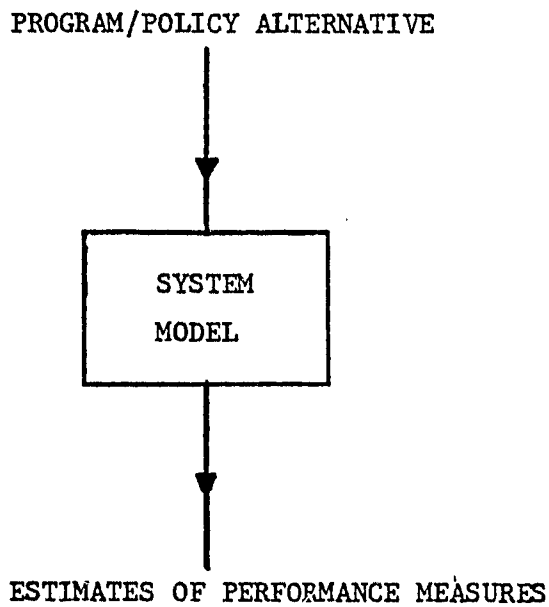


Figure 5. System Modeling

proceed on the basis of implementing and observing all the alternatives in the real world. The one which worked best would then be implemented permanently and the rest dropped. The expense associated with such a wholescale trial and error approach, if not the anticipated public reaction to program abandonment, usually precludes this decisionmaking strategy however. It is also possible for selection to proceed on a purely intuitive basis, but for reasons articulated previously it would not be clear what judgmental information was systematically or comprehensively incorporated in the final decision.

4.2 The Multiattributive Decision Problem

In order to set the stage for the specific choice methodologies which follow, we assume that the CPTED project team have completed three tasks. First, that from a set of elicited goals and objectives, a companion set of program attributes or performance measures has been established. Second, that corresponding to the program objectives and the specific attributes which reflect them, a set of program alternatives has been synthesized. And third, that through the use of expert judgment, predictive models, or combinations of these, each candidate program alternative has been given a performance rating on each attribute. Each of these ratings may be either a single value (*point estimate*), or a range of values (*interval estimate*). To simplify exposition, our illustrations will initially assume that only point estimates have been made. Later, we shall readdress the case of interval estimates, as well as the problem of acquiring the estimates themselves.

Figure 6 provides a mathematical overview of the table of performance values which have been obtained.* In order to keep our discussion concrete, we present in Figure 7 a specific, although highly simplified illustration of how the alternative/attribute matrix of Figure 6 might appear. Only point estimates are given for each alternative/attribute combination, and the attributes have not been subdivided into the more detailed measures of performance presented in the earlier sections.

If we assume that the design problem corresponding to Figure 7 entails reducing a community's burglary and robbery rates, for example, then the security effectiveness attribute might be measured by, say, the estimated weighted average percentage reduction in these crimes. Without going into a long digression on the validity of this measure, suffice it to say that the weights themselves might be chosen to reflect perhaps the Sellin-Wolfgang seriousness indices for these crimes (see Figure 8), or perhaps some local priorities vis-à-vis these crimes (22). On this measure, Figure 7 shows that alternatives A_1 through A_4 have been scored 10, 15, 8, 18, respectively, and that A_4 is judged superior to the rest for this particular attribute. On the

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*Throughout this chapter, formal mathematical notation and definitions will be used to provide clarity, rigor, and conciseness beyond that given in the verbal descriptions. The reader who is unacquainted with the mathematics involved, or does not find the formalities helpful, can skip these with no loss in conceptual understanding.

ATTRIBUTE	ALTERNATIVE A_1	A_2	$\cdots$	A_N
a_1	r_{11}	r_{12}	$\cdots$	r_{1N}
a_2	r_{21}	r_{22}	$\cdots$	r_{2N}
$\vdots$	$\vdots$	$\vdots$		$\vdots$
a_M	r_{M1}	r_{M2}	$\cdots$	r_{MN}

Key: a_i = i th attribute, i=1,2,...,M

A_j = j th alternative, j=1,2,...,N

r_{ij} = estimated performance rating on i th attribute for j th alternative

R = MxN matrix of ratings r_{ij}

M = number of attributes or performance measures

N = number of program alternatives

Figure 6. Alternative/Attribute Matrix

ATTRIBUTES		ALTERNATIVE PROGRAMS			
		A_1	A_2	A_3	A_4
a_1	Security-Effectiveness	10	15	8	18
a_2	Cost	5.3	8.5	1.2	10.1
a_3	Implementability	HI	MED	HI	LO
a_4	Compatibility	HI	HI	HI	MED
a_5	Operability	2	2	1	3

Figure 7. Illustrative Alternative/Attribute Matrix: CPTED Decision Problem

SEVERITY VARIABLES	INCIDENT WEIGHTINGS*
Number of Victims of Bodily Harm	
Received Minor Injuries	1
Treated and Discharged	4
Hospitalized & Discharged	7
Killed	26
Number of Victims of Forcible Sex Intercourse	10
Number Intimidated by Weapon	4
Number Not Intimidated by Weapon	2
Number of Premises Forcibly Entered	1
Number of Motor Vehicles Stolen	2
Value of Property Stolen,Damaged,or Destroyed ($)	
Under 10	1
10 - 250	2
251 - 2000	3
2001 - 9000	4
9001 - 30,000	5
30,000 - 80,000	6
Over 80,000	7

*These are additive for each crime having any of these characteristics.

Figure 8. Sellin-Wolfgang Crime Seriousness Index

attribute cost, measured in $100,000, say, the relative desirability of the alternatives is judged A_3, A_1, A_2, A_4. For this attribute, A_4 now appears inferior. If we limit our analysis to just these two attributes, we see very graphically the ingredient that makes multi-objective or multiattributive decisionmaking so difficult. When a particular goal and its associated attribute are examined, it is clear that some alternative will be preferable, perhaps uniquely so, while other alternatives will become preferable when another attribute is considered. As the number of relevant attributes and proposed alternatives grows, the decisionmaking problem becomes increasingly less tractable for the decisionmaker: there are too many comparisons to make and the dimensions or attributes of comparison are incommensurable.

The illustration just given also points up several other aspects of the alternative/attribute matrix. The attributes need not be expressed exclusively in quantitative terms, although the need for ultimately doing so through scaling techniques will be a requirement of some of the decision aids presented next. Thus, the implementability and compatibility attributes of Figure 7 are measured by the three qualitative (*categorical* or *nominal*) ratings of high, medium, and low; there could have been more or fewer such categories of course. The initial performance estimates can also be rankings (i.e., *ordinal* rather than cardinal or nominal measures), as is the case for operability, where 1 might denote best on a scale of 1-to-4, etc. In short, all levels of measurement are admissible for the attributes, from qualitative (nominal-scale) to quantitative (ratio-scale), and ties in values among alternatives are also permitted. Were this not the case, there would be immediate conflict with the present state of the art in measurement of crime and environmental variables, as noted earlier.

4.3 Multiple-Attribute Decisionmaking Aids

The following approaches to multiattributive decisionmaking draw from methods which can be conveniently characterized by the extent to which they reduce the dimensionality of the original decision problem (23, 24). Referring to Figure 6, what this means is that if M attributes have been enumerated as being important performance measures by which to judge a CPTED alternative (e.g., M = 5 in Figure 7), then the original dimensionality of the decision problem is M. As elaborated previously, the complexity of the decisionmaking situation grows with M and the number of alternatives to be considered, N. As we shall see, some of the decision aids which we present deal directly with all M attributes, while others attempt to reduce the problem to some lesser dimensionality than M. Of course, since each attribute is important in its own right, it would be desirable to consider simultaneously and explicitly all M without imposing any assumptions to collapse them or without omitting any of them. Methods which do so however suffer from either not producing unique solutions to the decision problem (i.e., yield a single best alternative to implement), or from not sufficiently reducing the complexity of the original problem to the point where it becomes tractable (i.e., as measured by the number of attributes which remain to be considered). At the other end of the spectrum of methodologies, there are techniques which reduce the decision problem of M attributes to a single, composite dimension. These approaches either impose assumptions that permit the M dimensions (attributes) to be combined or mapped into a one-dimensional space, or impose conditions that remove M-1 dimensions from consideration. Between these two ends of the spectrum, we find methodologies which reduce the original complexity to something less than M, but greater than 1. We shall present methods according to this typology and in order of their complexity reduction, highlighting the assumptions and informational requirements of each. A mathematical synopsis of each technique is provided in Appendix A.

4.3.1 Multidimensional Methods

4.3.1.1 Dominance

One of the principal techniques for treating multiattributive decision problems in their full dimensionality, M, is called *dominance* (25). In this approach, as in all full dimensionality approaches, each attribute is sovereign or independent. That is, an alternative's performance estimate on each attribute must stand on its own, and an unfavorable value on one cannot be traded-off against a more favorable rating on another. All attributes must be examined separately and independently.

The esential idea underlying the dominance approach is that if in comparing all alternatives one has higher scores on all attributes, then that alternative is said to dominate the rest. Actually, we can relax this definition slightly by saying that an alternative dominates another if it is better on one or more attributes and at least as good on the others. We can illustrate this simple concept of dominance by changing some of the attribute scores of Figure 7 to those in Figure 9. If we recall that the most desirable operability score is 1 and that low cost is more favorable than high cost, then Figure 9 shows that alternative 2 strictly dominates alternative 1 since it is better on all attributes.* Hence the decisionmaker can drop A_1 from further consideration. We also note that A_3 dominates A_2, although it is not strictly dominant since there is a tie on the attribute a_1, security-effectiveness. The second alternative can therefore also be dropped from the list. Finally, we note that A_4 does not dominate A_3 nor is it dominated by A_3. While A_4 is strictly better than A_3 on attribute a_1 and a_2 (security-effectiveness and cost), it is inferior on attribute a_3 (implementability) and merely tied on the rest. Hence, both A_3 and A_4 remain for additional consideration; a unique solution is not obtained.

*To simplify the interpretation of Figure 9, either the signs of a_2 and a_5 could be made negative or the attributes could be redefined so that higher values are always preferable.

ATTRIBUTES		ALTERNATIVE PROGRAMS			
		A_1	A_2	A_3	A_4
a_1	Security-Effectiveness	10	15	15	16
a_2	Cost	5.3	4.9	4.5	4.4
a_3	Implementability	MED	MED	HI	MED
a_4	Compatibility	LO	MED	HI	HI
a_5	Operability	3	2	1	1

Figure 9. Illustrative CPTED Decision Problem: Dominance and Satisficing Approaches

This simple example illustrates the key advantage and principal defect of the dominance approach to decisionmaking. On the positive side, the concept is easily understood, applied, and accepted. The decisionmaker can proceed solely on the basis of one attribute value being preferable to another and does not require numerical information to establish this preference (e.g., high compatibility is better or preferred to medium). No trade-offs are forced on the decisionmaker either, for each attribute is examined independently. On the negative side, we see that dominance will typically be of limited utility because there will be a number of alternatives remaining in the original set after the method has been applied. In our example, two remain from the initial set of four alternatives and, therefore, the decisionmaker is faced with having to make a final choice between these two. Moreover, in the course of applying the dominance procedure, we do not get any information regarding a decisionmaker's degree of preference for a particular attribute score (e.g., how much more is high implementability preferred to medium, etc.). Nor do we explicitly factor in the relative importance of each attribute. Thus, we do not know how much high security is preferred to low cost, or how a difference in security ratings trades-off against a difference in cost, cost against implementability, and so on.

4.3.1.2 Satisficing

This approach also preserves the full dimensionality of the decision problem in that M attributes are separately and independently considered. As with dominance, the method has strong intuitive appeal and centers on a simple idea. The decisionmaker states the smallest attribute scores that will be acceptable on each attribute, in effect, supplying the minimum objectives or performance values corresponding to his program goals (26).*

As a concrete example, suppose the decisionmaker supplies the following M acceptability thresholds: security-effectiveness, at least 15; cost, no more than 4.75 (x $100,000); implementability, at least MED; compatibility, at least MED; operability, not to exceed 3 (i.e., not below third in rank). Referring again to Figure 9, we see that the first alternative can be dismissed either for failing to meet the security-effectiveness, cost, or compatibility criterion. Similarly, the second alternative can be dropped since it fails the second criterion, i.e., it is too expensive. The last two alternatives are both feasible, however, in that both meet all criteria. Consequently, the decisionmaker must consider these two further.

Again, this simple example allows us to distill some general features of this *satisficing* (or *sufficing*) approach. It shares with dominance the possibility of being left with more than one alternative

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*As before, if the attributes are not defined so that bigger is better, either such attribute's scores can be negated (multiplied by -1), the attributes redefined, or simply a ceiling rather than a floor type threshold on performance can be stated (e.g., largest or worst value tolerable for program cost).

at the conclusion of its application. In contrast to dominance, however, the remaining set of feasible alternatives can be reduced to one alternative by successively increasing the acceptability thresholds. This process of more restrictive filtering will eventually culminate in one feasible alternative, the one to be implemented. Alternatively, if the initial set of thresholds is too restrictive so that there are no feasible alternatives remaining, the acceptability criteria can be selectively lowered until one alternative just meets them all. It is this iterative flexibility which makes satisficing a more powerfull decision aid than dominance.

Satisficing has a number of advantages and drawbacks. On the positive side, we appreciate its strong intuitive appeal, as with dominance. It also enables us to consider each attribute on its own merits and to allow attributes to be expressed in nonnumerical form. We only need to know which values of an attribute are preferred (not necessarily the degree of preference) and do not need information on the relative preference of the attributes themselves. It also allows us to relate the scores to specific acceptability criteria. The latter quality, however, dictates higher informational needs for satisficing than for dominance, i.e., the M performance thresholds. On the debit side, we also note, in addition to the need for more data, that none of the alternatives is credited for especially good attribute scores since only minimum values (thresholds) are invoked in inspecting each attribute. Thus, in the example given, the third alternative appears slightly inferior on the security and cost dimensions but is not credited (in its comparison with alternative four, say) for its high score on implementability relative to the threshold placed on this attribute. While this conveys the basic idea of noncrediting, we hasten to add that, except for cost, which is directly quantified at the highest level of measurement (ratio-scale), we do not really know what the true distance is between high and medium on implementability, nor perhaps between 15 and 16 on the security-effectiveness scale (i.e., these may be only rank or ordinal-level measurements). As we shall see, the ensuing procedures help to overcome this defect by attempting to credit alternatives which have some exemplary scores.

It should be recognized that both dominance and satisficing are probably both used, at least implicitly, during the design stage, even if not elected as the final decisionmaking strategy. That is, in the course of synthesizing alternatives, the astute designer will undoubtedly mull over numerous tentative designs, discarding obviously inferior ones and attempting to enhance those designs that appear weak on some attribute he considers salient. However, the designer will be imputing his own subjective scores to these designs; he may not be dealing with the decisionmaker's attribute set, the decisionmaker's operational definitions of the attributes, and his performance standards may not be congruent with the thresholds which the decisionmaker eventually specifies. Of course, were the designer advised of all these or solicited them at the outset, and if his attribute scorings were to be adopted without inputs from other experts, then the design and decisionmaking functions could be combined. Typically, such a designer might proceed sequentially, stopping with the first design which just met or exceeded the imposed performance criteria, i.e., the designer would have found a solution to a particular CPTED problem. Practically, of course, the decisionmaker might be reluctant to place all this authority in the designer's hands or to forego seeing and choosing from an explicit array of program options.

4.3.2. Unidimensional Methods

Dominance and satisficing are the main procedures available for treating and preserving the full dimensionality of multiattributive decision situations. Their chief advantage stems from reducing the number of alternatives to be finally considered, since their application need not end with one feasible alternative. Dominance uses an alternative-alternative comparative approach, while satisficing employs an alternative-goal threshold approach. Although they are both weak in reducing the original set of alternatives to a unique choice, at least satisficing can be applied iteratively to mitigate this defect. The two approaches can be strengthened when used in concert with the unidimensional techniques which we shall now define.

The essential feature of all the unidimensional methods which we shall describe is that the M attributes characterizing any alternative are collapsed to a single dimension. The methods which do this can be further dichotomized. The first three approaches accomplish the unidimensionalization by electing one of the original M attributes as the one criterion. The remaining methods work by mapping the original M-dimensional attribute information into a single numerical scale.

4.3.2.1 Maximin

The maximin approach has its conceptual roots in the weakest link metaphor: to select a chain we identify the weakest link in each alternative chain and then pick the one with the strongest such link. In the present context, the decisionmaker examines each alternative's attribute values, identifies the lowest (worst) score for each alternative, and then chooses the alternative with the highest score in its worst attribute (27). Even this so-called *maximin* value and its associated alternative could be rejected, of course, if it did not exceed some performance threshold. The designers would then be banished to the drawing boards in the hope of improving the maximin alternative, or coming up with some even better new ones.

As we shall illustrate momentarily, the maximin procedure has as its principal disadvantage the need for a high degree of comparability within and across attribute values. This is because the procedure calls for not only comparing attribute values within an alternative, but also comparing the worst attributes across all alternatives. Since these worst attributes need not all pertain to the same attribute, as is usually the case, it is not clear how the best of the worst values is to be ascertained. Thus, maximin requires all attributes to be measured on a common, though not necessarily numerical, scale.

We can easily illustrate this need by again referring to Figure 9. Although it is hard to decide without the benefit of some common, explicit scale -- the very point we are trying to make -- it appears that the first alternative's worst attribute score is on the fourth attribute, compatibility, while for the second alternative, the worst appears to be associated with the last attribute, operability. Since the third alternative has maximum scores on its last three attributes, its weakest score must lie among the first two, let's say the first one, security-effectiveness. Similarly, the last alternative appears to have its weakest rating in the third attribute, implementability. Even if we accept these easily contestable conclusions, how are we to decide which is the best of these worst scores? How does the low score for A_1 on a_4 compare to the score of 2 for A_2 on a_5, to the score of 15 for A_3 on a_1, and the score of medium for A_4 on a_3 -- which of these is best and therefore which alternative should finally be selected?

To illustrate a successful application of maximin vis-à-vis Figure 9, we shall assume that the four attributes have been scaled from 0 (i.e., no security-effectiveness, maximum cost, poorest implementability, compatibility, and operability) to 100 (i.e., maximum security, zero cost, highest implementability, etc.). Without digressing into the fundamentals and intricacies of scaling for the moment, our scaling exercise might result in the values shown in Figure 10. For the first alternative, A_1, it is now clear that a_4 is the worst attribute since it has the lowest value among all the comparably scaled attributes. A_2's

ATTRIBUTES		ALTERNATIVE PROGRAMS			
		A_1	A_2	A_3	A_4
a_1	Security-Effectiveness	50	75	75	80
a_2	Cost	47	51	55	56
a_3	Implementability	50	50	90	50
a_4	Compatibility	10	50	90	90
a_5	Operability	30	45	90	90

Figure 10. Illustrative CPTED Decision Problem: Minimax and Maximax Approaches

worst attribute is a_5 with a score of 45. A_3's worst score is 55, on a_2, and A_4's worst rating is on a_3, with value 50. In effect, at this stage, we have replaced each alternative and its M attributes by a single attribute value: we have unidimensionalized each alternative. Finally, from this set of N poorest attribute or performance scores, we pick the one with the highest value, viz., 55. Since this is associated with the third alternative, the decisionmaker concludes that this is the program option to implement.

This example also highlights another deficiency of the maximin procedure, beyond the requirement of comparability. The method does not take advantage of all the available performance data in arriving at a final choice. As we observed, one attribute becomes the proxy for each alternative, all M-1 other attribute values having been discarded in the course of searching for the worst score. Ties, of course, have no effect in this regard, since only one such worst value gets recorded for the final runoff. Consequently, even if an alternative is exemplary in all but one attribute, another alternative which is only mediocre on all attributes would be chosen over it as long as its poorest value was better than the former's. The chain analogy is thus seen to be rather crude, for in the decisionmaking context, the attributes (links) are not really homogeneous in measure, they are not interchangeable in regard to their performance description roles, nor do they pertain to simultaneously acting program features.

4.3.2.2 Maximax

The *maximax* procedure is the reverse of the maximin method and shares all of its benefits and drawbacks as a decision tool. If maximin can be regarded as pessimistic or conservative in its selection approach, then maximax might be characterized as optimistic or liberal. The reason for this is that the procedure calls for identifying the best attribute value for each alternative and then selecting the alternative which has the highest of these best scores (28).

Returning to the scaled version of Figure 9 given in Figure 10, we observe that A_1's best attribute value is 50 (on both attributes a_1 and a_3). Similarly, A_2, A_3, and A_4's best scores are 75, 90, and 90, respectively. The best of this set of N (i.e., 4) highest scores is 90, a value shared by A_3 and A_4. Hence, either alternative could be implemented, which is consistent with the maximax criterion, or the tie could be broken by a reassessment of the attributes on which A_3 and A_4 scored the 90.

The comparability assumptions and the informational inefficiency which inhere in the maximax and the maximin methods restrict their utility as decision aids. The comparability assumptions and selection criteria also imply equal weighting of attributes and therefore uniform priorities vis-à-vis the goals which they reflect. Such indifference is not the usual state of affairs in CPTED, nor in many other decisionmaking contexts. This defect is addressed by some of the methods which follow.

4.3.2.3 Lexicography

The *lexicographical* procedure, unlike those described so far, assumes that the attributes by which the alternatives are to be judged are not necessarily of equal importance and can be ranked accordingly (29). It belongs to the class of unidimensional techniques in the sense that one attribute (dimension) is considered at a time, starting with the attribute which is predominant in importance. If one alternative has a higher attribute value on this most salient dimension, it is selected and the decision process terminates. If there are several alternatives which are tied on this maximal value, then the nonmaximal alternatives are discarded and the procedure continues by considering the next most salient attribute. Again, either a uniquely maximal value is found or the tied alternatives are retained and the remainder dropped in yet another iteration of the procedure. The screening process is repeated in this way until either a unique alternative is obtained or the least salient attribute has been examined. As necessary, any ties at this last stage can be broken by appending additional attributes of decreasing saliency to the original set.

Figure 10 offers a simple illustration of this straightforward technique. We assume that the M attributes have already been ranked in relative importance and that the rows of the alternative/attribute matrix reflect this ranking so that the first row attribute a_1 (security-effectiveness) is most important, the second row a_2 (cost) is next most important, ... , and the last row a_M (operability) is least important. According to the lexicographical procedure then, a_1 is to be considered first. This leads to the maximal attribute value of 80, possessed only by A_4. Therefore the procedure ends here and the fourth alternative is selected for implementation.

Through Figure 11, a slight variation on Figure 10, we can illustrate the potentially iterative nature of lexicography. In Figure 11, the maximal value on a_1 is still 80, but now A_2, A_3, and A_4 are tied on this predominant attribute. A_1 is discarded therefore, and we now consider attribute a_2. On this next most important attribute, a maximal value of 55 is shared by alternatives A_3 and A_4. Iterating once more, we delete A_2 from further consideration and move on to the third attribute. On a_3 the maximal value is 90. Since this value is uniquely possessed by A_3, the procedure terminates and the third alternative is finally selected.

Lexicography, like the other unidimensional techniques, does not require numerical information and has basically modest informational requirements. Although it requires ranking of the M attributes, these rankings need not be numerically expressed (i.e., qualitative inputs such as the following suffice: most important, next most, ... , least). Moreover, lexicography does not necessitate the comparability and numerical scaling across attributes that maximin and maximax do. These features, coupled with the intuitive appeal and simplicity of the technique, make lexicography particularly useful as a decision aid. Its major weakness, as we saw in regard to Figures 10

ATTRIBUTES		ALTERNATIVE PROGRAMS			
		A_1	A_2	A_3	A_4
a_1	Security-Effectiveness	50	80	80	80
a_2	Cost	47	51	55	55
a_3	Implementability	50	50	90	50
a_4	Compatibility	10	50	90	90
a_5	Operability	30	45	90	90

Figure 11. Illustrative CPTED Decision Problem: Lexicographical Approach

and 11, is that it too does not take advantage of all the information in the alternative/attribute matrix. The following techniques attempt to overcome this inefficiency.

4.3.2.4 Conjoint Analysis

Conjoint analysis is a unidimensional decision scheme in the sense that a single numerical performance index or figure of merit is derived for each alternative (30, 31, 32, 33). It has the advantage over lexicography in that all attributes are weighed in during the computation of an alternative's performance index. In order to do this, it is assumed that the decisionmaker can do more than merely rank the attributes in importance, as in lexicography. If the decisionmaker can actually attach a numerical measure of importance to each attribute, i.e., supply a set of saliency weights, then he can apply these weights to each alternative's attribute values. The alternative which obtains the highest weighted average for its performance score is then selected for implementation. Usually this best score will be unique.

Before we examine the assumptions underlying conjoint analysis and their practical implications, we shall illustrate the method using the data of Figure 12. This figure is identical to Figure 11 in the alternatives' attribute scores, but now we have appended a set of M weights, w_i, to the attributes which reflect their importance vis-à-vis the context of CPTED application. For convenience in deriving each alternative's overall performance index and in seeing directly the relative importance of the attributes implied by the w_i, a set of

ATTRIBUTES		WEIGHTS		RELATIVE WEIGHTS		ALTERNATIVE PROGRAMS			
						A_1	A_2	A_3	A_4
a_1	Security-Effectiveness	w_1	35	w_1'	.35	50	80	80	80
a_2	Cost	w_2	30	w_2	.30	47	51	55	55
a_3	Implementability	w_3	20	w_3'	.20	50	50	90	50
a_4	Compatibility	w_4	10	w_4'	.10	10	50	90	90
a_5	Operability	w_5	5	w_5'	.05	30	45	90	90
TOTAL WEIGHTS		W	100	W'	1.00				
OVERALL PERFORMANCE INDEX						44.1	60.6	76.0	68.0

Figure 12. Illustrative CPTED Decision Problem: Conjoint Analysis

relative weights, w'_i, is also displayed. These w'_i are simply obtained by dividing w_i by the sum of all the w_i (i.e., 100 for the illustration). Thus, the absolute importance of security-effectiveness and cost is 35 and 30, while their relative importance is 35 percent and 30 percent respectively. For any set of weights we compute the performance index of an alternative as either the sum of the products of the attribute weights and attribute values divided by the sum of weights, or more simply, as the sum of the products of the relative attribute weights and the corresponding attribute scores. Both yield the same result. Thus, for the first alternative in Figure 12, we obtain the overall performance measure of (35x50 + 30x47 + 20x50 + 10x10 + 5x30)/(35+30+20+10+5) = 44.10 or alternatively, (.35x50 + .30x47 + .20x50 + .10x10 + .05x30) = 44.10. By repeating this procedure for all N alternatives, we find that in this case the third alternative has the highest overall performance rating, 76, and therefore should be selected for implementation.

As we have just seen, the conjoint method does not disregard any of the attributes since all M attribute values are utilized to form each alternative's performance index. This is a key point of departure from the methods described so far. Because the index computations involve the arithmetic operations of multiplication and addition, the attribute values must be both numerical (ratio-scale) and comparable, the same restrictive conditions which prevailed in the maxi procedures. Thus, if cost were directly valued in dollars (e.g., $530,000 for alternative 1, \$850,000 for A_2, as given earlier), the weighted values for cost would completely swamp the weighted values contributed by the other attributes unless high scores on each of them had approximately the same numerical value (e.g., as in Figure 12). Moreover, the weights themselves require both a high level of measurement (ratio-scale, not just rankings) and a reasonable basis for their formulation. In the context of our example, the weights imply that cost is one and one-half times as important as implementability, and that cost is as important as implementability and compatibility combined. Although there are techniques for eliciting such weightings, the meaningfulness and confidence of such judgments may remain quite dubious.

Even after satisfactory weights have been established and the attribute values made numerical and comparable, other unpalatable implications may also remain. In our example, the relative weights for cost and operability are .3 and .05, respectively. A score of 15 on cost and 90 on operability would therefore contribute the same amount, 4.5, to the total performance index for any alternative having these attribute values. Yet 15 may be considered a very poor cost rating, while 90 may be an exemplary operability score (we recall that all attributes are scaled so that "bigger is better"). This implies that such poor and high scores may offset one another. But do poor cost features and exceptional operability actually trade-off; in fact, can such judgments be made? In general then, we see that one of the defects in conjoint analysis is that unacceptably low performance on one or more attributes may be masked by high weighted attribute scores on others. Conversely, high-weighted attribute scores may be severely diluted by several low-weighted attribute scores. This defect can be mitigated somewhat by first applying the satisficing procedure, thereby eliminating any alternative which does not meet minimum performance thresholds on each attribute.

Related to the trade-off and masking problem is the assumption that weighted attribute scores have independent, additive effects on total performance. Thus, conjoint analysis does not allow for any interaction effects or complementarities (either positive or negative) among attributes, since only a simple additive model is employed. For example, an alternative may be excellent with respect to security and cost scores, yet be of little value unless its implementability rating is at least average and its compatibility and operability scores are not too low. An alternative with less exemplary security and cost ratings may become a much more valuable candidate because its other attribute scores are all at average levels, thereby making the overall package considerably more meaningful. Of course, to the extent that attributes can be identified which behave essentially independently and which jointly reflect all the important qualities of a program alternative, then the additive weighting approach can be a powerful multiattributive decisionmaking tool, much as linear programming is in the world of mathematical optimization.

4.3.2.5 Performance Indices

The conjoint method just described entails an additive model for obtaining an overall numerical *performance index* for each alternative. This need not be the functional form of the index, however, and should not be if there are significant interaction (nonlinear) effects (34, 35, 36). Figures 13 - 15 suggest a number of other indices which combine attribute scores according to mathematical formulas more complex than the additive model. All of them require the same measurement and comparability of attribute scores as in the additive scheme described previously.

The first of these figures, Figure 13, illustrates a nonlinear model which appends to an additive component a nonlinear component involving multiplicative terms. In this case, the interaction terms simply consist of all distinct pairs of attribute scores (without regard to order) for an alternative and an associated set of weights u_{ik} or u_{ik}' in analogy to the weights w_i and w_i' for the linear component. The subscripts i and k in the weight u_{ik} pertain to the corresponding i^{th} and k^{th} attribute pair. A weight of zero implies no interaction between the associated attribute pair. In this formulation, therefore, the decisionmaker must supply both sets of weights w_i and u_{ik} for the additive and nonlinear components of the performance index P. When this is done, as illustrated in Figure 13, we see that calculation of P_j for each alternative A_j results in alternative 3 having the highest overall performance index (based on the same ratings of attributes r_{ij} and

MODEL: $$P_j = w'_1 r_{1j} + w'_2 r_{2j} + \dots + w'_M r_{Mj} + u'_{12} r_{1j} r_{2j} + u'_{13} r_{1j} r_{3j} + \dots + u'_{1M} r_{1j} r_{Mj}$$
$$+ u'_{23} r_{2j} r_{3j} + u'_{24} r_{2j} r_{4j} + \dots + u'_{2M} r_{2j} r_{Mj}$$
$$+ \dots + u'_{M-1,M} r_{M-1,j} r_{Mj} \qquad j=1,2,\dots,N$$
$$= \sum_{i=1}^{M} w'_i + \sum_{i>k=1}^{M} u'_{ik} r_{ij} r_{kj} \qquad w'_i = w_i \Big/ \sum_{i=1}^{M} w_i \qquad u'_{ik} = u_{ik} \Big/ \sum_{i>k=1}^{M} u_{ik}$$

ATTRIBUTES		RELATIVE WEIGHTS LINEAR COMPONENT	RELATIVE WEIGHTS: NONLINEAR COMPONENT a_1	a_2	a_3	a_4	a_5
a_1	Security Effectiveness	$w'_1=.35$					
a_2	Cost	$w'_2=.30$	$u'_{12}=.2$				
a_3	Implementability	$w'_3=.20$	$u'_{13}=0$	$u'_{23}=0$			
a_4	Compatibility	$w'_4=.10$	$u'_{14}=.1$	$u'_{24}=0$	$u'_{34}=.1$		
a_5	Operability	$w'_5=.05$	$u'_{15}=.3$	$u'_{25}=.2$	$u'_{35}=0$	$u'_{45}=.1$	

OVERALL PERFORMANCE INDEX	ALTERNATIVE
$P_1 = 1376.1$	A_1
$P_2 = 3290.6$	A_2
$P_3 = 6446.0$	A_3
$P_4 = 6078.0$	A_4

Figure 13. Illustrative CPTED Decision Problem: Nonlinear Performance Indices -- I

$$\text{MODEL:} \quad P_j = (r_{1j})^{w'_1}(r_{2j})^{w'_2}\ldots(r_{Mj})^{w'_M} = \prod_{i=1}^{M} r_{ij}^{w'_i j} \qquad j=1,2,\ldots,N$$

ATTRIBUTES	RELATIVE WEIGHTS	ALTERNATIVE PROGRAMS			
		A_1	A_2	A_3	A_4
a_1 Security Effectiveness	w'_1=.35	50	80	80	80
a_2 Cost	w'_2=.30	47	51	55	55
a_3 Implementability	w'_3=.20	50	50	90	50
a_4 Compatibility	w'_4=.10	10	50	90	90
a_5 Operability	w'_5=.05	30	45	90	90
OVERALL PERFORMANCE INDEX P_j		40.73	58.98	74.50	66.24

Figure 14. Illustrative CPTED Decision Problem: Nonlinear Performance Indices -- II

MODEL: $P_j = \sqrt{2\, r_{1j}\, r_{5j}}\, [\, 1 - e^{-r_{2j}/100}\,]\, r_{3j}^{.2}\ r_{4j}^{.1}\, (\, r_{5j} + 5\,)^{.05}$

ATTRIBUTES		ALTERNATIVE PROGRAMS			
		A_1	A_2	A_3	A_4
a_1	Security Effectiveness	50	80	80	80
a_2	Cost	47	51	55	55
a_3	Implementability	50	50	90	50
a_4	Compatibility	10	50	90	90
a_5	Operability	30	45	90	90
OVERALL PERFORMANCE INDEX P_j		67.5	133.3	245.9	218.6

Figure 15. Illustrative CPTED Decision Problem: Nonlinear Performance Indices -- III

weightings w_i used earlier in Figure 12).

Figure 14 demonstrates the effects on final choice of a completely nonlinear model, the model being multiplicative with respect to the M attribute scores rather than additive. Here the normalized weights, w_i', enter the model as exponents. Applying this performance model to the ratings and weights given in Figure 12, we see that alternative 3 obtains the best overall index.

The mathematical forms that can be devised are limitless. A final example will illustrate another dimension of this variety. In the two previous indexes, the weights w_i were explicit. This is not a general requirement however. Figure 15 shows an index in which the attribute weightings are implicit. Here the functional form and its associated parameters serve the same role as the formerly explicit weights. Applying this index to the ratings of Figure 12, we observe that the third alternative again obtains the highest index score.

All of these index schemes share the same attribute measurement and comparability assumptions as the conjoint method. While the more general index models illustrated here have the potential for embodying the interactions or complementarities (both positive and negative) of the attributes, the problem becomes one of identifying an appropriate mathematical formulation to reflect these interdependencies (the so-called identification or specification problem of systems theory). Of course, where logical relations between attributes are known or can be deduced, as in systems or operations analysis studies, the functional form of the performance index no longer remains arbitrary. Since this is rarely the case in social systems, the structure of the index will usually be subject to much judgment. Among such structures, decision-makers will probably prefer additive weighting to nonlinear models because of its easy comprehensibility, albeit a simplistic representation.

In concluding our discussion of numerical performance indices, it is important to note that cost/benefit and cost/effectiveness measures are subsumed by such indices. That is, if cost is identified as an attribute of importance and if either benefit or effectiveness (themselves attributes) can be measured in terms of levels of other attributes, then numerical performance indices can be defined such as the ratio of cost to effectiveness, the difference between benefits and cost, and so on.*

4.3.2.6 Utility Measures (Worth Assessment)

Utility theory or *worth assessment* is a decision methodology which represents a significant departure from the attribute-oriented approaches discussed so far. Instead of focusing on attributes per se, worth assessment examines the distribution or scope of possible outcomes for each alternative (37, 38, 39, 40, 41, 42). The multidimensional nature of the decision problem stems from the multiple real world events which can affect the level of an alternative's performance, or outcome, rather than the alternative's multiple attributes. Thus, the outcome for an

*A fuller discussion of cost/benefit and cost/effectiveness measures is provided elsewhere in the CPTED Program Manual.

alternative may change radically with the rate of criminal adaptation (e.g., in tactics, target, time, place, etc.), unemployment levels, the introduction of new patrol policy, drug abuse levels, etc., which ensue after program implementation. The essential feature of the utility approach is that it captures the probabilistic aspect of these so-called states of nature, and explicitly recognizes that the worth or utility of an outcome need not relate linearly to the level of the outcome (43).

In analogy to the attribute-oriented schema of Figure 6, Figure 16 shows the informational requirements for the utility approach. As before, the A_j represent the candidate alternatives, and the decision problem is to identify and implement the one which is best in some sense. The s_i represent various *states of nature,* i.e., descriptive statements about real world events or conditions which may prevail. Important events which may impinge on the effectiveness of an alternative may include, for example, criminal adaptation rate (fast, or less than one year; slow, or at least one year), unemployment level (under 5 percent, 5-8 percent, over 8 percent), institution (or not) of a new patrol policy (e.g., one-man patrol cars, 50 percent plainclothes patrol, etc.). Thus, if these were the only states of nature of major importance in regard to an alternative's outcome, there would then be 2x3x2 or 12 mutually exclusive and exhaustive states s_i to be considered, along with subjective assessments of each of their probabilities or likelihoods p_i.

Figure 17 illustrates how these states and their associated probabilities can be derived from a list of the random variables and

STATES OF NATURE	PROBABILITIES	ALTERNATIVES					
s_i	p_i	A_1	A_2	$\cdots$	A_j	$\cdots$	A_N
s_1	p_1	u_{11}	u_{12}	$\cdots$	u_{1j}	$\cdots$	u_{1N}
s_2	p_2	u_{21}	u_{22}	$\cdots$	u_{2j}	$\cdots$	u_{2N}
$\vdots$	$\vdots$	$\vdots$	$\vdots$		$\vdots$		$\vdots$
s_i	p_i	u_{i1}	u_{i2}	$\cdots$	u_{ij}	$\cdots$	u_{iN}
$\vdots$	$\vdots$	$\vdots$	$\vdots$		$\vdots$		$\vdots$
s_M	p_M	u_{M1}	u_{M2}	$\cdots$	u_{Mj}	$\cdots$	u_{MN}
EXPECTED UTILITY U_j		U_1	U_2	$\cdots$	U_j	$\cdots$	U_N

U_j = Expected Utility of jth Alternative = $\sum_{i=1}^{M} p_i \, u_{ij}$, $j=1,2,\ldots,N$

s_i = ith State of Nature, $i=1,2,\ldots,M$

p_i = Probability that s_i Occurs

A_j = jth Alternative, $j=1,2,\ldots,N$

u_{ij} = Utility (Worth) of jth Alternative in State s_i

Figure 16. Utility Assessment Schema: Utility Matrix

RANDOM VARIABLE	OUTCOMES/EVENTS	PROBABILITIES
Criminal Adaptation Level	E_1 : Fast (< 1 yr.)	$P(E_1) = .25$
	E_2 : Slow ($\geq$ 1 yr.)	$P(E_2) = .75$
Unemployment Level	E_3 : High (>8%)	$P(E_3) = .1$
	E_4 : Medium (5%-8%)	$P(E_4) = .7$
	E_5 : Low (<5%)	$P(E_5) = .2$
Adoption of New Patrol Policy	E_6 : Yes	$P(E_6) = .4$
	E_7 : No	$P(E_7) = .6$

Figure 17. Illustrative Decision Problem: Utility Assessment -- I

their uncertain outcomes. The only constraint in estimating or attaching probabilities to the levels of each random variable is that each probability be a number from 0 to 1 and that the probabilities sum to 1 over all levels of a particular random variable. Figure 18 illustrates the computation of the final joint probabilities corresponding to each state s_i (a mutually exclusive and exhaustive set of outcomes for the random variables) under the assumption that all the events are independent and that all the p_i are to be derived from subjective probabilities estimated for all the simple events such as fast adaptation, slow adaptation, etc. Of course, the p_i can be assigned subjective probabilities directly, as long as the decisionmaker obeys the same rules regarding the limits and sum of the p_i as for the more elementary events. Because of the large number of constellations of conditions making up the set of s_i, it is much easier to assign the subjective probabilities at the level of the individual random variables themselves and then derive the p_i for the states, as we have done in Figure 18 (this is especially easy when the events are statistically independent, as we have assumed).

The next step in the procedure involves using implicitly or explicitly the design criteria or attributes to estimate the overall level of effectiveness (not necessarily numerical) of each alternative for each state of nature. That is, we consider the effect of each possible real world event, should it occur, on the alternative as a whole. Assuming a utility function has been constructed which maps

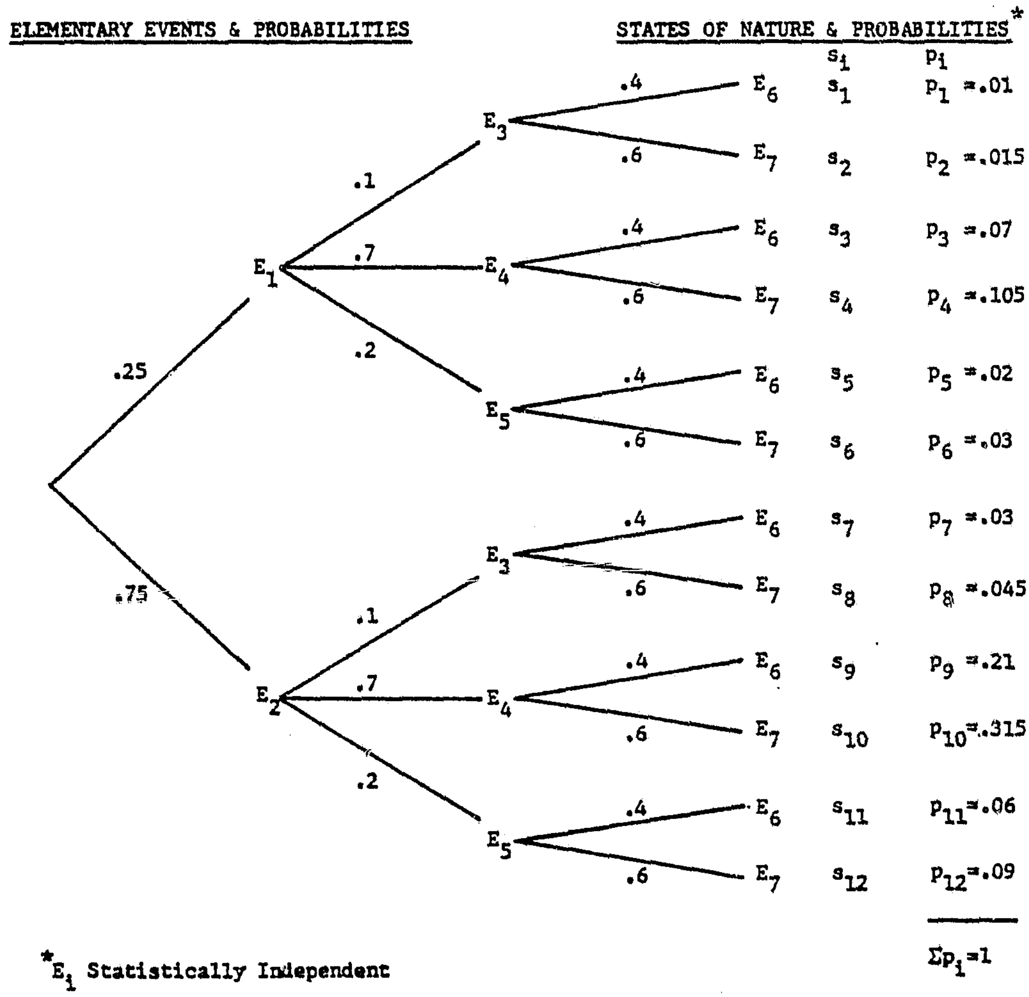


Figure 18. Illustrative CPTED Decision Problem: Utility Assessment -- II

these quantitative or qualitative outcomes into a numerical (interval level) utility or worth score, we can then assign a set of *utilities* u_{ij} to an alternative A_j operating under each assumed state of nature s_j.*

The final step involves a unidimensional scaling of the alternatives. A common measure used to accomplish this is to compute the expected utility corresponding to each alternative; i.e., to calculate the average worth associated with each alternative considering all the real world contingencies and their likelihoods. Figure 19 illustrates these computations. As we see, this culminates in the choice of alternative 4, since it yields the highest expected utility.

As we have just seen, the utility approach requires multi-dimensional information different from the other methods. This stems from treating the decision problem according to a different perspective; i.e., viewing impacts of alternatives as being dependent on uncertain real world contingencies with known likelihoods. Thus, the chief virtue of the method is its ability to explicitly account for and to directly cope with uncertainty in states of nature when the performance levels of the alternatives are otherwise reasonably certain and not too difficult to obtain. Toward this end, the decisionmaker must identify the states of nature, estimate their likelihoods, and derive a utility

*A number of systematic procedures are available for constructing utility functions (usually an S-shaped curve starting from the origin). Since the details and mathematical underpinnings are beyond the scope of this presentation, a rich set of references has been provided (44, 45).

STATE OF NATURE s_i	PROBABILITY p_i	ALTERNATIVES & UTILITIES A_1	A_2	A_3	A_4
s_1	.01	50	30	40	60
s_2	.015	40	50	60	40
s_3	.07	60	70	70	90
s_4	.105	30	45	65	70
s_5	.02	90	60	70	85
s_6	.03	55	55	75	65
s_7	.03	70	60	80	90
s_8	.045	30	55	65	85
s_9	.21	80	75	90	95
s_{10}	.315	45	90	65	90
s_{11}	.06	65	70	85	80
s_{12}	.09	75	45	95	25
EXPECTED UTILITY U_j		56.98	70.15	75.02	80.38
$U_j = \sum_i p_i u_{ij}$		U_1	U_2	U_3	U_4

Figure 19. Illustrative CPTED Decision Problem: Utility Assessment -- III

function (or functions) which maps the performance levels of alternatives operating under these states into degrees of utility or worth on an interval scale. Eliciting such probabilities and utility functions from decisionmakers is not an easy exercise. When the performance levels themselves are dependent on many factors or attributes, the method provides the decisionmaker with no direct assistance in dealing with this multidimensional form of complexity since the method itself is not attribute-oriented. The decisionmaker is left to his own devices in sorting out this information. Thus, the major contrast between the utility approach and the attribute-oriented methods is that utility puts applications context or contingencies in the foreground and program features or attributes in the background, while attribute schemes do just the opposite.

4.3.3 Intermediate Dimensionality

As we have seen, dominance and satisficing treat a decision problem in its full dimensionality while the other schemes presented thus far attempt by various means to compress the basically multiattributive nature of the decision problem into one dimension, the final composite measure of an alternative's performance. Between these two extremes lies the possibility for methodologies which represent an alternative's performance in a number of dimensions, k, greater than 1 and less than M, the original number of relevent attributes. One might consider, for example, a scheme which retained and treated separately the first three most salient attributes, ignoring the remaining M-3.

The dimensionality, k, of such an approach would therefore be 3. In general, any such procedure would have to address two sub-tasks: (1) Selection of the k dimensions or attributes to be considered and (2) determination of the best alternative based on these k dimensions.

4.3.1.1 Nonmetric Multidimensional Scaling

Multidimensional, *nonmetric scaling* is an approach to intermediate-dimensionality decisionmaking in the sense just described. While there are several variants of the method, we shall describe a particular scheme which displays most of the features of the other multidimensional scaling methods (46, 47, 48, 49). The basic theme in all of them is to derive the dimensionality of a set of complex alternatives, locate each alternative in that space, and compare each alternative to an ideal alternative located in the same space. If there is an alternative which is closest to the ideal on all dimensions, then it is selected as best. Since such simultaneity rarely occurs, the decisionmaker employs a composite measure which reflects the distance of each alternative from the ideal and then selects the one which is closest to the ideal according to the measure. As we shall see, while the level of measurement and computation necessary to accomplish this is relatively modest, the total number of inputs that the decisionmaker must supply can become unwieldy. The procedure which we shall examine takes nonmetric input information (i.e., ordinal preference for pairs of alternatives over all distinct pairs) and yields metric results (i.e., interval or ratio-scaled information on the proximities of a set of proposed alternatives to an ideal).

In order to deduce the k key dimensions underlying a set of alternatives, the procedure begins by having the decisionmaker or a panel of experts prepare a list of the principal attributes used in the decision problem and to indicate a range of values or to simply specify typical high, average, and low values for each attribute. From such lists, M attributes are selected on the basis of their highest frequency of mention as well as their relative independence. Although the final list must not omit any attribute considered crucial to the decision problem, there are no other assumptions regarding the relative importance or actual interdependence of the M attributes on the list.

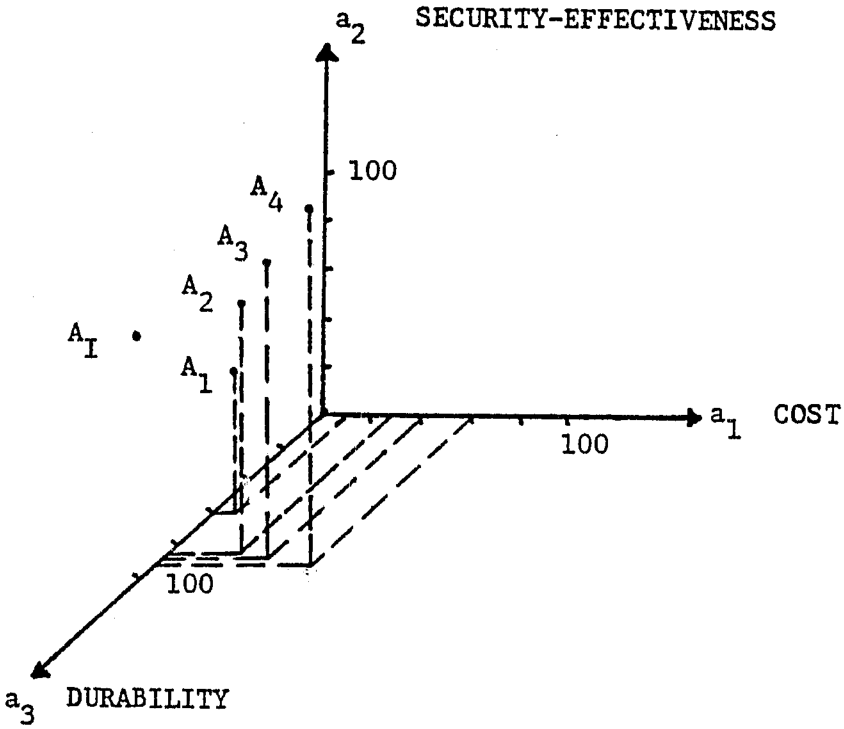
From the enumeration of attributes and values, the procedure goes on to fabricate a set of simulated or fictitious alternatives by systematically varying each attribute through all its values (e.g., generating 3M fictitious alternatives if each attribute is scored at typical low, average, and high levels only). Next, the decisionmaker is asked to judge the similarities of all distinct pairs of alternatives which can be drawn from the fabricated set (i.e., the $N(N-1)/2$ pairs A_1A_2, $A_1A_3, \ldots, A_1A_N$; A_2A_3, $A_2A_4, \ldots, A_2A_N$; $\ldots, A_{N-1}A_N$ wherein no alternative is paired with itself, nor is any pair such as A_1A_2 considered different from A_2A_1). The decisionmaker must therefore rank from highest to lowest similarity all such pairs, asking himself whether A_1A_2 is more alike than A_1A_3 and so on. To reduce ordering biases, the pairs themselves are presented randomly to the decisionmaker. To assist in ranking the typically large number of distinct pairs, the random pairs may be first assigned by the decisionmaker or panel to say one of eight different clusters, the first group containing pairs judged most similar, the second group, next most similar, etc. The final pass at ranking then involves ranking pairs within each cluster. As appropriate, some shifting of pairs between clusters is made so that the last pair in the first cluster is in fact judged more similar than the first pair in the second cluster, and so on. If a panel rather than a single judge is used, their judgements can be combined by averaging the ranks ascribed to each alternative pair. The degree of the judges' consistency in rankings can also be assessed using an appropriate correlational measure such as the Kendall coefficient of concordance.

The result of these initial steps is a measure of ranking of the perceived similarity of each fictitious alternative with respect to all others, a total of N(N-1)/2 rankings for N such alternatives. In effect, as in the earlier attribute-oriented schemes, we can picture each alternative as a point in an M-dimensional attribute space, with one coordinate axis for each attribute, and with one point on an axis for each level of that attribute. The more similar any two alternatives are, the closer they will lie in this space. In terms of the similarity rankings obtained for the N alternatives, it can be shown that the set of N(N-1)/2 rankings for any N alternatives can always be preserved in terms of the inverse interpoint distances in a space of N-1 dimensions.

That is, using N-1 coordinate axes, a configuration of interpoint distances for all alternative pairs can be found which correlates perfectly with the similarity rankings (i.e., the closer in similarity of two alternatives, the more proximate the locations of the alternative pair in space, with all such spacings being consistent with all the rankings). If the dimensionality N-1 of this space is sequentially reduced in unit steps to some value k less than N-1, then departures will occur from such a perfect fit between the similarity rankings and the corresponding interpoint distances. Using a goodness-of-fit or *stress* measure, we can construct such new spaces with fewer dimensions, the aim of *multidimensional scaling*, and measure their goodness-of-fit with respect to the original rankings (50). A stress of 0 indicates a perfect fit, while .05 is considered an excellent fit, and 1 corresponds to a complete mismatch. To the extent that the stress measure for these new configurations is not too high (e.g., above .10), we have then determined a less complex underlying set of dimensions which reflect the perceived similarities of the alternatives. As often happens, however, the coordinate axes corresponding to these lower dimensionality representations are not identical to the original M attributes and usually require familiarity with the problem or expert judgement to interpret their meanings.

The aforementioned steps answer the question of how many dimensions effectively underlie a decisionmaker's perceptions about the similarity of a set of complex alternatives. If this spatial representation adequately characterizes each alternative, then it can also be employed to identify which of N real proposed alternatives the decisionmaker most prefers. This final question is resolved in three steps. The first entails locating each of the N candidate alternatives in the previously derived space of k dimensions. Next, an *ideal* alternative is postulated and also located in this space; i.e., one whose attributes are all at the most desirable levels. The final step involves finding the distance, according to some acceptable metric, between the location of this ideal alternative in k-space and each of the N real candidate alternatives. This distance measure might be based on the so-called city-block metric (the sum of absolute displacements between candidate and ideal on each attribute), the Euclidean metric (the square root of the sum of squares of differences between candidate and ideal on each attribute), or some other such distance measure (e.g., other special cases of the so-called Minkowski p-metric) (50). Once chosen, the distance metric is computed for all N alternatives. The decision problem is then finally resolved by selecting the alternative which is closest to the ideal according to the distance measure used.

While it is beyond the scope of this presentation to describe the mathematical details or computer routines involved in finding the k dimensional configurations and their stresses, we can illustrate the basic idea and show how a distance measure can be applied to solve a complex decision situation. Figure 20 depicts the possible outcome for



ALTERNATIVE		COORDINATES	DISTANCE FROM IDEAL	
	A_j	(a_1,a_2,a_3)	CITY-BLOCK METRIC	EUCLIDEAN METRIC
	A_1	(10,50,60)	100	64.81
	A_2	(25,70,85)	70	41.83 *
	A_3	(40,85,87)	68 *	44.65
	A_4	(60,90,90)	80	61.64
IDEAL	A_I	(0,100,100)	--	--

Figure 20. Illustrative CPTED Decision Problem: Multidimensional Scaling

the aforementioned multidimensional scaling procedure. As in the earlier examples, we again assume that four hypothetical alternatives have been proposed. Since we can portray at most three dimensions, we also assume that the multidimensional scaling resulted in k=3 as the minimum number of relevant dimensions with reasonably good stress level (below .10). As Figure 20 indicates, the first two coordinate axes have been interpreted to correspond to security-effectiveness and cost, both original attributes that have not been transformed in any way by the multidimensional scaling. From the constellation of alternatives, it is inferred that the third axis appears to measure an alternative's durability, presumably a composite attribute reflecting what we earlier called implementability, compatibility, and operability. Having located an ideal alternative, A_I, as shown in Figure 20, we can now calculate the four distances between it and each of the proposed alternatives. Using a city block metric, we conclude that alternative A_3 is closest to ideal. Under the Euclidean metric, however, we conclude that A_2 is closest. Clearly, had we chosen to use the original M attributes or some subset of them, we could have employed the same distance measure to find the best alternative relative to an ideal without going through the initial steps of the multidimensional scaling prodecure; however, we would not have determined the possibly smaller set of attributes on which the decisionmaker's perception of best was founded.*

*This approach would then be equivalent to the nonlinear performance index scheme described earlier.

While illustrating the essential steps and concepts involved in the multidimensional scaling approach, this simple example glosses over several practical and conceptual difficulties. First, there is the need to identify a meaningful set of attributes and levels out of which to compose a simulated set of alternatives. These must be comprehensive or representative of the possibilities without becoming so unwieldy as to require a laborious number of paired comparisons. Second, in order to distill the underlying dimensionality of the decision problem, the decisionmaker must judge the similarity of N(N-1)/2 pairs drawn from the set of N simulated alternatives, a number of comparisons which grows exponentially (e.g., if N is only 15, there are 105 similarity judgements to be made). N itself can grow quickly. If, for example, there are thought to be M attributes with, say, only five levels each, then N = 5M. If M were only 5, as in our earlier examples, this would result in 25(25 - 1)/2 or 300 paired comparisons.

Apart from the gross magnitude of such an effort, the fact that the decisionmaker must rank the pairs for similarity calls for considerable discriminatory power and consistency in terms of the set of attributes he is really applying. We still know relatively little about the way individuals combine differences in pairs of objects over several dimensions so as to render overall similarity judgements. Moreover their models for doing so may change as the stimuli become more complex or greater in number (e.g., some dimensions may eventually be ignored as conflicting criteria arise or tedium sets in). There is also the assumption that the utility of an object or its preference is inversely proportional to its distance from an ideal and that the components that make up the distance metric can be simply added. The validity of averaging the rankings perceived by a set of judges may also be called into question. The distance measures discussed clearly imply that the underlying dimensions for the combined or average judge are independent or noninteractive. On the positive side, the procedure does allow the attribute information to be qualitative, rather than numeric, and it need not be comparably scaled across attributes as in most of the other unidmensional techniques. This is because the multidimensional scaling itself yields comparable, numeric scales on each of the k final dimensions. The computation involved, however, is usually not amenable to hand calculation as in the other approaches. Moreover, as in multiple factor analysis, these final k dimensions do not necessarily correspond to the M attributes originally used to construct the simulated alternatives. As illustrated, they may not therefore admit of easy interpretation or have any direct intuitive appeal.

4.4 Treatment of Uncertainty

In the preceding illustrations of the decision algorithms, we have assumed that each alternative was given a single attribute score on each attribute. As elaborated in the introduction to this section, the decisionmaker or experts who assign such scores are usually uncertain as to exact values. There are a number of ways to reflect this uncertainty in the attribute ratings. Depending on the approach adopted, some modifications may be necessary in applying the preceding decision schemes. As we shall discover, although the methods themselves do not change in any fundamental way, two problems emerge. First, the amount of computation involved, usually in the number of comparisons to be made, may increase. Second, and more importantly, the likelihood of being left with only one alternative at the conclusion of the modified procedures increases significantly.

Perhaps the simplest way of factoring in uncertainty in the attribute scores without changing the procedures at all is to let the actual score be some representative or *central value* in the underlying distribution. That is, the score actually assigned may be a measure of centrality such as the mode (most likely value), the median (the value which balances the series of possible values in the sense that the probability of an actual score being below the median is 1/2), or the mean (a balance point in the sense that the sum of squares of deviations in scores above the mean equals the sum of squared deviations below). Other so-called point estimates are also possible of course. Another possibility is to use an interval estimate, or range of scores, for each of the ratings (52). That is, we could state for each alternative and attribute a minimum and maximum score. Preferably, some probability statement would accompany these lower and upper bounds, thereby providing a *confidence interval estimate* for the attribute. Similarly, we could state a so-called 10-90 percentile range, such that scores falling below or above this range are each only 10 percent likely (53). Another common choice is the interquartile range. Here the bottom of the range is that value below which 25 percent of the scores would be expected to fall on the average, and the top range is that value such that there is a 25 percent chance of its being exceeded. Many other confidence interval estimates can be constructed along similar lines.

The dominance procedure is amenable to such range specifications. The extension is straightforward and may be carried out in several ways. In a stronger formulation of dominance, we could consider an alternative dominated if its upper range estimate on all attributes is exceeded by the lower range estimate for the corresponding attributes of some other alternative. A weaker form of dominance would entail pairwise comparisons of the corresponding maximum and minimum range values for each alternative. An alternative would be dominated if its extreme range scores were never better, but actually worse for at least one attribute vis-à-vis those of another alternative, again considering respective attribute pairs and all attributes. Clearly, the result of using range estimates would tend to exacerbate the problem of the dominance procedure's not providing a unique alternative at its conclusion.

The satisficing approach is also readily adaptable to range estimates. Here, we could consider an alternative unsatisfactory if one or more of its upper range attribute ratings were lower than

CONTINUED

1 OF 2

a prescribed threshold. While other definitions of satisficing are possible, the problem in using a criterion like this one is that, again, too many alternatives may remain at the conclusion of the procedure. This is because a best or optimistic (upper range) score is being employed to pass each attribute test, rather than a single most likely or some other typical attribute value.

The modification of the maximin and maximax procedures, while also straightforward, leads to somewhat more computational effort due to the larger number of necessary comparisons. Since each attribute is now given two extremal values, a new dimension is added to both the maximin and maximax approaches which results in several optional schemes for carrying them out. A conservative approach, for example, could entail using the lower or minimum range estimate for each attribute. This results in a *maximinimin* in the following sense. As in the ordinary maximin, we characterize or summarize each alternative by its minimum attribute score and then select the alternative which has the largest of these. In so doing, there is the extra step now of first minimizing across attribute scores for each attribute (i.e., assigning the lowest range estimate) and then minimizing across attributes within each alternative as before. In analogy to this, we could also develop a *maximinimax*, a *maximaximin*, or a *maximaximax* procedure. Clearly, just as the aforementioned maximinimin is much more pessimistic or conservative than the ordinary maximin, the maximaximax would be much more optimistic than the regular maximax.

The modification for the lexicographical scheme follows closely that for dominance. As before, after identifying the most salient attribute, we now simply reject any alternative whose upper attribute rating is exceeded by the lower range score for some other alternative. For this reduced set of alternatives, we repeat this procedure for the next most important attribute, and so on, until only one alternative is left or the last attribute has been considered. Here too, the use of extremal values rather than most likely values or other representative scores will probably lead us to examine more attributes in rank order than before and also heightens the chance of a non-unique alternative being left at the procedure's conclusion.

The conjoint and nonlinear index methods that we have described are not as amendable to handling uncertainty as the above techniques unless the scores used are simple point estimates (e.g., most likely values). The reason for this is the computational effort involved on the one hand, and the profusion of indices which result on the other. That is, if each of M attributes is considered at each of its two extremal values, we would obtain 2^M overall index scores instead of one for each alternative. Moreover, if the weights themselves are uncertain, as will likely be the case, then they would also be assigned range estimates. Thus, the total number of performance indices for all N alternatives would jump to $N\text{x}2^M\text{x}2^M$ or $N2^{2M}$ (e.g., for N=4 and M=5, as in our modest illustrations, we would have 4096 indices, or 1024 for each alternative). Apart from the need to generate all these, a process which could be expedited by a computer, we are still left with deciding which of the 2^{2M} index scores should represent each alternative. This underscores the virtues of the simpler decision schemes when uncertainty in attribute ratings is a feature of the decision context.

While the utility approach is designed to cope directly with uncertainty and need not be addressed further here, it should be recalled that the uncertainty is with respect to a set of contextual or real world contingencies and not directly in terms of the alternative's attributes. We shall also not consider further the multidimensional scaling approach as it too becomes extremely cumbersome when uncertainty is introduced.

4.5 Aggregation of Group Judgements

As we have seen, application of the preceding methodologies is not a purely mechanistic affair, nor is it likely to ever become so. It calls for considerable informed, responsible judgement with respect to identification of attributes, their operationalization, their ranking and scoring, the expression of uncertainty, explication of assumptions and limitations, and the corresponding selection of an appropriate decision aid. Failing such a careful, systematic approach to the choice and execution of a particular methodology, the results deserve a vote of no confidence. This is to be distinquished, however, from a healthy skepticism which stems from challenges of either the assumptions which have been made explicit, or the rationales which have been provided for the ratings and uncertainties ascribed to the alternatives' attributes.

While beyond the scope of the present treatment, the decisionmaker is advised that the formidable task of identifying superior alternatives in contexts as complex as social programming need not be a lonely one, nor is he bereft of complementary methodologies such as the Delphi method for eliciting and refining the judgments of assisting experts (54, 55). Toward this end, numerous references have been provided which probe more deeply the decision aids which we have presented.

5. Case Study

This section presents a case study to draw together the concepts and methodologies described earlier. The material stems from research done during 1970-71 under the auspices of the Mayor's Criminal Justice Coordinating Council of New York City (57). The research objective was to examine techniques for improving security in New York City Housing Authority buildings and to select one for implementation. The research phase involved several subtasks. First, crime patterns in the housing projects were analyzed from official police reports to determine the major threats to residential security. Next, a theoretical analysis was undertaken to develop criteria for judging the effectiveness and operational suitability of arbitrary security systems. This served as a basis for grading the effectiveness of 15 security alternatives that were synthesized from knowledge gained on criminality, security technology, and characteristics of the protected environment. These performance scores were finally coupled with cost estimates to ascertain the most cost-effective candidates for possible implementation. The following sections summarize the procedures used and the principal results.

5.1 Synthesized Security Alternatives

Analysis of the crime in public housing revealed that robbery, and especially robbery in elevators, ought to be the primary concern of a security improvement program. Because of the large incidence of burglaries, committed primarily by unskilled burglars, and because of the strong possibility that this crime could be reduced via tenant education and new, low-cost building hardware, burglary became the secondary focus of the study.

The set of security alternatives considered were broadly characterized by whether they primarily entailed tenant cooperation, physical security devices, or police/guard manpower. Because of their potentially long-term nature, or because of the difficulty in judging their effects, some potentially worthwhile measures in these three categories were not considered (a constraint imposed on the research team was to design alternatives that could be implemented within one year and which could provide significant performance information in a one-year trial). Concentration was on approaches which could reduce the opportunity and rewards for criminal activity, rather than on schemes which basically affected the desire or need to perpetrate crime or to be victimized.

The array of alternatives that were designed is summarized in Figure 21. The categories of alternatives were graduated in effectiveness and cost from a simple bell-buzzer/telephone intercom system, which offered little anticipated improvement over the existing security measures in the housing projects, to programs involving controlled building access, extended surveillance and monitoring of public areas, and increased police manning. The lowest cost options were of interest in that tenants expressed willingness to incur rent increases in support of construction and maintenance of such systems. The highest

SECURITY ALTERNATIVES AND ESTIMATED AVERAGE COST*				
I INTERCOM LOCKED LOBBY APARTMENT LOCKS	II HAPD PROJECT PATROLMAN	III CATEGORY I PLUS REMOTE GUARD SURVEILLANCE	IV CATEGORY I PLUS PERSONAL & APT. ALARMS	V CATEGORY I PLUS LOBBY GUARDS/POLICE
A_1 Intercom & Locked Lobby $2.65	A_7 Add 1 HAPD Officer per Project Full-time $5.44	A_8 Intercom, Exit Alarm, Apt. Door Armor, Full-time T.V. Lobby Surveillance by Remote Guard $6.20	A_{11} A_3 Plus Personal Transmitters, Burglar Alarms, Computer Monitoring Service $9.08	A_{12} A_9 But with Guard in Lobby One Shift $12.58
A_2 Phone Call-up & Locked Lobby $2.85		A_9 A_8 Plus Apartment Alarms to Guard Station $7.06		A_{13} A_{12} With Full-time Lobby Guard, Less Apt. Alarms $25.49
A_3 A_2 Plus Exit Alarm & Apt. Door Armor $3.08		A_{10} A_9 Plus Glass Guard Booth $7.08		A_{14} A_{13} Plus Apt. Alarms $26.35
A_4 A_3 Plus Deadbolt Chainlock $3.29				A_{15} A_{13} But with Full-time HAP in Lobby, Less Apt. Alarms $57.39
A_5 A_3 Plus Highly Resistant Vertical Deadbolt Lock and Cylinder $3.34				
A_6 A_2 Plus Alarm Lock $3.94				

*Dollars per apartment per month.

Figure 21. Description of Security Alternatives

cost options were interesting as theoretical benchmarks of security effectiveness, rather than as economically viable alternatives for security improvement (neither the tenants, whose average rent was then $70 per month, nor the Housing Authority could reasonably be expected to budget for such systems).

5.2 Security Program Effectiveness Ratings

In order to synthesize and judge the feasibility and merits of the specific plans for security improvement within the three mentioned categories, the study team closely collaborated with many experts, tenant groups, and agencies. Despite the heavy interaction with these groups and an extensive survey of the security literature, only a partial, qualitative characterization was possible of the threats, constraints, protective domain, and security alternatives (see also Section 3.4, Figure 2). In the absence of good predictors of security system effectiveness, as well as the quantitative inputs for such models, it was necessary to develop a heuristic decision scheme to obtain relative performance ratings for the 15 alternatives in Figure 21.

The following rating scheme (see also Sections 4.3.2.4 and 4.3.2.5) allowed the research team and a group of experts knowledgeable about security systems and the applications context to organize objective and subjective information into a ranking scheme for the security alternatives. The general schema is given in Figure 22. Before describing the specific application and results for the 15 alternatives, as summarized in Figure 23, the scheme will be elaborated.

PERFORMANCE RATING SCHEME FOR SECURITY ALTERNATIVES

Crime Types	Rating Percent	Desired Security Characteristics	Rating Percent	Security Alternatives and Ratings A_1	A_2	...	A_p
C_1	c_1	F_{11}	f_{11}	r_{111}	r_{112}	...	r_{11P}
		F_{12}	f_{12}	r_{121}	r_{122}	...	r_{12P}
		$\vdots$	$\vdots$	$\vdots$	$\vdots$		$\vdots$
		F_{1M_1}	f_{1M_1}	r_{1M_11}	r_{1M_12}	...	r_{1M_1P}
C_2	c_2	F_{21}	f_{21}	r_{211}	r_{212}	...	r_{21P}
		F_{22}	f_{22}	r_{221}	r_{222}		r_{22P}
		$\vdots$	$\vdots$	$\vdots$	$\vdots$		$\vdots$
		F_{2M_2}	f_{2M_2}	r_{2M_21}	r_{2M_22}	...	r_{2M_2P}
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$		$\vdots$
C_N	c_N	F_{N1}	f_{N1}	r_{N11}	r_{N12}	...	r_{N1P}
		F_{N2}	f_{N2}	r_{N21}	r_{N22}		r_{N2P}
		$\vdots$	$\vdots$	$\vdots$	$\vdots$		$\vdots$
		F_{NM_N}	f_{NM_N}	r_{NM_N1}	r_{NM_N2}	...	r_{NM_NP}

Figure 22. Performance Rating Scheme for Security Alternatives

ESTIMATED PERFORMANCE RATINGS FOR SECURITY ALTERNATIVES

Crime Types	Rating (percent)	Desired Security Characteristics	Rating (percent)	Security Alternatives Ratings[a]														
				A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9	A_{10}	A_{11}	A_{12}	A_{13}	A_{14}	A_{15}
1. Burglary Inside	24	1. Prevent Building Access	10	3	3	4	4	4	4	0	6	6	7	4	8	10	10	10
		2. Prevent Apartment Access	30	0	0	7	10	9	8	0	7	9	9	9	9	7	9	7
		3. Detect by Patrol or Surveillance	10	0	0	2	3	3	7	3	0	10	10	9	4	0	10	0
		4. Increase Crime Duration & Visibility	10	1	1	6	7	7	8	0	7	9	9	9	9	5	9	5
		5. Transmit Alarm Rapidly	10	0	0	1	1	1	2	0	5	8	9	8	8	9	10	9
		6. Respond Rapidly - Police/Guard	10	0	0	0	0	0	0	5	3	3	4	0	5	10	10	10
		7. Prevent Escape or Concealment	10	0	0	1	1	1	2	3	2	3	4	2	6	10	10	10
		8. Provide Identification Evidence	10	1	1	1	1	1	2	1	3	4	5	3	6	8	10	8
Subtotal Score/1000				1	1	9	11	11	12	3	11	17	18	15	18	18	23	18
2. Robbery Inside	76	1. Prevent Building Access	35	3	3	4	4	4	4	0	6	6	7	4	8	10	10	10
		2. Prevent Apartment Access	1	0	0	2	2	2	2	0	2	3	3	3	3	2	3	2
		3. Detect by Patrol or Surveillance	14	0	0	0	0	0	0	3	1	1	2	8	3	4	5	4
		4. Increase Crime Duration & Visibility	15	1	1	2	2	2	2	0	3	3	3	2	4	5	5	5
		5. Transmit Alarm Rapidly	5	0	0	1	1	1	1	0	5	5	6	8	8	9	9	9
		6. Respond Rapidly - Police/Guard	15	0	0	0	0	0	0	5	3	3	4	0	5	10	10	10
		7. Prevent Escape or Concealment	10	0	0	1	1	1	1	3	2	2	2	2	3	10	10	10
		8. Provide Identification Evidence	5	0	0	1	1	1	2	1	3	4	5	4	6	8	8	8
Subtotal Score/1000				9	9	15	15	15	15	12	29	29	35	28	43	62	63	62
Total Score/1000				10	10	23	26	25	27	14	40	46	53	43	60	80	86	80

[a]Ratings: 10 = most effective; 6 = good effectiveness; 3 = fairly effective; 0 = no improvement; -3 = detrimental; -6 = more harmful, and -10 = damaging.

Figure 23. Estimated Performance Ratings for Security Alternatives

The effectiveness ranking scheme itself is a linear performance index (see also conjoint analysis technique of Section 4.3.2.4) which comprises four steps:

(1) Description of the Threat/Security Domain

First, a list of the threats or crime categories which are to be treated is specified. Associated with each crime type C_i is a rating c_i which reflects the relative importance of crime C_i with respect to the total N crime types considered. As an illustration, C_1 might be burglary; C_2, elevator robbery; C_3, hallway robbery, etc. If these three crime types were the only ones to be considered, N would equal 3. The c_i themselves might reflect the Sellin-Wolfgang Serious Index (see also Section 4.2, Figure 8), or some subjective assignment. Thus, c_1 might be 50 percent for burglary; c_2=40 percent for elevator robbery; c_3= 10 percent for hallway robbery. In general, the value given to the c_i will be its percentage total importance so that the sum of the c_i is always 100; i.e.,

$$\sum_{i=1}^{N} c_i = c_1 + c_2 + \ldots + c_N = 100 \qquad N= \text{No. of crime categories}$$

Clearly, the values assigned to the c_i will depend on both available crime statistics for all N crime types (i.e., objective factors), as well as judgements about the magnitude of disbenefit incurred by each and all N crime types.

(2) Threat-Vulnerability Analysis

Next, an examination of the vulnerabilities in the existing (baseline) security system is made, employing the security criteria described in Section 3.4 and Figure 3. From these vulnerabilities, an enumeration of desirable security features (system or program attributes), F_{ij}, is made for each crime type C_i. For the i^{th} crime type, the total number of desired security characteristics is denoted by M_i. For example, for i=1, burglary, F_{11} might be ability to prevent ingress; F_{12}, enhanced lighting and crime visibility, etc.; for 1=2, elevator robbery, F_{21} might be building ingress limitation; F_{22}, increased elevator cab visibility, etc. As in step (1), a relative importance rating or weight f_{ij} is applied to each feature F_{ij}. Thus, f_{ij} is the percentage impact which factor F_{ij} in the security alternative contributes to the total resistance to crime type C_i. For any particular crime category, the M_i weightings f_{ij} will always sum to 100; i.e.,

$$\sum_{j=1}^{M_i} f_{ij} = f_{i1} + f_{i2} + \ldots + f_{iM_i} = 100 \qquad \text{For each } i = 1,2,\ldots,N$$

(3) Effectiveness Analysis

Third, each considered security alternative or proposed crime program is listed and denoted by A_k, where k is an index running from 1 to P, the total number of candidate programs. Figure 21 illustrates this notation. In analogy to the preceeding steps, each of these P alternatives is assigned a performance rating or score, r_{ijk}, which indicates on some arbitrary scale the estimated efficacy of the k^{th}

proposed alternative A_k in providing the j^{th} security feature (countermeasure) relative to the i^{th} crime type C_i. The numbers given to the r_{ijk} can be drawn from an arbitrary scale of, say, $-R$ to R, the negative numbers reflecting the possibility that a security measure that is productive in one crime context may be counterproductive in another.* Other aspects of the scaling and the aggregation of group judgments regarding the ratings r_{ijk} are discussed in Sections 4.3.2.4, 4.4, and 4.5. The security criteria presented in Section 3.4 (see also Figure 3) can provide useful guidelines for making the numerical assignments, especially when coupled with data on benefits and effectiveness drawn from experiences with similar crimes, security systems, and environmental contexts.

(4) <u>Performance Ratings</u>

Using the preceeding definitions, several individual and composite performance scores can be computed for each security alternative once the numerical assignments have been completed. Thus, the performance subtotal for the k^{th} security alternative A_k operating against the i^{th} crime type C_i can be calculated as T_{ik}, where

$$T_{ik} = c_i \sum_{j=1}^{M_i} r_{ijk} f_{ij} = c_i x(r_{i1k} f_{i1} + r_{i2k} f_{i2} + \ldots + r_{iM_i k} f_{iM_i})$$

Also, the total security performance score of the k^{th} alternative A_k

*Thus, if the value for R were chosen as 10, the scale would go from +10 to -10, with 10 indicating excellent; 6 good; 3 fair; 0 no change over baseline system; -3 detrimental; -6 more harmful; and -10, most damaging, for example.

operating against all N crime types C_i can be computed as T_k from the above subtotals as:

$$T_k = \frac{1}{100R} \sum_{i=1}^{N} T_{ik} = (1/100R)x(T_{1k} + T_{2k} + \ldots + T_{Nk})$$

The division by 100R provides a normalized score for T_k; i.e., each alternative's grand score falls in the interval (-100,100), independent of scale choice R.

Before combining the subtotals T_{ik} to form the grand totals T_k for each alternative, minimum acceptable performance levels should be set on the r_{ijk} ratings for each security criterion F_{ij}. Any alternative which does not meet these thresholds should be discarded from further consideration or redesigned accordingly. As elaborated in Section 4.3.2.4, the consolidation of individual, disparate scores T_{ik} into one overall measure may be misleading and mask the inevitably difficult trade-offs that must accompany the final selection of alternatives.

5.3 Composite Cost-Effectiveness Scores

The results of the cost and effectiveness analyses are summarized in Figures 21 and 23. The specific values for the performance subtotals and grand totals for the 15 security alternatives considered in the study are arrayed in Figure 23. As noted, these results reflect the average opinions and extant operational data derived from the agencies and security authorities who participated in the evaluative phase of the study. The decision aid just described provided the vehicle for blending these authoritative opinions, experiential judgements, and other subjective inputs with factual information derived from the growing body of knowledge on threat characteristics, causative factors, and the efficacy and cost associated with past efforts in crime control. The results of the preceeding rating exercise are of course limited by the extent and correctness of this knowledge. Toward improving such estimates, the ratings could be refined by a more carefully organized polling of authorities. Techniques such as the Delphi method for achieving this and attempting to derive a performance concensus are referred to in Section 4.5.

When the effectiveness scores T_k are combined with the cost estimates given earlier, ratios of effectiveness to cost can be calculated, in effect constructing a final nonlinear performance index (see also Section 4.3.2.5) by which to judge the security alternatives. Figure 24 shows the results of these effectiveness-to-cost computations in which the joint average effectiveness ratings for both burglary and robbery are represented (i.e., taken from Figure 23) and in which cost is expressed in dollars per apartment per month (from Figure 21). As indicated, the performance-to-cost ratios range from about 0 to 8, whereas the security system cost and effectiveness estimates individually vary by more than 10:1. Once a cost constraint is imposed (i.e., maximum dollar amount per apartment per month), the best security alternative can be easily identified from the figure. The line or envelope drawn in Figure 24 through the alternatives with the

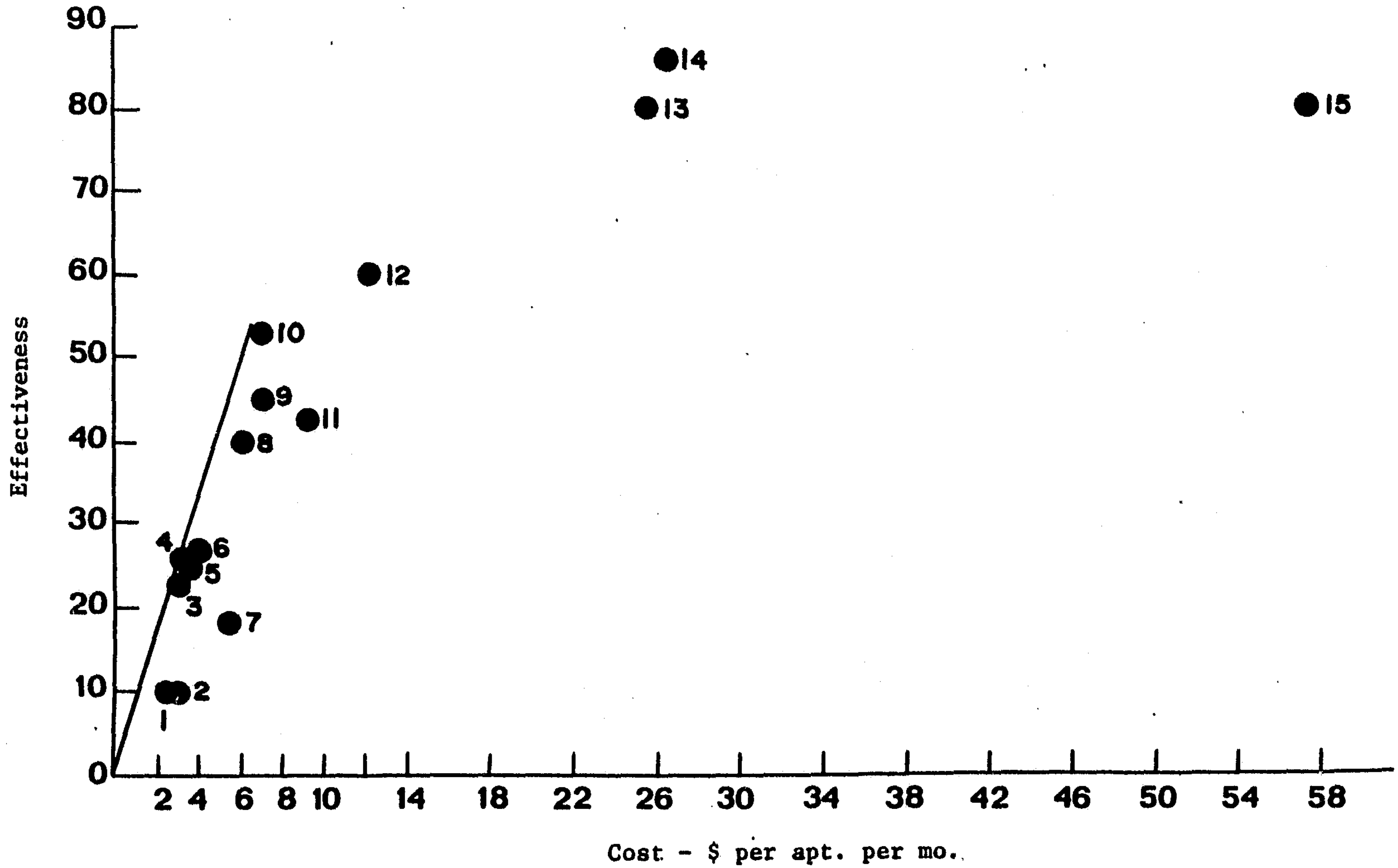


Figure 24. Average Effectiveness/Cost Ratios of Security Options

highest effectiveness at a given cost level can also be used to show which program alternatives are dominant. Any superior alternatives which are tied, or nearly so, can be subjected to more penetrating analysis, i.e., reiterating the cost and effectiveness analyses that led to the results of Figures 21 and 23.

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APPENDIX A

Mathematical Synopsis of Decision Aids

Appendix A: Mathematical Synopsis of Decision Aids

A.1 Introduction

The purpose of this section is to recapitulate the multi-attributive decision aids presented earlier, but with formal definitions and mathematical notation which will provide clarity, rigor, and conciseness beyond that given in the verbal descriptions. To further aid in the assessment of their relevance and practicality, assumptions will be restated along with informational needs and bounds on computational complexity. The reader who is unacquainted with the mathematics involved or doesn't find the formalities helpful can skip this section with no loss in conceptual understanding.

A.2 Preliminary Definitions

With respect to the alternative/attribute matrix of Fig. 4, let us define alternatives, attributes, and attribute scores as follows:

A_j = jth alternative, $j=1,2,\ldots,N>1$

a_i = ith attribute, $i=1,2,\ldots,M\geq 2$

r_{ij} = Estimated performance rating on ith attribute for jth alternative

R_j = Vector of performance ratings r_{ij} for alternative A_j

R = MxN matrix of performance ratings r_{ij}

M = Number of attributes (features, qualities, performance measures,etc.)

N = Number of proposed program alternatives (decision options)

V_i = Set of values which the ith attribute can assume

The set U of all possible alternatives which can be synthesized is then given by the Cartesian product of the V_i:

$$U = \{ \prod V_i = V_1 \times V_2 \times \ldots \times V_M \}$$

A particular set A of N alternatives A_j is thus a subset of U:

$$A \subset U$$

In turn, any particular alternative A_j is an element of A:

$$A_j \in A$$

A.3 Dominance

Consider the maximum number of pairwise comparisons $\binom{N}{2}$ or $\frac{1}{2}N(N-1)$ of alternatives A_j, A_k, $j \neq k$, without regard to order. For any pair A_j, A_k if $r_{ij} \geq r_{ik}\ \forall\ i$ and there is some $i = i'$ such that $r_{i'j} > r_{i'k}$, then A_j

dominates A_k and A_k is dropped from the original set A. Let S be the set of dominant A_j, A_{j*}, remaining after at most $M\binom{N}{2}$ such comparisons of alternatives and attributes, i.e.,

$$S = \{ A_{j*} \}$$

If n(S)=1, then the decision problem is resolved by selecting the corresponding unique A_{j*}. If n(S) $\neq$ 1, some other procedure must be applied to the set S to determine a final choice. The r_{ij} need not be of measurement level higher than nominal (categorical or qualitative) as long as the relative preference of the categories is known for each attribute.

A.4 __Satisficing (Sufficing)__

Let $L = (l_1, l_2, \ldots, l_m)$ be a vector of minimal attribute values (lower bounds) imposed on the set of attributes $\{a_i\}$ vis a vis their least acceptable values from among the sets V_i. We assume all attributes have been redefined so that larger r_{ij} are preferred to lower r_{ij}. A satisfactory alternative is then one for which $r_{ij} \geq l_i \ \forall\, i$. An unsatisfactory alternative is one for which there exists some i' such that $r_{i'j} < l_{i'}$. All such alternatives are dropped from the original set A. Let S^1 be the set of satisfactory A_j, A_{j*}, at the completion of the maximum MN comparisons, $R_j \geq L \ \forall\, j$:

$$S^1 = \{ A_{j*} \}$$

(1) If $n(S^1) = 0$, i.e., S^1 is empty, either design new alternatives or modify the threshold vector L to L^1 such that for some j, j* , $R_{j*} \geq L^1$ and $n(S^1) = 1$.

(2) If $n(S^1) = 1$, then the decision problem is resolved by choosing the unique corresponding alternative A_{j*}. At most, MN comparisons will be needed to complete this case.

(3) If $n(S^1) > 1$, then 2 or more A_{j*} have R_j which satisfy L. Let J^1 be the set of indices j* corresponding to the A_{j*} in S^1. Then if r_{ij*} corresponds to the ith attribute rating of A_{j*}, $j* \in J^1$, determine the set I^1 of attribute indices such that

$$I^1 = \{\min_i{}' \{ \min_{j* \in J^1} r_{ij*} \}\}$$

where min denotes minimization with respect to the domain of r_{ij*} values themselves and min' pertains to the members of the index set corresponding to the min r_{ij*}. This step requires at most $n(J^1)M(M-1)/2$ comparisons. Now increase the threshold of the attribute(s) with this index(es) so that

$$l_i > \min_i \min_{j*} (r_{ij*}) \quad , i \in I^1, \; j* \in J^1$$

Denote this new threshold vector L^2 and let the reduced set of alternatives A_{j*} which now satisfies L^2 be denoted S^2 and their subscript set, J^2. This requires $Mn(J^2)$ comparisons. If $n(S^2) = 1$, the decision problem is resolved. If $n(S^2) > 1$, determine the index set of attributes such that

$$I^2 = \{ \min_i{}' \{ \min_{j* \in J^2} r_{ij*} \}\}$$

and increase L^2 to L^3 so that

$$l_i > \min_i \min_{j*} (r_{ij*}) \, , \quad i \in I^2, \; j \in J^2$$

This procedure is repeated a maximum of M times. The informational requirements and level of measurement are the same as for dominance, plus the set of M thresholds comprising L.

A.5 Maximin

The maximin procedure assumes that the ratings r_{ij} derive from a scale common to all the attributes, although not necessarily numeric. The best alternative(s) then corresponds to the set S of A_{j*} given by

$$S = \{ A_{j*} \mid j* = \max_j{}' \{ \min_i \; r_{ij} \}\}$$

where max' pertains to the members of the index set corresponding to the maximum value(s) in the domain of maximization. That is, j* corresponds to the unique index, or to any one of the possible indices, for which $\max_j \min_i (r_{ij})$ is tied (max here used in the usual sense of the values r_{ij} themselves). If $n(S)=1$, then the corresponding unique A_{j*} in S is selected. If $n(S) \neq 1$, any of the tied A_{j*} may be selected. The sorting required to establish $\min_i r_{ij}$ need not require more than $NM(M-1)/2$ comparisons (i.e., using the transposition method). The sorting to establish $\max_j{}'$ need not require more than $N(N-1)/2$ comparisons. Hence, A_{j*} can be found through no more than $N(M^2-M-N-2)/2$ comparisons.

A.6 Maximax

All the data requirements, definitions, and computational bounds of maximin apply here. The best alternative(s) then corresponds to the set S of A_{j*} given by

$$S = \{A_{j*} \mid j* = \max_j{}' \{\max_i r_{ij}\}\}$$

A.7 Lexicography

Let the attributes be ordered in strictly decreasing importance so that $a_1 > a_2 > \dots > a_M$, there the symbol > denotes "more important than." Let J^1 be the original set of alternative subscripts $J^1 = \{1,2,\dots,N\}$. Let S^1 be the subset of $A = \{A_j\}$ given by

$$S^1 = \{ A_{j*} \mid j* = \max_{j \in J^1}{}' \; r_{1j} \}$$

(1) If $n(S^1) = 1$, the corresponding unique A_{j*} is selected. This requires $N(N-1)/2$ comparisons at most. Otherwise, denote the subscripts of the tied A_{j*} by J^2 and obtain S^2 as

$$S^2 = \{ A_{j*} \mid j* = \max_{j \in J^2}{}' \; r_{2j} \} \subset S^1 \qquad , J^2 \subset J^1$$

(2) If $n(S^2) = 1$, the corresponding unique A_{j*} is selected. This requires $n(J^2)[n(J^2) - 1]/2$ comparisons at most. Otherwise, denote the subscripts of the tied A_{j*} by J^3 and obtain S^3 as

$$S^3 = \{ A_{j*} \mid j* = \max_{j \in J^3}{}' \; r_{3j} \} \subset S^2 \qquad , J^3 \subset J^2$$

(3) If $n(S^3) = 1$, the corresponding unique A_{j*} is selected. This requires $n(J^3)[n(J^3) - 1]/2$ comparisons at most. If $n(S^3) \neq 1$, then iterate as above, continuing for at most M iterations.

A.8 Conjoint Analysis

Suppose we have a function which maps the set of M attributes $\{a_i\}$ into the corresponding set of real numbers or weights $\{w_i\}$. Then if the ratings r_{ij} derive from scales at the ratio-scale level of measurement and if these are scaled for comparability, then the most preferred alternative(s), A_{j*}, is any member of the set given by

$$S = \{ A_{j*} \mid j^* = \max_j{}' \{ \sum_{i=1}^{M} w_i' r_{ij} \} \} \quad \text{where} \quad w_i' = w_i / \sum_{i=1}^{M} w_i$$

If $n(S) = 1$, then the decision problem is resolved through the unique choice A_{j*}. If $n(S) > 1$, any one of the corresponding tied A_{j*} can be selected. The set of weights w_i may also be reconsidered in the context of the application to help derive a unique alternative A_{j*}.
The conjoint method requires 2M-1 arithmetic operations and N(N-1)/2 comparisons to determine the set S.

A.9 <u>Performance Indices</u>

Let the overall performance, P, be characterized by some function of the attributes a_i which are measured on a ratio-scale level and let the function's range be the real half-line $(0,\infty)$, i.e.,

$$P = f(a_1, a_2, \ldots, a_M) \quad , \; P \geq 0 \; .$$

For the jth alternative and set of attribute ratings $\{a_i = r_{ij}\}$, let A_j's performance be denoted as P_j where

$$P_j = f(r_{1j}, r_{2j}, \ldots, r_{Mj}) \qquad j=1,2,\ldots,N$$

Compute $P_j \; \forall j$. Then the best alternative A_{j*} is a member (usually unique) of the set S given by

$$S = \{ A_{j*} \mid j^* = \max_j{}' P_j \}$$

Conjoint analysis is a special case in which the function f is linear in terms of the a_i. The amount of computation involved in finding A_{j*} depends on the specific structure chosen for f.

A.10 <u>Utility Measures</u>

Consider M designated states of nature or real-world contingencies s_i, $i = 1,2,\ldots,M$ and N proposed alternatives A_j, $j=1,2,\ldots,N$. Let p_i be a set of probability measures over the s_i such that

$$\sum_{i=1}^{M} p_i = 1 \quad , \; p_i \geq 0 \quad \forall i \; .$$

Let u_{ij} be the worth or utility of implementing alternative A_j given that s_i actually occurs, where u_{ij} is some function of the attribute ratings r_{ij}, the ratings themselves possibly being subject to uncertainty and characterized by their own probability density functions or discrete distributions, i.e.,

$$p_{ij}(r) = f(r \mid A_j , s_i) \qquad i=1,2,\ldots,M \quad j=1,2,\ldots,N$$

Then the alternative to be selected as best is any member (usually unique) of the set S given by

$$S = \{ A_{j*} \mid j* = \max_j{}' \sum_{i=1}^{M} p_i u_{ij} \} .$$

A.11 <u>Multidimensional Scaling</u>

Let N' simulated alternatives be constructed by allowing each of the M original attributes (elicited from experts) to range over a set of specified typical values $S_i = \{ v_i \}$, $i=1,2,\ldots,M$ with $m_i = n(S_i)$ being the number of such values selected for the ith attribute. Thus,

$$N' = \sum_{i=1}^{M} m_i$$

Next, form all distinct pairs without regard to order from the set of N' alternatives, i.e., determine the set S of N'(N'-1)/2 pairs given by

$$S = \{ (A_j,A_k)_{j>k} \}$$

Let this set of pairs be ranked in similarity from 1 (the most similar pair A_j,A_k) to N'(N'-1)/2 (the least similar pair) by a single judge or a panel of P judges. Let r^i_{jk} be the rank given the j-kth pair by the ith judge. Form the average ranking of the j-kth pair, $\bar{r}_{jk}$, as

$$\bar{r}_{jk} = \frac{1}{P} \sum_{i=1}^{P} r^i_{jk}$$

and list the pairs (A_j,A_k) in order of their mean rankings $\bar{r}_{jk}$. Define the distance (i.e., Minkowski q-metric) between each such pair of alternatives as d_{jk} where

$$d_{jk} = \left[\sum_{s=1}^{K} \left| a_{js} - a_{ks} \right|^q \right]^{1/q} \qquad q \geq 1$$

in which a_{js} or a_{ks} is the attribute rating of the jth alternative, etc., with respect to the s th attribute (in the former procedures, these were referred to as the r_{si}) and where K is the dimensionality of the attribute space and q is any real number not less than 1 (e.g., when q=1, d_{jk} becomes the city-block metric; when q=2, d_{jk} becomes the commonly used Euclidean metric).

Next, we find the value of K such that the rank orders of the d_{jk} are congruent, or nearly so, to the rank orders of the (A_j,A_k) similarities (i.e., so that the goodness-of-fit or "stress" lies between 0 and .1).*

Now consider N real, proposed alternatives A_j and a postulated ideal alternative A_I positioned in this K-space. The coordinates of A_I will correspond to the K most desirable levels of the attributes on which this K-space is dimensioned (typically, the K axes are transformed versions of the original M attributes out of which the N' fictitious alternatives were fabricated). For the chosen value of q and corresponding distance metric, compute the distances d_{jI} between each of the N proposed alternatives A_j and the ideal A_I according to

$$d_{jI} = \left[\sum_{s=1}^{K} | a_{Is} - a_{js} |^{q} \right]^{1/q} \qquad j=1,2,\ldots,N$$

Then the best alternative A_{j*} is any member (usually unique) of the set S given by

$$S = \{ A_{j*} \mid j* = \min_j{}' \, d_{jI} \}.$$

* See Kruskal, J.B., "Multidimensional Scaling by Optimizing Goodness of Fit to a Non-Metric Hypothesis," Psychometrika, Vol. 29 (1964), pp. 1-27, for a definition of "stress," or Shepard, R.N., "The Analysis of Proximities: Multidimensional Scaling with an Unknown Distance Function," Psychometrika, Vol. 27 (1962), pp.125-140, for a development of a correlational measure for the $\bar{r}_{jk}$ and the d_{jk}.

APPENDIX B

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