Matrix for Evaluation of Sustainability Achievement (MESA): determining the sustainability of development

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Abstract

Decisions generally made by planners, designers, economists, engineers, and politicians occur in a multi-objective environment and are based upon non-standardised and imprecise data. In the past, projects were justified almost solely on economic grounds, with insufficient consideration of environmental and social issues. The shifting of societal values has placed greater emphasis upon careful management of the resources. Techniques are therefore required to deal quantitative and qualitative information. The MESA methodology has been developed to promote ‘sustainable’ planning decisions. Decisions are based upon a formal rigorous decision strategy involving Fuzzy Set Theory allowing quantitative and qualitative values to be evaluated. The MESA method is able to incorporate public opinion with expert knowledge, which is vital in the development and assessment of environmental policy.

1 Introduction

Most development decisions are multi-objective in nature, involving economic, political, social and environmental issues. This reality is often unsatisfactorily addressed as most development decisions are justified almost solely on economic grounds (employing cost-benefit or cost-effectiveness analysis), with little or no consideration of other issues. A holistic review of development proposals is necessary to avoid unsustainable development that benefits only a few to the detriment of many others. Procedures for quantifying environmental and social impacts are time consuming and occur late (if at all) in the planning process because there are often conflicting objectives that cannot be expressed in commensurable units [1]. Attempts at expressing environmental, social and political impacts in monetary terms have been made with limited success [2].
Many problems occur within cost-benefit analysis when attempting to include social and environmental issues. The imputation of market prices to intangible items is questionable; while equity problems are typically ignored [3]. There has been an acceptance that parameters which are non-quantifiable in monetary terms must be considered in the evaluation of alternatives. A wide range of multi-objective decision-making techniques have been developed to facilitate the involvement of the public in planning efforts. In fact, there are so many multi-objective techniques available that methods have been developed to assist in the selection of the most suitable technique [4],[5],[6]. Multi-objective methods should try to meet the following criteria [1], [7]:

- address the prediction of futures, both with and without the project;
- allow consideration of alternatives both separately and in combination;
- quantify probabilistic nature of economic, environmental and social impacts;
- be based on principles and assumptions that are valid and easily illustrated;
- employ qualitative and quantitative information in a sound way;
- make explicit subjective and value judgments;
- communicate the predicted impacts with respect to their spatial and temporal distribution;
- involve inter-agency coordination and public involvement;
- yield results that are understandable to decision makers and the public;
- should be completed within a reasonable time frame; and
- require minimal expenditure for project evaluation.

Goicoechea et al. [8] identify the shifting of societal values, relating to the use and management of natural resources, as a prime motivation in the development of multi-objective analysis. Shafer and Davis [9] state that it is essential to include all the perceived costs and benefits in project evaluation because the quality of life and of environments in the future are shaped by the long-term planning priorities, decisions and activities undertaken today.

The expansion of population in almost every region of the world has led to increased use of the Earth's resources [10] and a focus on sustainable development. A realistic method is needed that includes and evaluates quantitative and qualitative values.

2 Development of the MESA method

The Matrix for the Evaluation of Sustainability Achievement (MESA) has been developed to concurrently address economic, environmental and social issues, indicating whether a project assists or retards the achievement of sustainability. MESA aims to ensure:

- public involvement in the establishment of priorities;
- evaluation of qualitative and quantitative information on costs and benefits;
- assessment and comparison of multiple projects or alternatives;
• consideration of the consequences of development relative to current conditions (i.e. 'with' versus 'without' the project);
• combination of impact assessments in a methodologically sound way without resorting to estimating monetary values of intangible items; and
• a simple, logical technique that allows a relatively quick appraisal.

A matrix style of decision-making was selected because it is a simple yet effective medium for surveying development consequences in environmental impact analysis [11]. In an attempt to eliminate the need to place monetary values on costs and benefits, coupled with the desire to use the unavoidable subjective responses to some criteria, use of fuzzy set theory was adopted. Fuzzy set theory has the ability to represent multi-objective decision problems involving vague or fuzzy objectives or constraints [12]. Fuzzy sets combine quantitative and qualitative information by assigning to each of the criteria (for a given alternative) a number, in the range 0 to 1. The number 0 indicates that the criterion is not achieved, while 1 refers to satisfaction of the criterion. Some early attempts to include fuzzy set theory into engineering project decision-making were Ragade et al. [13], Daniell [14], Znotinas and Hipel [15], and Alley et al. [16]. In recent years fuzzy set theory has re-emerged and found increasing acceptance in natural resource management [8], as well as civil engineering and water resources applications [17], [18], [19].

3 Undertaking the MESA method

The MESA technique combines information on the pre-development condition, the potential impacts of a range of development alternatives and the importance attached to each evaluation criterion.

Evaluation by the MESA method adopts the following procedure:
1. Define the problem which has initiated the development investigations, and outline the objectives that alternative solutions should meet.
2. Determine the criteria and values (in addition to those presented in the MESA) that are important in the selection of the best alternative.
3. Develop alternative schemes to meet these objectives.
4. Assemble a multi-disciplinary team possessing knowledge and expertise in areas such as economics, engineering, law, the natural environment and social issues. Assess the importance of each of the assessment criteria to develop a weight factor to be attached to each criteria.
5. The members of the multi-disciplinary team should assess the degree to which the present conditions satisfy the designated Goals and Constraints. The alternatives should then also be evaluated.
6. Combine these assessments mathematically to provide an indication of the performance of each alternative relative to the criteria under consideration:

\[ WP_i = (PC_j \times PP_{ij})^{\alpha_j} \]  

(1)

where
\begin{align*}
  i & = \text{the alternative number,} \\
  \end{align*}
Computer Techniques in Environmental Studies

\[ j = \text{the sustainability goal or objective}, \]
\[ a_j = \text{weight attached to criterion } j, \]
\[ PC_j = \text{Present Condition rating for criterion } j, \]
\[ PP_{ij} = \text{Project Performance rating for alternative } i \text{ and criterion } j, \text{ and} \]
\[ WP_{ij} = \text{Weighted Performance of alternative } i \text{ relative to criterion } j. \]

7. The Fuzzy Set Combination is the minimum \( WP_{ij} \) for each alternative; that is, the minimum value in the column corresponding to each alternative.

8. A Dominance Matrix is constructed to examine the cumulative benefits of one alternative over another. The Dominance Factor is calculated as an effectiveness measure of one alternative relative to all other alternatives.

9. The Weighted Performance and Dominance Factor product determines the final ranking of alternatives. The closer the product is to 1, the greater the satisfaction of the criteria and provision of benefits over other alternatives.

Perhaps the most important task is the specification of criteria against which alternatives are assessed. An evaluation by practitioners in South Australia of key criteria of a sustainable water resources management strategy for a peri-urban area of Adelaide has been undertaken [20]. Deason and White [21] note that despite the growth in number of multi-objective methods, they are yet to enjoy wide success in solving real problems.

**Table 1 Sustainability evaluation criteria**

<table>
<thead>
<tr>
<th>Maintenance of habitat and ecosystems</th>
<th>Local infrastructure compatibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preservation of native plant species</td>
<td>Involvement of the community</td>
</tr>
<tr>
<td>Preservation of native animal species</td>
<td>Use of renewable energy sources</td>
</tr>
<tr>
<td>Preservation of areas of landscape/amenity value</td>
<td>Airborne disposal within assimilative capacity</td>
</tr>
<tr>
<td>Preservation of areas of cultural value</td>
<td>Energy efficiency</td>
</tr>
<tr>
<td>Reclamation &amp; reuse of wastewater</td>
<td>Public acceptability</td>
</tr>
<tr>
<td>Wastewater disposal within assimilative capacity</td>
<td>Groundwater extraction within sustainable yield</td>
</tr>
<tr>
<td>Minimisation of greenhouse gas emission</td>
<td>Improved access to public open spaces</td>
</tr>
<tr>
<td>Improvement in surface water quality</td>
<td>Improved recreational opportunities</td>
</tr>
<tr>
<td>Improvement in groundwater quality</td>
<td>Full cost recovery for good or service</td>
</tr>
<tr>
<td>Productive use of fertile soils</td>
<td>Annual equivalent cost-benefit ratio</td>
</tr>
<tr>
<td>Prevention of erosion</td>
<td>Costs borne by consumers</td>
</tr>
<tr>
<td>Application of clean technology</td>
<td>Equitable cost-benefit distribution</td>
</tr>
<tr>
<td>Waste recycling or use</td>
<td>Unit cost for good or service</td>
</tr>
<tr>
<td>Material utilisation allowing recycling</td>
<td>Increased in employment opportunities</td>
</tr>
<tr>
<td>Increased use of metal substitutes</td>
<td>Capital cost funding capability</td>
</tr>
<tr>
<td>Compatibility with existing operations</td>
<td></td>
</tr>
</tbody>
</table>

### 3.1 Selection of criteria for project evaluation

The specification of an appropriate and operational set of objectives is as difficult as it is important. The MESA Table 1 lists 33 goals and constraints, and includes criteria relating to the economic, environmental and social aspects of development. Many modifications to this list were required to achieve the final list. It is considered that the list contains the fundamental objectives that would constitute a strategy for the achievement of sustainability, while
maintaining sufficient generality to be applicable to all large project conditions. Any issues or objectives which are project specific should also be included.

3.2 Assigning the relative importance to each criterion

Many different methods have been developed for investigating the relative importance of different criteria or objectives. These methods range from simple ordinal ranking of objectives, to more sophisticated mathematical methods. The method proposed for use with the MESA is that developed by Saaty [22]. This technique determines a ratio scale for the group of criteria or objectives, based upon a pairwise comparison of the individual criterion. The importance assigned to each criterion is calculated from each member's responses. The weights determined by each member are then averaged across each criterion. Assume that a comparison is being made between criterion j and criterion j+1 to determine which of these two criteria are more important. A value is assigned based on this judgment and then combined to construct an nxn matrix A, so that the following rules are satisfied:
1. if criterion j is more important than j+1, assign a number to a_{jj+1} (Table 2);
2. a_{jj} = 1; and
3. a_{j+1j} = 1/a_{jj+1}.

<table>
<thead>
<tr>
<th>Intensity of importance</th>
<th>Definition</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Equal importance</td>
<td>Two activities contribute equally</td>
</tr>
<tr>
<td>3</td>
<td>Weak importance of one over the other</td>
<td>Experience and judgment slightly favour one activity over another</td>
</tr>
<tr>
<td>5</td>
<td>Essential or strong importance</td>
<td>Experience and judgment strongly favour one activity over another</td>
</tr>
<tr>
<td>7</td>
<td>Demonstrated importance</td>
<td>Activity is strongly favoured and its dominance is demonstrated in practice</td>
</tr>
<tr>
<td>9</td>
<td>Absolute importance</td>
<td>The evidence favouring one activity over another is of the highest possible order of affirmation</td>
</tr>
<tr>
<td>2, 4, 6, 8</td>
<td>Intermediate values between adjacent judgments</td>
<td>When compromise is needed</td>
</tr>
</tbody>
</table>

Saaty [23] showed that the eigenvector corresponding to the maximum eigenvalue of A is a ratio scale for the criteria compared. This eigenvector is further modified to produce a vector where the average importance is unity. There can be a large number of comparisons to be made in the process of evaluating the weights. Given that there are n criteria, then the number of comparisons to be made can be calculated using the equation:

\[ \text{Comparisons, } f = \frac{n(n-1)}{2} \]  

(2)

It is recommended that the number of items for comparison be limited to between 7 and 12. Where the number of criteria exceeds 10, then a hierarchical structure could be used to segregate the criteria into categories, thereby
reducing the number of comparisons in any group. The pairwise method does help reduce the decision-maker to two alternatives in any one decision task.

3.3 Assessing criteria satisfaction
The members of the project evaluation team should be retained to assess the satisfaction of the criteria under existing conditions, and the potential beneficial or adverse impacts of each alternative. Each member of the team would undertake an assessment relevant only to their field of expertise.

The alternatives are assessed to determine the satisfaction of each of the listed criteria. A value in the range of 0 to 1 is assigned to represent this level of satisfaction, where 0 is analogous to no satisfaction, and 1 represents complete satisfaction. A value between 0 and 1 represents an intermediate condition. Where quantitative information exists, such as minimum or maximum acceptable conditions, these can be assigned 0 and 1. However, in some cases the assessment must be subjective, in which case the value 0 can be considered to correspond with the linguistic classification of ‘very bad condition’, whereas 1 corresponds to ‘very good condition’.

The assessment of present conditions and criteria satisfaction for each alternative project are combined by taking the mathematical product, since this corresponds to the linguistic ‘and’ condition. This accounts for the impact of an alternative with respect to the current circumstances, i.e. would acceptance of an alternative result in an adverse impact and compound an existing problem area where the satisfaction of the criteria is already low?

Raising this product to the power of the criterion weight serves to further modify the grade of membership in the overall fuzzy set combination for each alternative. The cumulative satisfaction of all criteria for each alternative is determined to be the minimum membership value in each column. This reflects the minimum level of satisfaction of any criteria for each alternative. This is referred to as the ‘minimal aggregation’ since it assumes that the worst evaluation of any feature for an alternative should be taken into consideration. Fuzzy set theory suggests that the alternative corresponding to the largest of these minimum membership values is the best alternative.

3.4 Dominance Matrix
The use of a Dominance Matrix was first suggested by Alley et al.[16], and was used with similar evaluations of criteria satisfaction to rank a set of alternatives. An alternative was defined to be superior to a second alternative if it dominates the second alternative in more features than the number of features in which the second dominates the first.

In order to display the dominance structure between all possible pairs of alternatives, a square matrix $D$ of order $p$ is used (where $p$ is the number of alternatives or projects) and is called the Dominance Matrix. In the matrix [16] the element $d_{ij}$ was the number of criteria for which the membership value of alternative $j$ dominates or is greater than alternative $i$. A dash is entered for the
diagonal elements. If the $k$th column is summed, the total number of
dominances of alternative $k$ over all other alternatives is obtained. Similarly, if
the $k$th row is summed, the number of times the $k$th alternative is dominated by
all the other alternatives is determined. A modification to this technique is
suggested. The situation existing with the original dominance matrix was that
the dominance of one alternative over another for a low importance criterion
possessed equal weight to that corresponding to a criterion of high importance.
To improve this situation, the element $d_{ij}$ is redefined; $d_{ij}$ becomes the sum of
the weights corresponding to each criterion for which alternative $j$ dominates
alternative $i$. The Dominance Factor, $DF$, has been devised as an overall
measure of the superiority of an alternative, and is defined as:

$$DF = \frac{MD - RT_k}{MD} \times \frac{CT_k}{MD} = \frac{(MD - RT_k)CT_k}{MD^2}$$

Maximum Dominance, $MD = n(p-1)$

where

- $MD$ = the maximum possible dominance, which is equivalent to one
  alternative dominating all other alternatives in all criteria;
- $n$ = the number of criteria used in the assessment of alternatives;
- $p$ = the number of alternatives being considered;
- $RT_k$ = the row total for alternative $k$; and
- $CT_k$ = the column total for alternative $k$.

The more favourable alternatives have higher column sums and lower row
sums, that is reflected in the way the DF is formulated. A high column total and
low row total will produce a DF close to 1. Similarly, a low column total and
high row total will produce a DF close to zero. Therefore, a DF near 1 indicates
a favourable alternative while a DF near zero is a poor alternative. Taking the
product of the DF with the weighted performance measure, tempers the
pessimistic aggregation produced using fuzzy set theory, to identify the
alternative which most effectively meets all criteria, and is consistent with the
priorities assigned via the allocation of weights. The results should be checked
for consistency and errors, and to ensure that no unacceptable impacts exist
with the preferred solution.

4 Benefits and limitations of the MESA method

The MESA technique provides a methodology for dealing with multi-objective
development problems at the planning level. The numerous advantages of the
MESA technique are:

- The method is logically sound, standardised and repeatable.
- Quantitative and qualitative data can be incorporated into the decision-
  making process without resorting to estimations of the monetary value of
  costs and benefits.
- Available quantitative data is valuable and easily incorporated into the
  technique. The data can be used to set limits of acceptability (e.g. total
available funds, allowable levels of pollutants, etc.) against which the performance of alternative projects can be assessed.

- It provides a decision-making ‘audit trail’, a result of the formal structure and the method of combining the evaluations of dissimilar criterion.
- The use of weights to reflect the importance of the assessment criteria, and the assignment of impact ratings through membership values, inherently reflects people's attitudes to risk and uncertainty.
- A major shortcoming of many forms of public participation is that pressure or loud groups are heard rather than a balanced public cross-section [24]. MESA allows the coordinator to place a weight on the relative importance of the input of groups thereby partially overcoming this problem.
- The use of pairwise comparisons in the evaluation of criteria importance is a simple yet effective technique to compare a large number of criteria.
- The use of fuzzy set theory and the pessimistic aggregation method ensures a risk averse selection of the ‘best’ alternative.
- There is considerable flexibility and scope for sensitivity analysis of the fuzziness of membership values and criteria weights. The potential impact of differing political viewpoints can be examined through application of criteria weights offered by each member of the evaluation panel.
- The numerical evaluation of project alternatives and combination of assessments is mathematically simple.
- The method accommodates the selective comparison of dissimilar criteria and consideration of the potential trade-offs between alternatives.
- The spatial scale of alternative projects and the implications for sustainability can be tested quickly, as membership values (of criteria such as cost, use of fertile land, increase in salinity, etc.) could be constructed as functions of spatial size.

There are some limitations to the MESA method which include:

- Results depend upon the subjective evaluations or approximation of social, economic, political and environmental values (improvements can be made as better information comes available).
- Results reflect only the knowledge and judgment of the panel participants.
- The method is new and unfamiliar to decision makers.
- The issue of sustainability is the subject of ongoing debate, therefore the criteria listed for evaluation of alternatives is a good basis for discussion.
- There is a requirement that decision-makers overlook short-term interests to the long-term interest of the community as a whole. The discount rate used in economic evaluation reflects this preference, and so it is important that longer-term goals be evaluated using the MESA.
- Bias in selection of members for the evaluation committee by the views and nature of the assessment agency, thereby influencing the results obtained.
- There are a large number of comparisons to be made in the process of evaluating the importance of criteria. In most instances computer software would be required to combine and determine the criteria weights.
5 Conclusions

The MESA methodology attempts to encourage development that is 'sustainable'. It accounts for subjective judgment and contains a formal rigorous decision strategy that takes the place of intuition when quantitative and qualitative values of environmental activities need to be evaluated. The MESA method is capable of incorporating public opinion, a vital component in the development and assessment of environmental policy. Use of the multi-disciplinary approach enables public opinion to be combined with expert knowledge for the successful preparation and promotion of environmental policies and development plans.

The effectiveness of any multi-objective approach in practice will depend in part on how easy it is to understand, how well it addresses the appropriate issues or problems. The MESA approach does not eliminate subjectivity, but rather makes it explicit, spelling out the basis of the judgment and facilitating discussion of that assessment. If an honest appraisal of a project is required and there is the will to carry out an evaluation of the development proposals using the MESA methodology, then the process will enable a greater comprehension of the problem and a method for determining the ‘best’ alternative.

6 References


