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Qualitative multicriteria evaluation for environmental management

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Abstract

One of the main differences among evaluation models is between monetary and non-monetary evaluation. Cost–benefit analysis and cost-effectiveness analysis are well-known examples of a monetary evaluation. In the past decades the degraded state of the natural environment has become a key issue, and it is increasingly taken for granted that environmental and resource problems generally have far-reaching economic and ecological consequences. Economic-environmental evaluation and decision problems are conflictual in nature and, therefore, multicriteria techniques seem to be an appropriate modelling tool. This paper attempts to analyse in a critical way some essential aspects of multicriteria decision methods. In particular, the paper deals with uncertainty and measurement problems in environmental policy analysis, seen from the viewpoint of the measurement level of information (including fuzzy set methods). Particular emphasis will be placed on methods for concerted planning evaluation.

Key words: Cost–benefit analysis; Environment; Evaluation; Fuzzy sets; Multicriteria methods

1. Introduction

The growth of world population and the rapid growth of economic activity have caused environmental stresses in all economic systems, from the poorest to the very rich. Within the past two centuries the rise of industrialism has transformed the planet in ways that natural processes and previous civilisations would have taken many centuries to achieve.

The awareness of actual and potential conflicts between economic progress in production, consumption, and technology and the environment has led to the concept of "*sustainable development*".

The concept of sustainability already has a long history. The most widely accepted definition of *sustainable development* is the one given by the World Commission on Environment and Development (1987) where sustainable development is

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defined as paths of human progress which meet the needs and aspirations of the present generation without compromising the ability of future generations to meet their needs. [1]

According to Daly (1991), we can identify three main conflicting values of economics: allocation (efficiency), distribution (equity), and scale (sustainability). While an optimal allocation in theory could result from the individualistic marketplace, the attainment of an optimal scale (or at least any scale that is not above the maximum carrying capacity) requires *collective action by the community on a regional, national or international level according to the problems faced.*

The spatial issue can be examined from the viewpoint of local trends causing global effects (e.g., deforestation) and global trends leading to local effects (e.g., acid rain) (Nijkamp et al., 1991). The present paper focuses on the meso scale spatial dimension of environmental management. At this level of analysis, the concept of evaluation has a great importance.

2. Evaluation as a part of planning

The planning process has become a rather complicated matter in technical, physical, social and economic respects. In order to guide a decision-maker in choosing the most appropriate alternative, a set of rules is required to transform the facets of a certain planning proposal into statements about society's well-being. This set of rules is called an *evaluation method.*

Evaluation aims at rationalising planning and decision problems by systematically structuring all relevant aspects of policy choices (for instance, the assessment of impacts of alternative choice possibilities). Evaluation is usually not a one-shot activity, but takes place in all phases of decision-making (for instance, on the basis of learning principles). Besides, it has to be realised that the planning environment is usually highly dynamic so that judgements regarding the political relevance of items, alternatives or impacts may exhibit sudden changes, hence requiring a policy analysis to be flexible and adaptive in nature. Rigid evaluation techniques run the risk that an evaluation does not cover all issues of a planning problem in a satisfactory way (Nijkamp et al., 1990; Munda et al., 1993). Evaluation may be considered as a continuous activity that permanently takes place during the planning process. It is noteworthy that evaluation processes often have a cyclic nature. By "cyclic nature" is meant the possible adaptation of elements of the evaluation due to continuous consultations between the various parties involved in the planning process at hand. Such a learning process is a necessary condition to bridge the gap between technicians, researchers and planners. The degree of complexity of an evaluation process depends, among other things, on the evaluation problem to be treated, the time and knowledge available and the organisational context.

It should be noted that different kinds of evaluation can be distinguished in a policy analysis, one of the important discriminating characteristics being between monetary and non-monetary evaluation. *A monetary evaluation* is characterised by an attempt to measure all effects in monetary units, whereas a non-monetary evaluation utilises a wide variety of measurement units to assess the effects. Cost–benefit analysis and cost-effectiveness analysis are well-known examples of a monetary evaluation (Mishan, 1971; Dasgupta and Pearce, 1972; Pearce and Nash, 1989; Böjo et al., 1990). Multicriteria methods belong to the family of non-monetary evaluation methods.

According to Tinbergen (1956), it may be useful to make a distinction between the analytical aspect and the political aspect of public decision-making. *The analytical aspect* is concerned with links between all variables relevant in the decision-making process as well as with all side-conditions resulting from the economic, social and technological structure of society. This analytical aspect of a decision problem can in theory be

[1] For an extensive discussion on the concept of sustainability, see, e.g.: Goodland and Ledec, 1987; Lovelock, 1988; Barbier, 1989; Pearce et al., 1989; Pezzey, 1989; Archibugi and Nijkamp, 1990; Costanza, 1991; Daly, 1991; Folke and Kaberger, 1991; Opschoor, 1992; Wallace and Norton, 1992.

represented by a set of formal statements or an impact model (or structural model). *The political aspect* concentrates on the way in which the instruments should be manipulated to realise the policy objectives. These policy objectives can be operationalized as fixed targets to be strived for or as arguments of a community welfare function to be optimised. In particular the latter approach has received much attention in the literature about policy-making and in welfare economics.

The history of plan and project evaluation before World War II showed first a strong tendency towards a financial trade-off analysis. Later on, much attention was focused on cost-effectiveness principles. After World War II, cost–benefit analysis gained increasing popularity in public policy evaluation by using willingness to pay notions, consumer surplus principles and shadow prices. Social cost–benefit analysis can be regarded as an effective kind of applied welfare economics.

The social returns are composed of all gains and losses of all members of society whose well-being will be affected by the plan if implemented. These gains and losses are measured by the preferences of the individuals who are affected. The hypotheses underlying monetary evaluation methodologies took for granted rational choice behaviour based on a one-dimensional well-defined performance indicator. The use of such conventional optimisation models has been criticised from many sides. The optimising approach is based on the assumption that different objectives can be expressed in a common denominator by means of trade-offs, so that the loss in one objective can be evaluated against the gain in another. This idea of *compensatory changes* underlies both the classical economic utility theory and the traditional cost–benefit analysis. The determination of a common denominator is, however, fraught with difficulties. Interview methods frequently provide unsatisfactory results, while revealed preference methods are only effective as an ex post procedure. From a theoretical point of view, the optimising principle is very elegant, since it provides an unambiguous tool to evaluate alternative strategies on the basis of their contribution to community welfare. From an operational point of view, the value of the traditional optimising approach is, however, rather limited because the specification of a community welfare function requires complete information about all possible combinations of actions, about the relative trade-offs between all actions and about all constraints prevailing in the decision-making process.

Furthermore, in the past decades, the degraded state of the natural environment has become another key issue in evaluation because of the externalities involved, and it is increasingly taken for granted that environmental and resource problems generally have far-reaching economic and ecological aspects which cannot always be encapsulated by a market system. The estimation of a project lifetime, for instance, as well as of the social rate of discount is generally overloaded with uncertainties so that a cost–benefit analysis has to be accompanied at least by a sensitivity analysis. The limits inherent in conventional evaluation methodologies and the necessity of analysing conflicts between policy objectives have led to a need for more appropriate analytical tools for strategic evaluation (van Pelt, 1993).

3. Multicriteria evaluation in environmental management

Environmental management is essentially conflict analysis characterised by technical, socio-economic, environmental and political value judgements. Therefore, in an environmental planning process it is very difficult to arrive at straightforward and unambiguous solutions. This implies that such a multi-related planning process will always be characterised by the search for acceptable compromise solutions, an activity that requires an adequate evaluation methodology. Multiple criteria evaluation techniques aim at providing such a set of tools. Multicriteria methods provide a flexible way of dealing with qualitative multidimensional environmental effects of decisions. However, this does not mean that multicriteria evaluation is a panacea that can be used in all circumstances without difficulties; it has its own problems.

During the last two decades, it has increasingly been understood that welfare is a multidimensional variable that includes, inter alia, average income, growth, environmental quality, distribution equity, supply of public facilities, accessibility, etc. This implies that a systematic evaluation of public plans or projects has to be based on the distinction and measurement of a broad set of criteria. These criteria can be different in nature: private economic (investment costs, rate of return, etc.), socio-economic (employment, income distribution, access to facilities, etc.), environmental (pollution, deterioration of natural areas, noise, etc.), energy (use of energy, technological innovation, risk, etc.), physical planning (congestion, population density, accessibility, etc.) and so forth (Nijkamp et al., 1990).

In order to operationalize environmental management in a regional context, issues such as economic-ecological integration, multiple use, inter-regional spatial links and trade-offs and uncertainty are of a fundamental importance (van den Bergh and Nijkamp, 1991).

A proper use of multicriteria analysis presupposes the existence of an adequate environmental-economic model. It is increasingly taken for granted that environmental and resource problems have far-reaching economic and ecological implications, often of an unpriced nature. This implies that such problems are characterised, inter alia, by social, psychological, physico-chemical and geological aspects. Models aiming at structuring these cross-boundary problems of an economic and environmental nature are therefore called *"economic-environmental" or "economic-ecological" models* (Hafkamp, 1984; Braat and van Lierop, 1987). Since the complexity of this type of problem is high, there is a need for appropriate models offering a comprehensible and operational representation of a real-world environmental situation. The strong quantitative tradition in economics has enabled researchers to include environmental elements fairly easily in conventional models. Nevertheless, in integrating economic and environmental models some methodological problems have to be faced, such as *differences in time scales* (compared to ecology, economics is mainly analysing short-term and medium-term effects), *differences in spatial scales* (the spatial scale of many ecological variables is sometimes very small, whereas the scale of many economic variables is rather big) and *differences in measurement levels of the variables* (there is a clear need for methods taking into account information of a "mixed" type).

In designing models for environmental and resource policy-making, the following three main types of policy objectives may be distinguished (Braat and van Lierop, 1987):

(1) nature conservation objectives, e.g., "minimum exploitation of natural systems", "optimum yield";
(2) socio-economic objectives, e.g., "maximum production of goods and services at minimum (private and social) cost";
(3) mixed objectives, e.g., "maximum sustainable use of resources and environmental services".

It is clear that in policy-relevant economic-environmental evaluation models, socio-economic and nature conservation objectives are to be considered simultaneously. Consequently, multicriteria methods are, in principle, an appropriate modelling tool for combined economic-environmental evaluation issues.

Multiple use is the simultaneous use of natural resources for different social and economic objectives, e.g., a forest that is used for outdoor recreation as well as timber production at the same time. Three broad categories of use of natural resources can be identified: *consumptive use*, *non-consumptive direct use* and *non-consumptive indirect use.* The terms consumptive and non-consumptive use are employed in an ecological sense, i.e., they refer to the resource population (Braat, 1992). Consumptive use of a resource may, of course, lead to production in an economic sense, i.e., income may be derived from transforming the resource into a marketable product. This can be clarified by referring to the case of water resources management, the essential economic implication of the term "use" is that water is no longer suitable for subsequent desirable uses, and costs must be incurred before the water can be used again. If one type of use of a water supply creates quality deterioration partially or wholly precluding another potential use of the water, then the water has been used consumptively. An important aspect of this problem of water use compared to other economic resources is that water has a wide *quality dimension* and different qualities of water are required for different uses (Funtowicz et al., 1993).

Generally, ecosystems are used in several ways at the same time by a number of different users. This complies with the definition of multiple use. Such situations lead almost always to conflicts of interest and damage to the environment. The consequences range from suboptimal use due to unregulated access, to degradation of resource systems due to limited knowledge of the ecological processes involved. Thus, in the area of environmental and resource management and in policies aiming at an ecologically sustainable development, many conflicting issues and interests emerge. In real-world situations of public decision analysis two main cases can be distinguished (Stewart, 1991):

(1) *Broad Commonalty of Goals* (i.e., differences among parties are revealed through various trade-offs which they perceive to be most in their interest).

(2) *Direct Conflict of Goals* (i.e., a case where public policy involves an explicit division of resources among different sectors of the society or where attitudes have led to unreconcilable strong antagonism (e.g. environmentalists versus industrialists).

In the context of conflicting interests, it is also noteworthy that in environmental management there is often an interference from local, regional or national government agencies, while there is at the same time a high degree of diverging public interests and conflicts among groups in society. At an *intraregional level* many conflicting objectives may exist between different actors (consumers, firms, institutions, etc.) which can formally be represented as multiple objective problems and which have a clear impact on the spatial organisation of a certain area (e.g., industrialisation, housing construction, road infrastructure construction). At a *multiregional level* various spatial linkages exist that affect through spatial interaction and spillover effects a whole spatial system (e.g., diffusion of environmental pollution, spatial price discrimination), and which in a formal sense can be described by means of a multiple objective programming framework. At a *supraregional level* various hierarchical conflicts may emerge between regional government institutions and the central government or between regional branches and the central office of a firm, which implies again a multiple objective decision situation.

As a tool for conflict management, multicriteria analysis is then an important evaluation method, which has demonstrated its usefulness in many environmental management problems. *From an operational point of view*, the major strength of multicriteria methods is their ability to address problems marked by various conflicting interests. Multicriteria evaluation techniques cannot solve all these conflicts, but they can help to provide more insight into the nature of these conflicts by providing systematic information and ways to arrive at political compromises in cases of divergent preferences in a multi-group or committee system by making the trade-offs in a complex situation more transparent to decision-makers.

4. Qualitative information in environmental evaluation models

It has been argued that the presence of qualitative information in evaluation problems concerning socio-economic and physical planning is a rule rather than an exception (Nijkamp et al., 1990). Thus there is a clear need for methods taking into account qualitative information. In multicriteria evaluation theory, a clear distinction is made between quantitative and qualitative methods. The strong quantitative tradition in economics has enabled researchers to include environmental elements – measured in a cardinal metric – fairly easily in conventional models focusing on the interface of economics and the environment. However, qualitative aspects are harder to deal with in traditional models and, therefore, there is a clear need for methods that are able to take into account information of a "mixed" type (both qualitative and quantitative measurements). Another problem related to the available information concerns the uncertainty contained in this information. Ideally, the information should be precise, certain, exhaustive and unequivocal. But in reality, it is often necessary to use information that does not have those characteristics so that one has to face the uncertainty of a stochastic and/or fuzzy nature present in the data (Munda et al., 1993). If it is impossible to establish exactly the future state of the problem faced, a *stochastic uncertainty* is created. This type of uncertainty is well known; it has been thoroughly studied in probability theory and statistics. Another type of uncertainty derives from the ambiguity of this information, since in the majority of the particularly complex problems involving men, much of the information is expressed in linguistic terms so that it is essential to come to grips with the fuzziness that is either intrinsic or informational typical of all natural languages. Therefore, a combination of the different levels of measurement with the different types of uncertainty has to be taken into consideration. The following taxonomy can be useful (see Table 1).

Fuzzy uncertainty does not concern the occurrence of an event, but the event itself in the sense that it cannot be described unambiguously. This situation is very common in human systems. Spatial-environmental systems in particular are complex systems characterised by subjectivity, incompleteness and imprecision (e.g., ecological processes are quite uncertain and little is known about their sensitivity to stress factors such as various types of pollution). Zadeh (1965) writes: "as the complexity of a system increases, our ability to make a precise and yet significant statement about its behaviour diminishes until a threshold is reached beyond which precision and significance (or relevance) become almost mutually exclusive characteristics" (*incompatibility principle*). Therefore, in these situations statements such as "the quality of the environment is good", or "the unemployment rate is low" are quite common. Fuzzy set theory is a mathematical theory for modelling situations in which traditional modelling languages that are dichotomous in character and unambiguous in their description cannot be used. Human judgements, especially in linguistic form, appear to be plausible and natural representations of cognitive observations. We can explain this phenomenon by *cognitive distance.* A linguistic representation of an observation may require a less complicated transformation than a numerical representation, and therefore, less distortion may be introduced in the former than in the latter.

Table 1
Possible combinations of information measurement levels and uncertainty

	Quantitative information	Qualitative information
Certainty		
Uncertainty		

In traditional mathematics variables are assumed to be precise, but when we are dealing with our daily language, imprecision usually prevails. Intrinsically, daily languages cannot be precisely characterised on either the syntactic or semantic level. Therefore, a word in our daily language can technically be regarded as a fuzzy set.

Fuzzy sets as formulated by Zadeh (1965) are based on the simple idea of introducing a degree of membership of an element with respect to some sets. The physical meaning is that a gradual instead of an abrupt transition from membership to non-membership is taken into account. Let us assume that the symbol U means the entire set (Universe of discourse). In classical set theory, given a subset A of U, each element $x \in U$ satisfies the condition: either x belongs to A, or x does not belong to A. The subset A is represented by a function $f_A : U \rightarrow [0,1]$:

$$f_A(x) = \begin{cases} 1, & \text{if } x \in A, \\ 0, & \text{if } x \notin A. \end{cases} \quad (1)$$

The function f_A is called a characteristic function of the set A. Fuzzy sets are then introduced by generalising the characteristic function f_A. Let U again be a universe of discourse. Let $x \in U$. Then a fuzzy set A in U is a set of ordered pairs

$$\{[x, \mu_A(x)]\}, \quad \forall x \in U, \quad (2)$$

where $\mu_A: U \rightarrow M$ is a membership function that maps $x \in U$ into $\mu_A(x)$ in a totally ordered set M (called the membership set), and $\mu_A(x)$ indicates the grade of membership of x in A. Generally, the membership set is restricted to the closed interval [0,1]. A fuzzy set is completely determined by its membership function. For $0 < \mu_A(x) < 1$, x belongs to A only to a certain degree; thus there is ambiguity in determining whether or not x belongs to A. The physical meaning is that a gradual instead of an abrupt transition from membership to non-membership is taken into account. A classical example is that of age. Let U be the set of all non-negative integers. Let us take into consideration the primary terms young and old. These terms can be considered the label of two fuzzy sets A and B. No doubt the ages 6 or 10 are young, whereas the ages 30 or 40 are less young. Thus it is possible to define a membership function $\mu_{A\text{young}}$ showing the degree of compatibility of the age x to the concept of young.

Fuzzy information can be represented in decision models in two different ways:
- by using linguistic variables
- by using fuzzy numbers.

Both approaches will be discussed concisely in Sections 5 and 6, respectively.

5. Linguistic variables

Formally, a linguistic variable is represented by a quintuple $(X, T(x), U, G, M)$ (Zimmermann, 1986; Leung, 1988) where:
X is the name of the variable, e.g., age;
$T(x)$ is the term set of X, finite or infinite, such as young, very young and so on, in a universe of discourse U. A primary term in $T(x)$ is a term whose meaning must be defined a priori, and which serves as a basis for the computation of the meaning of the non-primary terms in $T(x)$;
G is a syntactic rule by which the non-primary terms in the term set are generated. It is possible to use a context-free grammar or a regular grammar; in G it is possible to find *primary terms*, *hedges* (not, very, more or less, etc.), *relations* (younger than, older than, etc.), *conjunctions* (e.g., and), and *disjunctions* (e.g., or). Thus computer implementation of such an approach presents a high degree of complexity and generally requires artificial intelligence oriented languages;
M is a semantic rule that associates each term with its meaning (a fuzzy subset in U). Through M, a compatibility (membership) function $\mu: U \rightarrow [0,1]$ is constructed (e.g., μ_{young} shows the degree to which a numerical age is compatible with the concept of young and equivalently μ_{young} may be viewed as the membership function of the fuzzy set young).

Therefore, a linguistic variable is a fuzzy variable whose values are fuzzy subsets in a universe of discourse. The base variable of the linguistic variable is a precise variable which takes an individual value in its domain, i.e., the universe of discourse U. The domain of the linguistic variable is the collection of all possible linguistic values, fuzzy sets defined in the same universe of discourse through the base variable. However, in some cases the fuzzy set which is assigned to the fuzzy restriction may not have a numerically-valued base variable.

In order to allow a formal analysis, a mathematical translation of such linguistic propositions is needed. This can be done by means of possibility theory (Dubois and Prade, 1980).

In the qualitative information available for an evaluation or decision model, two different types of linguistic variables may be present:
(1) the meaning can be translated in a measure on an interval or ratio scale (quantitative base variable), e.g., age, distance, etc.;
(2) there is no meaning on an interval or ratio scale and, therefore, the base variable is also qualitative in nature, e.g., appearance, comfort, beauty, etc.

6. Fuzzy numbers

A *fuzzy number* is simply a fuzzy set in the real line and is completely defined by its membership function such that

$$\mu(x): R \rightarrow [0,1]. \quad (3)$$

For computational purposes, this definition is restricted to those fuzzy numbers which are both normal and convex;

$$\text{normality: } \sup\{\mu(x)\} = 1, \quad \text{with } x \in R, \tag{4}$$

$$\text{convexity: } \mu\{\lambda x_1 + (1-\lambda)x_2\} \geqslant \min\{\mu(x_1),\mu(x_2)\}, \quad \text{with } x \in R \text{ and } \lambda \in [0,1]. \tag{5}$$

The requirement of convexity implies that the points of the real line with the highest membership values are clustered around a given interval (or point). This fact allows one to easily understand the semantics of a fuzzy number by looking at its distribution and to associate it with a properly descriptive syntactic label (e.g., "approximately 10").

The requirement of normality implies that, among the points of the real line with the highest membership value, there exists at least one that is completely compatible with the predicate associated with the fuzzy number.

A standard normal convex *trapezoidal fuzzy number* can be characterised by a 4-tuple (a, b, α, δ) where $[a,b]$ is the closed interval on which the membership function is equal to 1, α is the left-hand variation and δ is the right-hand variation. If only one point in the real line with $\mu(x) = 1$ exists, the fuzzy number is called a *triangular fuzzy number*.

A more general type of fuzzy number is the *L-R fuzzy number*; it is defined as follows:

$$\mu_A(x) = \begin{cases} F_L(x-m)/\alpha, & \text{if } -\infty < x < m,\ \alpha > 0 \\ 1, & \text{if } x = m \\ F_R(x-m)/\delta, & \text{if } m < x < +\infty,\ \delta > 0 \end{cases} \tag{6}$$

where m, α, δ are the "middle" value, the left-hand and the right-hand variation, respectively. $F_L(x)$ is a monotonically increasing membership function and $F_R(x)$, not necessarily symmetric to $F_L(x)$, is a monotonically decreasing function. If a closed interval on which the membership function is equal to 1 exists, it is called a *flat fuzzy number*.

In the next section we will pay attention to multicriteria analysis, in order to provide a platform for incorporating fuzzy sets in evaluation methods.

7. Multicriteria evaluation: a concise overview

During the 1970s and at the beginning of the 1980s, a great number of multicriteria methods were developed and used for different policy purposes in different contexts (Roy, 1985; Vincke, 1989; Bana e Costa, 1990a; Nijkamp et al., 1990).

In general, a multicriteria model presents the following aspects:

(1) There is no solution optimising all the criteria at the same time and, therefore, the decision-maker has to find *compromise solutions*.

(2) The relations of preference and indifference are not enough in this approach because when one action is better than another for some criteria, it is usually less better for others, so that many pairs of actions remain incomparable.

A multicriteria evaluation problem can be tackled by means of the following steps:

(1) definition and structuring of the problem
(2) generation of alternatives
(3) choice of a set of evaluation criteria
(4) identification of the preference system of the decision-maker
(5) choice of an aggregation procedure

7.1. Problem definition

The results of any decision model depend on the available information; since this information may assume different forms, it is useful that decision models can take them into account. But it has to be noted that this available information depends on the problem definition phase, which briefly may be described as the process by which data are transformed into information; where *information* may be defined as a "collection of organised data (for instance, by means of statistical techniques, modelling or transformation) so as to provide structured and systematic insight regarding a phenomenon" (Nijkamp et al., 1990). According to systems methodology, such a process may be synthesised in the following hierarchy of epistemological levels of systems (Klir, 1969; Cavallo, 1979):

- *source systems* (all possible data that may be gathered)
- *data systems* (measurement of all variables)
- *generative systems* (relations among variables)
- *structure systems* (simplified representation of the whole system)
- *metasystems* (changes in time and space of the structure system)

The following considerations may be made:

(1) The information used as input for decision models may be handled and structured in different ways; therefore, a subjective component is always present.

(2) It is generally accepted by the scientific community that the performance of each particular MCDA method is context dependent and that the model must fit real-world problems as closely as possible. It must be noted that in decision problems, in a last analysis, "reality" is the result of the problem definition phase. Furthermore, it is not exact to assume that between the problem definition phase and the choice of the model there is a pure relationship of causality. In fact, often the two phases are deeply interrelated (e.g., sometimes the same problem may be formulated both in continuous and discrete terms, and then the problem definition phase depends on this choice).

7.2. Generation of alternatives

The number of alternatives may vary between 1, any discrete number and infinity. The problem with only one alternative is essentially a 0–1 choice system, in which a choice has to be made between the status quo and a new situation.

7.2.1. Continuous methods

The main characteristic of multiobjective programming methods is that the feasible alternatives are only implicitly defined, so that in principle, their number is infinite. This problem has been analysed by various authors who have developed a large number of theorems and algorithms (Steuer, 1986).

An important concept is that of *Pareto solution* (or non-dominated solution). A Pareto solution is based on the characteristic that the value of an objective function cannot be improved without reducing the values of the other objective functions.

A multiobjective programming method can be divided into two phases:

(1) generation of the set of efficient solutions
(2) exploration of this set in order to find a "compromise solution" by means of interactive procedures (see below).

7.2.2. Discrete methods

A discrete multicriteria problem may be described in the following way: A is a set of feasible actions (or alternatives); m is the number of different points of view or evaluation criteria g_i, $i = 1,2,\ldots,m$, considered relevant in a decision problem, where $g_i : A \rightarrow R$, $\forall i = 1,2,\ldots,m$ is a real valued function representing the ith criterion according to a non-decreasing preference, while the action a is evaluated to be better than action b (a, $b \in A$) according to the ith point of view iff $g_i(a) > g_i(b)$.

In this way a decision problem may be represented in a tabular or matrix form. Given the sets A (of alternatives) and G (of evaluation criteria) and assuming the existence of n alternatives and m criteria, it is possible to build an $n \times m$ matrix P called evaluation or impact matrix whose typical element p_{ij} ($i = 1,2,\ldots,m$; $j = 1,2,\ldots,n$) represents the evaluation of the jth alternative by means of the ith criterion. The impact matrix may include qualitative, quantitative or both types of information.

This general description implies that evaluation problems may lead to different kinds of outcomes; for instance, some methods only aim at determining a set of acceptable alternative solutions while other methods aim at the selection of one ultimate alternative.

7.3. Choice of a set of evaluation criteria

In choosing a set of evaluation criteria, two main tendencies can be distinguished. On one hand, one may wish to build a decision model as close as possible to the real-world problem; this may increase the number of evaluation criteria to a level such that its applicability becomes almost impossible. On the other hand, one may wish to use a small number of criteria so that the model is simpler and faster to use; this may bring to an oversimplification of the model used.

However, a family of criteria must also satisfy a number of technical properties, leading to the concept of a *consistent family of criteria* (Roy, 1985).

7.4. Identification of the preference system of the decision-maker

The main approaches by which subjectivity is taken into account in MCDA models are two:

7.4.1. Weighting of criteria

The main advantage of this procedure is its simplicity since the weighting of criteria takes place before the utilisation of the model, so that once the weighting of the different criteria has been established, the analyst may proceed towards the solution of the problem. In discrete MCDA problems, there are several procedures aiming at obtaining the decision-maker's priorities in the form of weights. All these methods present different features in terms of time needed, complexity, transparency, etc., and, therefore, their performance depends on the specific problem faced. But in general, the weighting of criteria is open to criticism for the following reasons:

1. An abstract hypothesis is when the decision-maker has a clear idea in his mind of his own scale of preferences, and he is capable of expressing these clearly without contradiction, while concretely, the logic of the choice assumes a reduction of the confusion inevitably present in the mind of the decision-maker when he is about to face a problem (Munda, 1993).
2. Another important point concerns the interpretation of the meaning of the weights supplied by the decision-maker. Weights are used to refer either to "scaling factors" or to "coefficients of importance". Such a meaning is strictly connected to an important discriminant feature of multicriteria methods, i.e., the concept of *compensation* (Bouyssou, 1986; Vansnick, 1986; Vincke, 1989).

In the case of non-compensatory methods, the intercriteria information required is a relation of relative importance between coalitions of criteria. Such a concept of relative importance is often translated into numbers called weights.

In the case of compensatory methods (e.g., weighted sum) the weights must be considered as scaling factors and then their meaning is of a trade-off ratio.

The above considerations imply that given an aggregation procedure, there should be consistency between the aggregation procedure used and the questions asked of the decision-maker in order to elicit a set of weights. Otherwise, one runs the risk of combining weighting techniques with aggregation models with which they are not theoretically compatible. Even if the weights are elicited in a well-defined and consistent procedure, it may be that such weights are not precisely determined. In such cases two solutions are possible:

- sensitivity analysis aiming at verifying (by means of different vectors of weights) the robustness and stability of the results obtained with the initial vector of weights. But as has been noted, "one has to recognise that this procedure does not directly and specifically deal with imprecise weights, being only, a way of bypassing the problem" (Bana e Costa, 1990b);
- procedures aiming at directly facing situations of poor weighting information (e.g., the expected value method (Rietveld, 1989); Outweigh Analysis (Bana e Costa, 1990b); Regime Analysis (Nijkamp et al., 1990)). A common problem with this kind of procedure is that strong assumptions need to be made for their correct axiomatization.

3. In cases of group decisions, it is often an impossible task to establish a weighting of the different criteria that satisfies all the decision-makers. For this reason, Roy, after the experiment regarding the building of the Paris underground network in ELECTRE IV, decided to eliminate the weighting of criteria.

7.4.2. Interactive procedures

Interactive procedures, since they are useful in order to explore the efficient frontier, are typical of those models that operate in a continuous context, although they exist also in some discrete models. Unlike the criterion weighting process, the closest collaboration between decision-maker and analyst occurs in interactive procedures when the model has already been put to use. The interaction process can rely on the following types of phases:

- search for a candidate for a compromise solution
- communication to the decision-maker
- reaction of the decision-maker

Interactive procedures have several benefits. They provide information to the decision committee in a stepwise way; they can easily be included in a dynamic decision environment; they lead to an active role of all participants involved; and a priori specification of preferences or weights is not strictly necessary, although they can be inferred ex post. A limitation of this approach is that the final solution can depend on the procedure followed and especially on the starting solution. In addition, for several continuous evaluation methods there is no guarantee that the compromise solution can be obtained within a finite number of interactive cycles, unless it is assumed that the decision committee is acting in a consistent way.

7.5. Choice of an aggregation procedure

The choice of an aggregation procedure is a fundamental step for the decision problem faced. In fact, the results obtained mainly depend on the aggregation procedure used. The main aggregation procedures are:

(1) utility-based models (Keeney and Raiffa, 1976)
(2) outranking methods (Roy, 1985)
(3) the lexicographic model (Fandel et al., 1983)
(4) ideal point approaches (Zeleny, 1982; Yu, 1985)
(5) aspiration levels models (Spronk, 1981; Wierzbicki, 1982)

7.6. Decision support in multicriteria decision aid theory

The main advantage of these models is that they make it possible to consider the large number of data, relations and objectives (often in conflict) that are generally present in a specific decision problem, so that the problem can be studied from every aspect.

The main disadvantage of a multicriteria model is that an action *a* may be better than an action *b* according to one criterion and worse according to another, thus since different conflicting evaluation criteria are taken into consideration, a multicriteria problem is mathematically ill-defined. The consequence is that a complete axiomatization of multicriteria decision theory is very difficult (Arrow and Raynaud, 1986).

In these cases the following attitudes are unproductive:

(1) to leave the decision-maker entire liberty for the decision,
(2) to introduce, consciously or not, restrictive hypotheses, so that the problem can be solved by a classical method.

The methods used in multicriteria analysis lie between these two extremes: they are based on models constructed partly from necessarily restrictive mathematical hypotheses, and from information gathered from the decision-maker.

On this subject the distinction introduced by Roy between *multiple criteria decision-making* (MCDM) and *multiple criteria decision aid* (MCDA) is of great importance. According to Roy (1990), the MCDM models assume that the decision-maker's preferences are made perfectly explicit, so that the only thing left to do is to consider a well-formulated mathematical model. But "in general [it] is impossible to say that a decision is a good one or a bad one by referring only to a mathematical model: organizational, pedagogical and cultural aspects of the whole decision process which leads to a given decision also contribute to its quality and success..." As a consequence, it is necessary to move over from an MCDM analysis to an MCDA one, whose principal aim is not to discover a solution, but "to construct or create something which is viewed as liable to help an actor taking part in a decision process either to shape, and/or to argue, and/or to transform his preferences" (*constructive or creative approach*).

However, it must be noted that all results obtained can provide "justifiable" or "defensible" decisions to policy-makers, but in real-world environmental decision-making, it is necessary to interact with many actors (often each single actor is represented by complex organizations, such as town councils, trade unions, associations, and so on), each of them having different goals and values. Therefore, since real-world problems are generally not direct win–lose situations and a certain degree of compromise is needed, a procedure aimed at supporting real environmental policy-makers would ideally consider this problem of different (and often conflicting) evaluations. Multicriteria evaluation techniques cannot solve all these conflicts, but they can help to provide more insight into the nature of these conflicts and into ways to arrive at political compromises in cases of divergent preferences in a multi-group or committee system. For this aim the possibilities of coalitions between different interest groups whose preference patterns do not show significant differences have to be explored.

The aim of coalition formation theory is to predict a set of coalitions that are likely to be formed in a given political situation. An application of a fuzzy multigroup conflict resolution for environmental management can be found in Munda et al. (1992b).

8. Qualitative multicriteria evaluation

8.1. Ordinal information

From measurement theory (Roberts, 1979; Vansnick, 1990), we know that in structuring a problem, given a set A and some information about this set, there is a need to express this information by assigning to each element $a \in A$ a real number $m(a)$. This real number is called the measure of a, and the application $m: A \rightarrow R$ is called a *scale of measurement*. The main scales of measurement are:

- nominal scale
- ordinal scale
- interval scale
- ratio scale

For simplicity, we will refer to *qualitative information* as information measured on a nominal or ordinal scale, and to *quantitative information* as information measured on an interval or ratio scale. In multicriteria evaluation theory, a clear distinction is made between quantitative and qualitative methods. Essentially, there are two approaches for dealing with qualitative information: a direct and an indirect one (Nijkamp et al., 1990). In the *direct approach*, qualitative information is used directly in a qualitative evaluation method; in the *indirect approach*, qualitative information is first transformed into a cardinal one, and then one of the existing quantitative methods is used. Cardinalisation is especially attractive in the case of available information of a "mixed type" (both qualitative and quantitative data). In this case the application of a direct method would usually imply that only the qualitative contents of all available (quantitative and qualitative) information is used, which would give rise to an inefficient use of this. In the indirect approach, this loss of information is avoided; the question is, of course, whether there is a sufficient basis for the application of a certain cardinalisation scheme. Two examples of cardinalisation of qualitative evaluation matrix are the expected value method (Rietveld, 1984, 1989) and multidimensional scaling techniques (Kruskal, 1964; Nijkamp, 1979; Keller and Wansbeek, 1983).

An example of a multicriteria method that may use mixed information is the so-called REGIME method; this method is based on pairwise comparison operations (Hinloopen and Nijkamp, 1990; Nijkamp et al., 1990). Its point of departure is an ordinal evaluation matrix and an ordinal weight vector. Given the ordinal nature of the evaluation criteria, by means of pairwise comparison of alternatives, no attention is paid to the size of the difference between the impacts of alternatives; it is only the sign of the difference that is taken into account. Ordinal weights are interpreted as originating from unknown quantitative weights. A set S is defined as containing the whole set of quantitative weights that conform to the qualitative priority information. In some cases the sign will be the same for the whole set S, and the alternatives can be ranked accordingly. In other cases the sign of the pairwise comparison cannot be determined unambiguously. This difficulty is circumvented by partitioning the set of feasible weights so that for each subset of weights a definite conclusion can be drawn about the sign of the pairwise comparison. The distribution of the weights within S is assumed to be uniform and, therefore, the relative sizes of the subsets of S can be interpreted as the probability that alternative a is preferred to alternative b. Probabilities are then aggregated to produce an overall rating of the alternatives, based on a success index or success score.

Another interesting method to tackle mixed information is the EVAMIX method (Voogd, 1983). The EVAMIX approach concerns the construction of two measures: one only dealing with the ordinal criteria and the other one dealing with the quantitative criteria. By making various assumptions about standardisation and aggregation, several methods can be defined by which an appraisal score for each alternative can be calculated. The most important assumptions behind the EVAMIX approach concern the definition of the various standardisation functions (at least three different techniques can be distinguished). Other assumptions concern the weights for the ordinal and cardinal criteria, and finally the additive relationship of the overall dominance measure.

8.2. Fuzzy information

In a decision problem it is possible to distinguish two main elements, available information and manipulation rules for this information. Accordingly, in multicriteria evaluation in a fuzzy environment two main classes can be distinguished:
(1) fuzzy manipulation rules of crisp information
(2) fuzzy manipulation rules of fuzzy information

A general multicriteria decision model (Δ) characterised by fuzzy information can be synthesised as follows:

$$\Delta = \{G, A, C, P, W, M\},$$

where G is the set of objectives, criteria or goals, A is the set of feasible alternatives, C is the set of constraints, P is the set of relevant parameters, W is the set of the subjective preferences of the decision-maker, and M is the set of relevant membership functions.

Thus a fuzzy decision model is essentially characterised by the presence of a set of membership functions. These membership functions can be defined on one or more of the other components of the model; therefore, the degree of fuzziness of the model may vary accordingly. Both continuous and discrete fuzzy multicriteria methods exist in the literature. Recently a new discrete multicriteria model whose impact (or evaluation) matrix may include either crisp, stochastic or fuzzy measurements of the performance of an alternative a_n with respect to a criterion g_m has been developed by the present authors (Munda et al., 1992a). This method will be described briefly here. It can be subdivided into four main steps.

8.2.1. Definition of a fuzzy region of satisfactory alternatives

Given a "consistent family" of mixed evaluation criteria $G = \{g_m\}$, $m = 1,2,\ldots, M$, and a finite set $A = \{a_n\}$, $n = 1,2,\ldots, N$, of potential alternatives (actions), a region of satisfactory alternatives can be obtained by defining a fuzzy interval of feasible and acceptable values for each criterion.

From an operational point of view, in public decision-making a single point-value solution (e.g., weights) tends to lead to deadlocks in the evolution of the decision process because it imposes too rigid conditions for a compromise. On the contrary, when a higher degree of flexibility is allowed, the definition of a fuzzy region of satisfactory solutions could in principle make more room for mutual consensus.

8.2.2. Comparison of fuzzy sets

In order to overcome some of the limitations typical of fuzzy approaches to multicriteria evaluation, we have developed a new distance metric (preference index) that is useful in the case of continuous membership functions, allowing also a definite integration. The main characteristic of this semantic distance is the comparison of fuzzy sets by means of areas instead of intersections or α-cuts.

8.2.3. Pairwise comparison of the alternatives

Evaluation normally requires a judgement of the relative performance of distinct alternatives based on dominance relationships. Six different fuzzy relations are considered.

Given such information on the pairwise performance of the alternatives according to each single criterion, it is necessary to aggregate these evaluations in order to take into account all criteria simultaneously; this is done taking into account the degree of compensation to be introduced in the model, and a measure of the "incertitude" of the evaluations given by the entropy concept.

8.2.4. Evaluation of the alternatives

The information provided by such "fuzzy preference relation" can be used in different ways, e.g., the degree of truth (τ) of statements as, "according to most of the criteria"

- a is better than b,
- a and b are indifferent,
- a is worse than b

can be computed by means of proportional linguistic quantifiers and approximate reasoning rules.

Such pairwise evaluations can be used directly by the decision-maker(s) in order to isolate a set of satisfactory solutions, or if in a given decisional environment there is a need to perform further elaborations in order to obtain a ranking of the alternatives (in a complete or partial preorder), this can also be done by using further elaborations of approximate reasoning taking into account the entropy levels and the relations with all other actions.

The empirical performance of this fuzzy multicriteria method will be illustrated by means of a transportation problem.

Suppose that there are three possibilities for improving the transportation system in a region, viz., highway construction, a road/bus system and a new train (railroad) system. Each of these three alternatives will be judged on the basis of five criteria, viz., costs, travel time, capacity, NO_x emissions and landscape impacts. Some of these impacts are quantitative, but others are qualitative in nature. The qualitative part of the relevant information for this problem can be formulated in fuzzy terms.

The fuzzy impact (or evaluation) matrix related to the above transportation problem is supposed to be the following (Table 2).

By applying our fuzzy multicriteria procedure for each pair of actions, the following degrees of truth τ of a linguistic evaluation are obtained:

a_1 is better than a_2 $\tau = 0$
a_1 and a_2 are indifferent $\tau = 0$
a_1 is worse than a_2 $\tau = 0.57$

a_1 is better than a_3 $\tau = 0.67$
a_1 and a_3 are indifferent $\tau = 0$
a_1 is worse than a_3 $\tau = 1$

a_2 is better than a_3 $\tau = 0.53$
a_2 and a_3 are indifferent $\tau = 0$
a_2 is worse than a_3 $\tau = 1$

Then based on the procedure described in Munda et al. (1992a), we obtain the following preorder:
$a_3 \rightarrow a_2 \rightarrow a_1$.

Table 2
Fuzzy evaluation matrix of a transportation problem

Criteria	Units	Highway (a_1)	Road/bus (a_2)	Train (a_3)
Costs	Dutch Guilders (million)	200 (1)	250 (1)	400 (0.6)
Travel time	linguistic	excellent (1)	good (0.85)	moderate (0.6)
Capacity	km/year (million)	20 (0.5)	30 (0.8)	40 (1)
NO_x emissions	ton/year	1000 (0.3)	750 (0.6)	100 (1)
Landscape	linguistic	bad (0.2)	bad (0.2)	moderate (0.6)

The values in brackets are the membership degrees of each action to the interval of feasible and acceptable values defined on each criterion.

This ranking is a function of all actions taken into consideration; the pairwise linguistic evaluations give information only on each single pair of actions. Thus both together can help the decision-maker(s) to reach a final decision.

9. Conclusions

We have shown that multicriteria methods provide a flexible way of dealing with qualitative environmental effects of decisions. However, this does not mean that multicriteria evaluation is a panacea that can be used in all circumstances without difficulties. It has its own problems, and some of these problems have also been illustrated. Finally, one must note that the results of a multicriteria analysis depend on:

- available data
- structured information
- chosen aggregation method
- decision-maker's preferences

This means that when an attempt is made to model a real-world situation, the presence of a certain subjective component appears to be an inevitable phenomenon. In general, this is a desirable feature; in fact, when a model without any creative personal or subjective influence of a model designer is used, it is inevitably characterised by a certain rigidity that prevents it from adhering completely to the situation modelled. This could make it necessary to "force reality" because in the end the tendency will be to make reality fit the model. The use of models with characteristics of subjectivity or of subjectivism depends in the latter analysis *on the ability and ethical behaviour of the researcher constructing the model*. It is important to remember this above all when MCDA methods are used to "justify" or "defend" political decisions (Funtowicz and Ravetz, 1991).

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