Multicriteria Analysis for Land-Use Management

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An algorithm for computing multiple attribute additive value measurement ranges under a hierarchy of the criteria: application to farm or rangeland management decisions

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Abstract
A decision tool is described and applied to the problem of evaluating farm or rangeland management systems with respect to both economic and environmental criteria. The method quickly computes the possible range of value from the most optimistic to the most pessimistic (best to worst) for any given hierarchy of the multiple attributes. The method is to be applied after commensurate attribute values have been determined for each alternative without requiring one to specify or determine explicit weights on the attributes. The decision tool is particularly useful for examining alternatives from numerous decision-making viewpoints or by multiple decision makers. The importance order of the criteria or attributes at any tier in the hierarchy can be changed and the value range computed again using a simple algorithmic method that does not require a linear programming solver. This solution method makes it easy to determine the result of modifying priorities in portions of the hierarchical architecture without recalculating the contributions of unaffected parts. The method is applied to the problem of determining a possible replacement farm management system for several fields in western Iowa. Environmental and economical improvement over the current farming system is indicated by several of the alternative systems. Current projects are underway to develop indices of rangeland and soil health.

Keywords: decision making, multiple attribute, multiple objective, agriculture, environmental management.

1. Introduction

This work is prompted by the need for tools that can be easily and quickly understood and sensibly applied to multiple attribute decision making situations that occur in land management. The tool presented in this paper, however, is not limited to applications for land management. It is readily applicable to any decision-making situation that can be similarly described. Examples among the problems that could be considered include: determining which among a suite of feasible farm management practices should be preferred on a given field; or determining which field from among several feasible locations is best for a given management system; ranking rangeland watersheds or other ecosystems for the purpose of determining where limited funds and time should be concentrated. *Project* or *portfolio selection* is analogous to the latter, while *product comparison* or *suitability* to the former. Alternative *facility layouts* and *transportation planning* are other decision making areas that the method described herein could benefit.

The development of our decision support tool was encouraged by statements in Dyer *et al.* (1992) that simple, understandable, and usable approaches for solving multiple criteria decision making (MCDM) or multiple attribute utility theory (MAUT) problems are still needed. The added complications of multiple decision makers as well as concerned and/or involved parties in environmental decision-making, mandated that much of the subjectivity (single decision maker perspective) involved in existing MCDM/MAUT methods be eliminated.

We consider a problem that has been formulated as a hierarchical multi-attribute or multiple criteria decision problem. The development here is related to earlier work of Salo and Hämäläinen (1992) and Yakowitz *et al.* (1992, 1993a) that considers the impact on an additive value function caused by allowing the attribute weights to vary subject only to an importance ordering of the criteria. These works fall under the category of partial information or interval weights in MAUT (Fishburn, 1965; Kirkwood and Sarin, 1985; Claessens *et al.* 1991; Bana e Costa and Vincke, 1995; Hazen, 1986 contains a discussion and numerous references).

Most techniques proposed in the literature for assessing weights, either solicit weights directly, or seek to discern them indirectly, from the decision maker (Goicoechea *et al.*, 1982; Keeney and Raiffa, 1976; Saaty, 1980 are examples). The resultant ranking of the alternatives are often extremely sensitive to the importance order of the attributes, and therefore the weights. The calculations for examining this sensitivity are straightforward in the case of a simple ordinal priority ranking of all of the attributes (Yakowitz *et al.*, 1993a). However, the complexity imposed by a hierarchical architecture of the criteria at first appears to be difficult to overcome in a simple way. Yet, it is just this type of structure that is needed to define many complex decision making problems.

Under a hierarchical structure, the decision priorities alone do not necessarily imply an ordinal ranking of each individual attribute. Therefore, examining the solutions of the linear programs given in Yakowitz *et al.* (1993a) and elsewhere, which are described in the next section, without considering the possible added freedom (or relaxation of the weights) due to the hierarchical structure, does not provide the full range of value of the additive value function. The method presented here does. It allows one to quickly compute the range of values from the *best* to the *worst* for a hierarchically arranged multiple attribute problem under the assumption of an additive value function. The method allows the decision maker (DM) to quickly assess the most optimistic and most pessimistic DM viewpoint given multiple importance orders of the attributes at any tier in the hierarchy. We assume that the attribute values for each alternative are already in common units and common range as determined by some multiple attribute or scoring method. For example, the Analytic Hierarchy Process (AHP) of Saaty (1980), or scoring functions such as those of Wymore (1988) or others could be used to assess the attribute values or convert data to unit common values and ranges.

Computing the range of value of an additive value function makes it possible for various stakeholders or interested parties to determine the sensitivity of the ranking of alternatives to the hierarchical order. Often this order is a compromise between various objectives. Examining the range of the value function under other possible hierarchical scenarios, may reveal an alternative choice that is favored by each party and eliminates the need for the often contentious task in group decision making of discerning the weights explicitly.

We begin by defining what we mean by a hierarchy. This is followed by a brief description of the algorithm for computing the range of the value function. Algorithmic details are then developed, followed by a detailed description of the calculations needed for a specific hierarchical structure. The generalization to more complicated hierarchical structures is readily apparent. This method is then used for evaluating four alternative farming systems with respect to specific economic and environmental decision criteria. The concluding section includes a discussion of current projects under consideration using the evaluation tool developed in this paper.

2. Defining the hierarchy

A generic hierarchical architecture for a multi-attribute decision problem is illustrated in Figure 1. Note that we have assumed a quite generic structure where branches of the hierarchy may terminate at different tiers or levels. Dummy elements may, of course, be added at intermediate levels if equal depth branches are desired. The *Major Goal* is at the highest level (Tier 1). This level could be choosing a *Sustainable Agricultural System* from a finite number of alternatives for a given farm/ranch or region; or choosing the best *Traffic Plan* from among several alternative plans. The subsequent levels (Tier 2 through N) contain sub-elements of the parent or previous levels. Thus, for example in the sustainable agriculture problem, Tier 2 could include environmental, economic, and social sub-goals. Subsequent levels of the environmental branch could then include surface water, sub-surface water, species diversity, and soil, followed by criteria including fertilizer and pesticide impacts, and erosion under the proper category. Of interest here is the effect of changing the importance order of the elements of the hierarchy on the range of values of the additive value function. For example, one may want to know how alternative farm or range management alternatives would be ranked if environmental criteria were given a higher priority than economic criteria. However, the farmer or rancher may want to give a higher priority to the economic criteria considered. Importance order is often the key issue of contention when there are multiple stakeholders. In all figures, it is assumed that the importance order is from left to right. That is, for elements in the same tier, that emanate from a common branch, an element to the left has a higher priority and therefore more "weight" in the decision making process at that level. No assumption is made regarding the priority relationship between elements emanating from different branches even if they are in the same tier.

As is the case in most multi-attribute solution methods, the goal of the methodology is to determine the value of an additive value function that can be used to rank the set of alternatives.

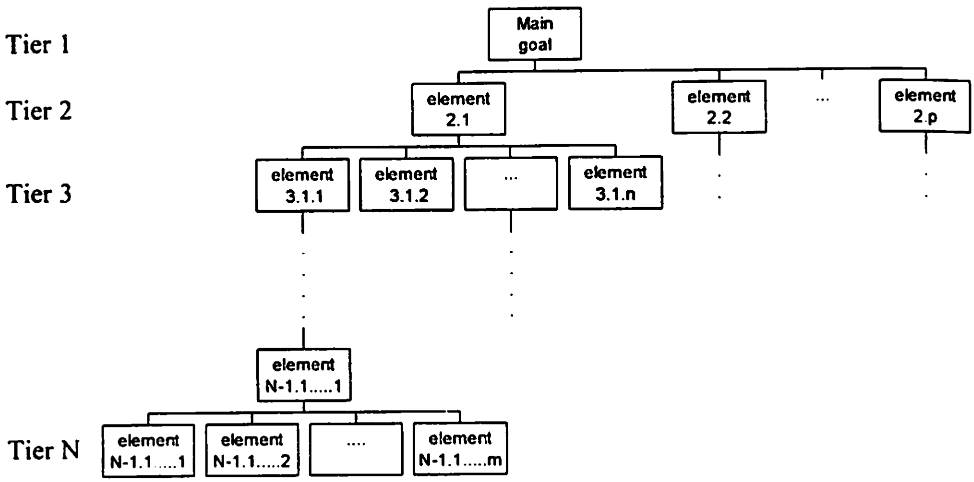

Figure 1. Generic decision hierarchy.

An additive value function takes the following form:

$$V(w,v) = \Sigma_i \; w_i v_i \;,$$

where i ranges over the terminal elements of each branch in the hierarchy; v indicates the value assigned to the alternative with respect to each terminal element; and the weights, w, are consistent with the hierarchy and normalized so that they sum to a finite number (assumed to be 1 in all calculations given below). We emphasize that V is a function of both the individual criterion values determined for each alternative and the weights (unknown) for each attribute or criteria. Since we are primarily concerned with the effects on the above function caused by changing hierarchical element priorities, we will assume that for each alternative, v_i is fixed for all i. We refer to the above as V, or with subscript, V_j , when wishing to distinguish between alternatives (in this case the values, v, will be double subscripted, v_{ij}).

The algorithm for assessing the full range from the *best* to the *worst* under our ssumptions begins at the lowest tier of each branch of the hierarchy. Best and worst dditive values are computed for each element using analytic solutions to two simple near programs that maximize and minimize V at the parent element over all weights onsistent with the importance order of the decision elements. These same programs are sed at intermediate elements, substituting the maximum (or minimum) values reviously computed as the values for those elements that have descendent elements, ntil the main or first tier is reached. Altering the priority at any level requires redoing nly those calculations that occur after that point to the main or first tier. This fact nakes it easy to examine the effects of changing priorities or decision maker references, which may be especially useful if there are more than one decision maker r affected party involved.

3. Algorithmic details

3.1. *Computing best and worst subvalues for the lowest tier of each branch*

Given the priority order of the criteria at the lowest tier of each branch, best and worst additive values can be found without requiring the decision maker to set specific weights for each of the criteria (see Claessens *et al.*, 1991; Salo and Hämäläinen, 1992; or Yakowitz *et al.*, 1992, 1993a). Referring to the notated branch at Tier N of Figure 1, it is assumed that if $i < j$ then criterion i has a higher priority than criterion j (i.e. criterion 1 has higher priority than criterion 2 and so forth). Since there are m criteria, the importance order suggests that we should require that the weights, w_i, $i=1,m$, have the following relation:

$$w_1 \geq w_2 \geq \ldots \geq w_m.$$

Therefore, given the importance order and the criteria values for alternative j, the best (worst) composite score that alternative j can achieve is determined by solving the following linear programs (LPs):

Best (Worst) Additive Value:

$$\max(\min)_w \ V_j = \sum_{i=1}^{m} w_i v_{ij}$$

$$s.t. \ \sum_{i=1}^{m} w_i = 1$$

$$w_1 \geq w_2 \geq \ldots \geq w_m \geq 0.$$

The best additive value is found by maximizing the objective function while the worst additive value is found by minimizing the objective function. The first constraint is a normalizing constraint. The second, fixes the importance order and restricts the weights to be positive. The above linear programs can be easily solved analytically. For $k=1,\dots,m$, let

$$S_{kj} = 1/k \, \Sigma_{i=1,\dots,k} v_{ij}. \tag{1}$$

Then, the best or maximum additive value, *Max V*, for alternative *j* is given by :

$$Max\ V_j = max_k \{S_{kj}\}. \tag{2}$$

The worst or minimum additive value, *Min V*, for alternative *j* is given by :

$$Min\ V_j = min_k \{S_{kj}\}. \tag{3}$$

For proofs see Yakowitz *et al.* (1993a) or Fishburn (1965). The above is equivalent to evaluating the objective function at the extreme points of the constraint set, which occur at the points {1,0,0...,0}, {1/2,1/2,0,...,0}, {1/3,1/3,1/3,0,...,0},..., {1/N,1/N,...,1/N}, and selecting the vectors that produce the min and max. All other feasible weight vectors can, of course, be written as linear combinations of these N vectors. This result is also known as Paelinck's Theorem and is proved and described in Claessens *et al.* (1991).

In the case of equal importance of some criteria, there are strict equalities in the importance order constraint set, i.e. $w_j = w_{j+1}$ for j in a subset, $\bar{I}$, of the integers 1 through m. If we define $K = \{1, 2, \dots, m\} \setminus \bar{I}$, then the above formulas for *Max* and *Min V* apply if k is restricted such that $k \in K$.

Calculations for cases in which it is desired to specify the level of preference between criteria (for example, criterion 1 is to have a weight at least twice that of criterion 2) require a modified definition of (1). Suppose that one supplies constants $c_i \geq 1$, i=2,...,m, that imply the following relationships:

$$w_1 \geq c_2 w_2,\ w_2 \geq c_3 w_3,\ \dots,\ w_{m-1} \geq c_m w_m \geq 0.$$

Then if we let $c_1 = 1$ the required modification to (1) is as follows[1]:

$$S_{kj} = \frac{1}{\sum_{i=1}^{k} \frac{\prod_{p=1}^{k} c_p}{c_i}} \sum_{i=1}^{k} \frac{v_{ij}}{c_i} \prod_{r=i}^{k} c_r \ . \tag{4}$$

For each alternative, the solutions (2) and (3), using (1) or (4), determine the maximum and minimum additive value possible for any combination of weights that are

[1] This formula corrects a typographical error on page 175 of Yakowitz, Lane and Szidarovszky (1993a).

consistent with the importance order of the criteria/attributes. Having these two objective values available immediately alerts the DM to the sensitivity of each alternative to the weights possible with the current importance order of the criteria. These values can be displayed graphically (illustrated later) in the form of side by side bar graphs with the best value for each alternative at the top of each bar and the worst value at the bottom.

An alternative that exhibits little difference between the *best* and the *worst* values indicates that this alternative is relatively insensitive to the weights consistent with the given importance order. Additionally, if the worst value of one alternative is greater than the best value of another alternative, then clearly, that alternative dominates the other alternative. These alternatives are a subset of those that dominate in additive value with respect to a given importance order and are said to *strongly* (Yakowitz *et al.*, 1993a) or *absolutely* (Salo and Hämäläinen, 1992) *dominate*. With respect to the given importance order and in the absence of strong or absolute dominance, one can determine dominance in additive value of Alternative j by Alternative k if and only if $S_{ik} \geq S_{ij}$ for all $i=1,2,\ldots,m$, and $S_{ik} > S_{ij}$ for at least one i (see Yakowitz *et al.*, 1993a, for a discussion and theorems).

3.2. Computing the best and the worst values for a multi-level hierarchy

One way to account for a hierarchy of the criteria and still provide the range from the *best* to the *worst* composite scores is to include additional constraints in the LPs given above. For example, suppose we have a three tier hierarchy, and each element i in Tier 2 is composed of t_i sub-criteria in Tier 3, the terminating level. Let $v_{i,k,j}$ and $w_{i,k}$, $k=1,\ldots,t_i$ indicate the values (scores) for alternative j, and sub-weights (unspecified), respectively, associated with sub-criteria k of criteria i. Then, the following two constraints for each i are added to best/worst LPs to account for this hierarchy:

$$w_i = w_{i,1} + w_{i,2} + \ldots + w_{i,t_i}$$
$$w_{i,1} \geq w_{i,2} \geq \ldots \geq w_{i,t_i} \geq 0.$$

The objective functions of the best/worst LPs for alternative j are then replaced by:

$$\max(\min) \textstyle\sum_{i,k} w_{i,k} v_{i,k\,j} .$$

Again, one can obtain the range from maximum to minimum without the need to specify weights or sub-weights. Linear modifications due to more general hierarchical considerations are easily made in this manner. Note that the above formulation makes no assumptions regarding the ordinal ranking of attributes on different branches, a desirable feature in cases when it is not possible or undesirable to prioritize attributes across branches. An explicit linear program for computing the maximum and minimum

V for any hierarchy can be formulated and solved. The notation needed to indicate each level of the hierarchy, however, becomes very cumbersome. Solving the resulting linear programs explicitly for each alternative is not necessary, however, since a simple algorithm that considers each portion of the hierarchy in an optimal manner is developed here. The algorithm, which could also be described in dynamic programming (Sniedovich, 1992) terms, is more suitable for examining the effects of changing priorities than a linear programming model. Calculating min and max V is an intuitively simple procedure when performed from the lowest tier up. The contribution of each level is solved optimally in an iterative manner yielding the optimal objective values (min or max) once the top tier is reached. To illustrate this fact, the solution procedure will be described for the four tier decision hierarchy of Figure 2 and then applied to the problem of considering an alternative farming system on a small watershed (field size) in western Iowa.

3.3. Algorithm for computing the range of values under a given hierarchy

The following procedure is described to obtain the range from the *best* to the *worst* of the additive value function under the hierarchy illustrated in Figure 2. The procedure for any other hierarchical variation is handled in a similar manner and will become transparent.

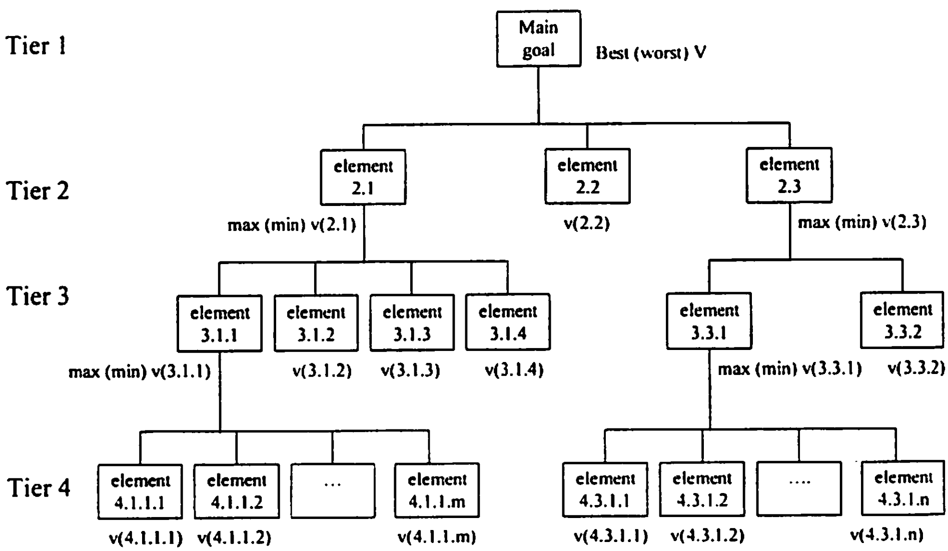

Figure 2. Decision hierarchy for algorithmic explanation.

For each alternative under consideration, we assume that the associated value for the minal elements has been determined by some means. Thus, for Figure 2, the values licated by $v(2.2)$, $v(3.1.2)$, $v(3.1.3)$, $v(3.1.4)$, $v(3.3.2)$, $v(4.1.1.1)$,...., $v(4.1.1.m)$, $t.3.1.1)$,..., $v(4.3.1.n)$, are known for each alternative and are in a common range. All lices are with respect to the hierarchy of Figure 2, which indicates the inputs and lculations required. Calculations start at the lowest Tier in the hierarchy. In this case, er 4.

er 4.

Compute for each alternative j,

$S(4.1.1)_{kj} = 1/k\ \Sigma_{i=1,\dots,k}\ v_j(4.1.1.i),\ k=1,\dots,m,$

and $S(4.3.1)_{kj} = 1/k\ \Sigma_{i=1,\dots,k}\ v_j(4.3.1.i),\ k=1,\dots,n.$

Then according to Eq. (1) and (2),

$max\ (min)\ \ v_j(3.1.1) = max\ (min)_k\ \{S(4.1.1)_{kj}\}$, and

$max\ (min)\ \ v_j(3.3.1) = max\ (min)_k\ \{S(4.3.1)_{kj}\}$.

ier 3.

Compute the following for each alternative j:

$S_{max}(3.1)_{kj} = 1/k\ \Sigma_{i=1,\dots,k}\ v_j(3.1.i),\ for\ k=1,\dots,4,$

with $v_j(3.1.1) = max\ (v_j(3.1.1))$, and

$S_{min}(3.1)_{kj} = 1/k\ \Sigma_{i=1,\dots,k}\ v_j(3.1.i),\ for\ k=1,\dots,4,$

with $v_j(3.1.1) = min\ (v_j(3.1.1))$.

$S_{max}(3.3)_{kj} = 1/k\ \Sigma_{i=1,\dots,k}\ v_j(3.3.i),\ k=1,2,$

with $v_j(3.3.1) = max\ (v_j(3.3.1))$, and

$S_{min}(3.3)_{kj} = 1/k\ \Sigma_{i=1,\dots,k}\ v_j(3.3.i),\ k=1,2,$

with $v_j(3.3.1) = min\ (v_j(3.3.1))$.

Then:

$max\ (min)\ v_j(2.1) = max\ (min)_k\ \{S_{max(min)}(3.1)_{kj}\}$, and

$max\ (min)\ v_j(2.3) = max\ (min)_k\ \{S(3.3)_{kj}\}$.

'ier 2.

Compute the following for each alternative j:

$S_{max}(2)_{kj} = 1/k\ \Sigma_{i=1,\dots,k}\ v_j(2.i),\ for\ k=1,\dots,3,$

with $v_j(2.1) = max\ (v_j(2.1))$, and

$v_j(2.3) = max\ (v_j(2.3))$, and

$S_{min}(2)_{kj} = 1/k\ \Sigma_{i=1,\dots,k}\ v_j(2.i),\ for\ k=1,\dots,3,$

$v_j(2.1) = min\ (v_j(2.1))$, and

$v_j(2.3) = min\ (v_j(2.3))$.

Then:

$Best\ (Worst)\ \ V_j = max\ (min)_k\ \{S_{max(min)}(2)_{kj}\}$.

A bar graph indicating the range from the *Best V*, the top of each bar, to the *Worst V*, the bottom of each bar, for each alternative would aid the decision maker by indicating possible domination and the sensitivity of each alternative to the priorities in the hierarchy. As discussed and described in Yakowitz *et al.* (1992, 1993a), the alternatives can be ranked based on the average of the *Best* and the *Worst* V_j. Clearly from the end of Section 3.1 above, this ranking preserves all dominance relationships and provides a means of ranking non-dominated alternatives that takes into account all possible DM perspectives with respect to the current importance ordering. It is well known that for non-dominated alternatives it is possible to have rank reversal even for weight sets that are consistent with the hierarchy importance orders. Therefore, ranking based on the midpoint can be viewed as less risky than ranking based on a single set of weights since the midpoint ranking includes information from the most pessimistic as well as most optimistic viewpoints considering the entire decision hierarchy structure.

Changing an importance ordering in any tier in the hierarchy, requires only recalculating appropriate max and min values in the tiers that appear above the point at which the change is made. For example, suppose one wishes to consider the scenario in which the elements previously ordered in Tier 2 of Figure 2 are reversed. Then, only those calculations indicated under Tier 2 given above, need to be computed again. Other scenarios that reflect the differing priorities of interested parties or multiple decision makers could be quickly examined. If one or two alternatives stand out as doing well under multiple decision scenarios, one would have a defensible basis for supporting these alternatives and avoiding unnecessary argument. In fact, if two alternatives are non-dominating and changing priorities still produces midpoint values that prefer one alternative over the other, then ranking based on the midpoint values is less risky in the sense that it preserves the ranking of the majority of decision makers that agree with one or the other of the decision hierarchy structures examined.

4. Evaluating alternative farming systems for a field in western Iowa, USA

Under the management of National Soil Tilth Laboratory of the US Department of Agriculture - Agricultural Research Service(USDA-ARS) is the Deep Loess Research Station located near Treynor, Iowa. Watershed #1 is a 32 hectare field that has been planted annually with corn (*Zea mays* L.) on the contour since research on the watershed was initiated in 1964. The tillage practice in current use is known as deep disking. The current system was used to determine baseline values of each of the attributes. To improve farm net return as well as concern for nitrate concentrations in the ground water, a corn and soybean (*Glycine max* L.) crop rotation is being considered along with four different tillage practices: deep disking (DD), chisel plow (CP), ridge till (RT), and no till (NT). As an indication of the benefit obtained by changing the cropping system alone, an alternative that uses the no till practice but continues the planting of only corn (NT-c) is also included. The alternatives are compared based on predicted amounts of sediment, nutrients, and pesticides leaving the field, which have an impact on surface and ground water quality, as well as the farmer's predicted net returns for each of the five alternative management systems. Figure 3 illustrates the structure of the decision hierarchy and the attributes used to evaluate each management system.

Table 1 contains the values for each attribute for each alternative determined using a USDA-ARS decision support system (see Yakowitz *et al.*, 1992, 1993b). Each management system was simulated for 24 years and the average annual values of the predicted amounts of the listed attributes were scored compared to the predicted amounts for the existing management system. All scores range from 0 to 1 for all attributes. A score of better than 0.5 indicates that that management system improved with respect to that attribute over the current system, while a score of less that 0.5 indicates a less desirable result.

Table 1. Attributes and values or scores for four simulated farm management systems on a field in western Iowa.

	Alt. #1 DD	Alt. #2 RT	Alt. #3 CP	Alt. #4 NT	Alt. #5 NT-c
net income	0.67	0.82	0.71	0.82	0.66
nitrates (s)	0.51	0.98	0.91	0.99	1.00
nitrates (ss)	0.74	0.66	0.73	0.52	0.30
phosphorus	0.38	0.93	0.81	0.95	0.96
sediment	0.34	0.97	0.91	0.99	1.00
pesticide A	0.92	0.81	0.97	0.85	0.44
pesticide B	0.94	0.79	0.98	0.86	0.44

Applying the algorithmic steps detailed above, the results for the importance orders (left to right on common branches) indicated in Figure 3 are illustrated in the Figure 4a bar graph. When economic improvement has a higher priority than environmental improvement, all alternatives except #5 do better than the baseline or current management system (indicated at the 0.5 point), even at their worst scores. Alternatives #2 and #4 attain the highest best scores. Ranking based on the midpoint of the bars (average of best and worst) puts Alternative #2 on top, Alternatives #3 and #4 tied in second place, followed by Alternative #1 and then #5. This order of the alternatives never ranks an alternative above one that it is dominated by (Yakowitz *et al.* 1993a). Figure 4b indicates the results when the importance order at the first branch (tier 2) is reversed. In this case, environmental improvement is given a higher priority than economic improvement.

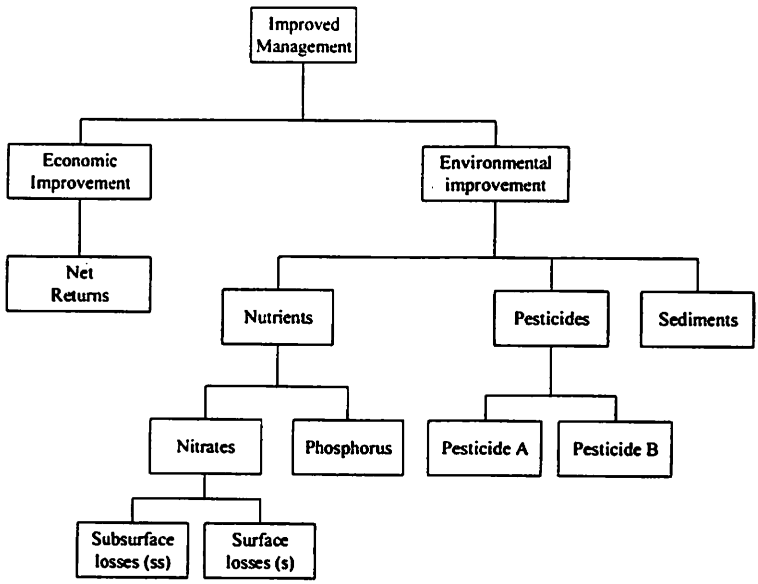

Figure 3. Decision hierarchical structure for farm management system selection.

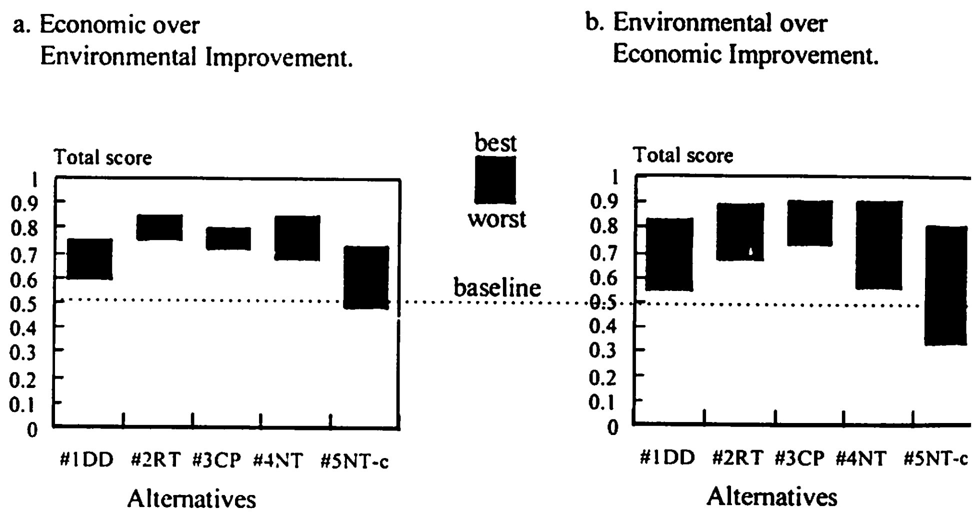

Figure 4. Value range from best to worst for farm management system problem. Results when economic improvement is preferred over environmental improvement (a.) and results when environmental improvement is preferred over economic improvement (b.).

While all of the first four alternatives do at least as well as the baseline, Alternative #3 could be preferred over the others since it has both a high best and worst score. The range of values possible for Alternative #3 indicates that this alternative is the least sensitive to the weights. In other words, this alternative is affected the least by any particular decision maker's weight preferences given the importance order structure of the hierarchy of Figure 3. Alternatives #2 and #3 perform well with respect to both goals. In fact, the farmer and the community would benefit by adopting any one of the alternatives considered in this example study and would benefit the most with respect to the given criteria by adopting either Alternative #2, RT, or #3, CP. Other decision hierarchy scenarios that take into account both on and off farm impacts, long and short term risks, additional criteria, and other alternatives could be examined to provide further confidence in a choice.

5. Other applications, extensions and concluding remarks

The method described herein explicitly calculates the full range of values possible for an additive value function subject to the priorities of a hierarchical decision structure. The procedure involves the solutions to two simple linear programs and a solution method not requiring an LP solver was presented. This procedure also minimizes the number of calculations needed to examine the effects of changes to the hierarchical structure and can lend insight into the evaluation process. The methodology has the advantage of including all possible decision maker points of view, from the most pessimistic to the most optimistic, within the structure of the hierarchy.

Some remarks with respect to the bar charts and evidence of domination or non-domination need to be addressed. First, ranking based on the midpoint is a basis for a decision but other factors should be considered. For example, it is clear that if the results produce a lengthy sized bar (additive value range) for an alternative, that alternative is sensitive to weights consistent with that hierarchy. Therefore an alternative that has a high and narrow range from best to worst does well and is less risky with respect to the feasible weights for the given hierarchy. If the bar for one alternative contains the range of the bar for another alternative, then clearly those alternatives are non-dominating and rank reversal with respect to specific weight vectors can occur. It is also possible that if the bars of two alternatives overlap, one may or may not be in a situation of domination, and rank reversal is possible in this case too. However, these are exactly the alternatives that one requires a method for ranking. In this latter case, overlapping bars, one can determine additive value function domination under a hierarchy only by looking at all of the extreme point solutions, which is not a trivial problem in a deep hierarchy. The method presented here for determining the full range an then ranking captures all possible decision maker opinions on the weights and uses all of this information by ranking based on the midpoint. When there is not a clear preference for one alternative over another (overlapping situation) one can observe what happens to the results when one considers a change in the hierarchy at an upper level (in the example presented in the last section, this meant switching the order of importance of the economic and environmental sub-categories). If this switch still supports one alternative over another based on the midpoint, then it is further support for this ranking since now, not only does this ranking capture the majority of possible decision makers that agree with the first hierarchy but also those that agree with the second. The ranking is in this sense less risky.

The method proposed above is well suited for determining a quality index for various purposes. For example, currently under development is the determination of a decision hierarchy that will properly define an *Index for Rangeland Health*. This index could then be used as a decision aid in determining, for example, where remedial action is needed, or to which areas limited funding might be allotted or which land areas are best suited for a given purpose or for purchase or exchange. A hierarchical structure that includes Biodiversity Conservation, Soil Stability and Watershed Function, and Animal Production at the second tier level followed by those elements that define or contribute to these topics is being proposed. This work is being conducted by cooperative research between scientists with the Agricultural Research Service (ARS) and the Natural Resources Conservation Service (NRCS) of the United States Department of Agriculture (USDA). In addition, the methodology described in this paper has been proposed for use in the development of a *Soil Quality Index* by the above agencies for all regions of the United States.

Index ranges can be compared and contrasted in many different ways. For example, given a specific hierarchy structure, the index range for a number of rangeland sites can be viewed side by side. Alternatively, a single site's index ranges for multiple decision hierarchy structures or scenarios could be viewed in a single graph. Temporal comparison of the index range for a single site given a single hierarchical structure may also be of interest for long term planning.

As illustrated in the farming system problem above, the method can be a valuable aid to decision makers especially in the case of multiple decision makers or stakeholders. The ability of the method to take into account other viewpoints and to examine the impact of many scenarios on the ranking of the alternatives, could make it a strong negotiation tool between conflicting parties.

We suggest that the procedure introduced here could also be a valuable tool in the analysis of hierarchies with more than two levels which according to final remarks in Lootsma (1996) has several open research issues. The effect of changes to the structure such as splitting criteria on the additive value measurement range is easily examined for any permutation, addition or deletion to the existing structure. Furthermore, this information is available at each branching point in the hierarchy for each alternative and can be used to determine the impact of any changes. A generic spreadsheet macro program has been developed to apply the method.

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