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Methods for Generating Land Suitability Maps: A Comparative Evaluation

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Land resource inventories to determine land suitabilities have become a standard part of planning analysis at many scales. Any attempt to review, compare, evaluate, or improve upon the myriad of case studies, many only partially documented and in limited circulation, suffers from the lack of reference to a common framework. This article develops a general statement of the purpose and character of land suitability analysis, a taxonomy of existing methods for identifying homogeneous areas and rating them as to suitability for specific uses, and a comparative evaluation of these methods.

A suitability map shows the spatial pattern of requirements, preferences, or predictors of some activity. Although the use of the word suitability is often restricted to analyses related to development, the analytical concepts involved are much more general. Using the word loosely, a suitability map for natural hazards (Patri, Streatfield, and Ingmire 1970) identifies the pattern of and characteristics associated with some hazard, such as earthquakes. A suitability map for vulnerability to impact (Murray, et al. 1971) shows the pattern of characteristics that portend varying degrees or likelihoods of damage from some action elsewhere. For example, low lying lands near flood plains are vulnerable to flooding if there is additional development upstream. Suitability maps for natural hazards, vulnerability to impacts, or off-site impacts are usually preliminary steps in the development of suitability maps for the location of land uses, which might range from nature preserves to nuclear power plants. All of these applications of suitability mapping rest on the same general analytical base. The methods described here might be applied to any of them. For simplicity in this article, most of the discussion focuses on land use rather than in terms of hazard, vulnerability, or impact.

Determining the levels of particular costs or impacts is not the central issue here. The primary issue is how such cost or impact information can be manipulated and combined to generate suitability maps for land uses. In this article *suitability* will be assumed to include market, nonmarket, and nonmonetary costs and impacts. The difficulties in obtaining such measures in practice, of course, remain; but discussing these difficulties simultaneously would muddle the attempt to distinguish among methods for generating suitability maps. MacDougall and Brandes (1974) provide a bibliography covering many of the aspects of land resource analysis not covered in this article.

The output of a land suitability analysis is a set of maps, one for each land use, showing which level of suitability characterizes each parcel of land. This output requirement leads directly to two necessary

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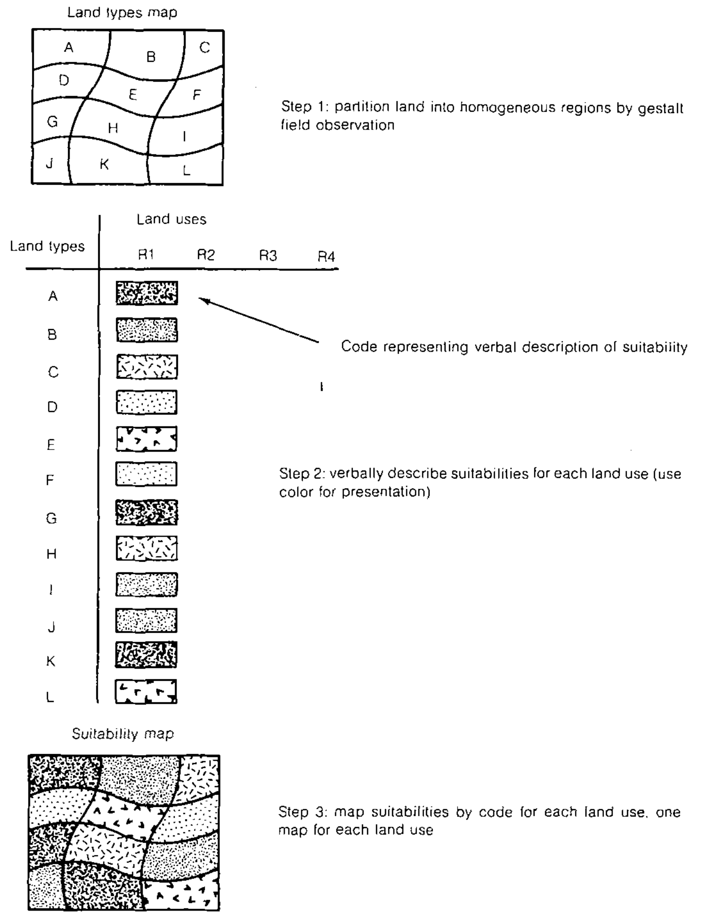
Figure 1. Gestalt method



components of any method: (1) a procedure for identifying parcels of land that are homogeneous and (2) a procedure for rating these parcels with respect to suitability for each land use. The next section describes a method in which each of these components is carried out directly without any consideration of the factors that determine the homogeneity of regions and the suitability of land uses. This method sets the stage for considering other methods that explicitly combine factors.

Gestalt method

The essence of the gestalt method is that the homogeneous regions are determined directly through field observation, or perhaps aerial photographs or topographic maps, without consideration of individual factors such as slope, soils, vegetation, and so on. A gestalt is a whole that cannot be derived through consideration of its parts. A strict interpretation of gestalt would mean that individual factors that could be manipulated to provide understanding of the whole do not even exist.

The gestalt method of suitability analysis can be described in three steps and is diagramed in Figure 1. First, the study area is partitioned by implicit judgment into homogeneous regions, such as uplands and valley floors. Second, a table is developed that verbally describes the effects or problems that will occur in each of the regions if each of the potential land uses is located there—e.g., this region presents no construction problems, but has no amenities that would render it a pleasant place in which to live. Note from Figure 1 that some regions identified in step 1 may be determined in step 2 to be of equal suitability for some uses, because the homogeneous regions in step 1 are based on perceived natural land types, not on suitabilities for any one land use. Third, a set of maps, one for each land use, is drawn to show the homogeneous regions in terms of their suitability. Graphic presentation of the map requires that each descriptive suitability comment be represented by some color or symbol as in Figure 1.

It can be argued that any land suitability analysis must rely on gestalt judgments at some level of specificity. For example, vegetation cover types might be observed in the field and noted on aerial photographs. The determination of cover type is thus based on implicit judgment rather than on explicit rules. Cover types can be thought of as a combination of various lower level factors—age, understory species, canopy species, and management practices. In this case, a gestalt method is being used to generate vegetation cover type, a factor to be combined with other factors in a later step. Once a factor such as cover type is identified, however, one can no longer use the gestalt method at some higher level because by definition it does not combine factors. Thus, although the gestalt method may underlie any other method at the elemental level, in this article gestalt method refers to attempting to determine land suitability directly in one gestalt judgment.

Limitations of gestalt method

Few people have the capability, and planners seldom have the longstanding local experience, to deal with land classification and interpretation as a gestalt. Some land resource inventory processes are specifically intended as a means of immersing the planner in a study region, "understanding the place" as McHarg (1969) calls it, so that gestalt judgments can be made. However, land suitabilities generated without identification of the factors considered are difficult for other people to scrutinize or confirm. The results are therefore difficult to communicate convincingly to decision makers.

Given both the scarcity of people capable of using the gestalt method and the frequent necessity of communicating results in public forums, more explicit methods must be found for generating land suitability maps. More explicit methods inherently require the consideration of factors—the variables or dimensions such as soils, slope, vegetation, and existing land use—that enter into the determination of suitabilities. The remainder of this article is concerned with how such factors can be combined in relatively explicit ways to yield land suitability maps.

Two early land suitability studies demonstrate the evolution from the gestalt method toward more explicit procedures. Hills (1961) devised a system of land types so that homogeneous regions, observable as gestalts in the field, could be grouped or partitioned to various levels of specificity for various planning tasks. Realizing that identifying homogeneous regions or natural land types as gestalts was a rare skill, Hills also devised a numerical rating scheme so that less-skilled personnel could derive land type regions from individual factors. The "weights" in Hills's rating scheme were fitted so as to replicate the suitabilities obtained by the gestalt method. The assumption was that the gestalt method yielded correct results. The only interest in the numerical rating scheme was that it could be used by less-skilled personnel and could be forced to yield the same results as obtained through a gestalt method.

The early work of Lewis (1969) can be viewed as testing a hypothesis that river corridors, which are readily observable as gestalts on aerial photographs or topographic maps, are excellent surrogates for regions of high cultural and scenic amenity. River corridors are indeed good surrogates, especially in glaciated midwestern landscapes. Once this hypothesis was confirmed, statements could be made about the suitability for various uses of the river corridor without mapping and explicitly combining the individual cultural and scenic elements each time a suitability analysis was conducted.

Another general response to the difficulties of applying gestalt was to devise explicit methods of combining factors in order to *discover* suitabilities. The assumption in this case is that the method yields valid suitability ratings because of the properties of the method itself. The results are not judged by conformation to some gestalt or empirical standard. This general approach was the one taken by McHarg. The ordinal and linear combination methods presented in the next section are generally perceived from this perspective.

Determining suitabilities by mathematical combination

This section describes three general methods for generating suitability maps by mathematical operations. These operations simultaneously identify homogeneous regions and determine suitability ratings.

Ordinal combination method

The ordinal combination method, sometimes referred to as the McHarg method because of its use in the Richmond Parkway study (McHarg 1969), is diagramed in Figure 2. The first step is to map for each of a set of factors (e.g., soils, slope, vegetation, land use) the distribution of types (soil types, slope classes, vegetation types, land use types). Factors are distinct dimensions along which variations among parcels of land can be described. Types are nominal labels for particular characteristics along a particular dimension (e.g., Drummer soil). The first step is illustrated in Figure 2 using one factor with three types and a second with four types. An actual study would include many factors and more types of each, but such expansion leads only to confusion for the purposes at hand.

The second step consists of filling in a table that indicates (in this case by levels of gray) the relative suitability rating for each land use of each type (e.g., soil type) of each factor (e.g., soils). The ratings assume consideration of all the characteristics of the type (e.g., for soil type this might include permeability, productivity, water table, etc.) and all the costs and impacts of the land use if located on this type. These ratings may be derived through use of other tables, maps, and extensive study (see, for example, Lyle and von Wodtke 1974), but the process of deriving them is not the central issue here.

The third step consists of making a suitability map for each land use based on each factor. For each land use the type designations on each factor map from step 1 are replaced with the appropriate gray levels from the particular land use column in the table from step 2. Step 3 is illustrated in Figure 2 for land use R1.

The fourth step consists of overlaying, for each land use, the suitability maps of individual factors. A composite suitability map is thus obtained for each land use. Each of these composite maps shows the spatial pattern of levels of suitability for the given land use.

Limitations of ordinal combinations. By describing the same process using a numerical index to represent gray levels some assumptions emerge that implicitly underlie the ordinal combination. Figure 3 is identical to Figure 2 except that gray levels have been replaced by an equivalent ordinal number system, an ordering of types for each factor. Step 4 in Figure 3 involves the addition of what appear to be numbers on an ordinal scale. This addition is an invalid mathematical operation in the sense that the mathematical properties usually assumed do not hold.

It is possible to manipulate numbers using any set of rules one might concoct; the point is, however, that one must be careful not to assume the usual mathematical properties when the required conditions are not being met. For the above described procedure to be valid in the usual system of arithmetic operations, the numbers must be assumed to be on an interval scale, such that the distances (intervals) between various ranks are equal. Further, the numbers assigned to the types of each factor must be assumed to be numbers in the same interval system, meaning the units used to measure intervals of suitability must be the same. Before considering modifications to handle these inapplicable assumptions, it may be helpful to read the appendix, which establishes some frequently cited, but still frequently misunderstood, characteristics of alternative measurement systems.

Because the operation of overlaying maps in the ordinal combination method is equivalent to addition, an assumption that the ratings of each factor are independent is also implied. This method cannot deal with the situation where the relative suitability for a particular use of a given soil type depends on the slope type with which the soil type occurs. A slope of 25 percent occurring on well-drained soil over clay might be quite disastrous for high cost residential development, as demonstrated in California, and therefore receive a low rating. At the same time, a slope of 25 percent and well-drained soil on a dif-

Figure 2. Ordinal combination method with gray levels

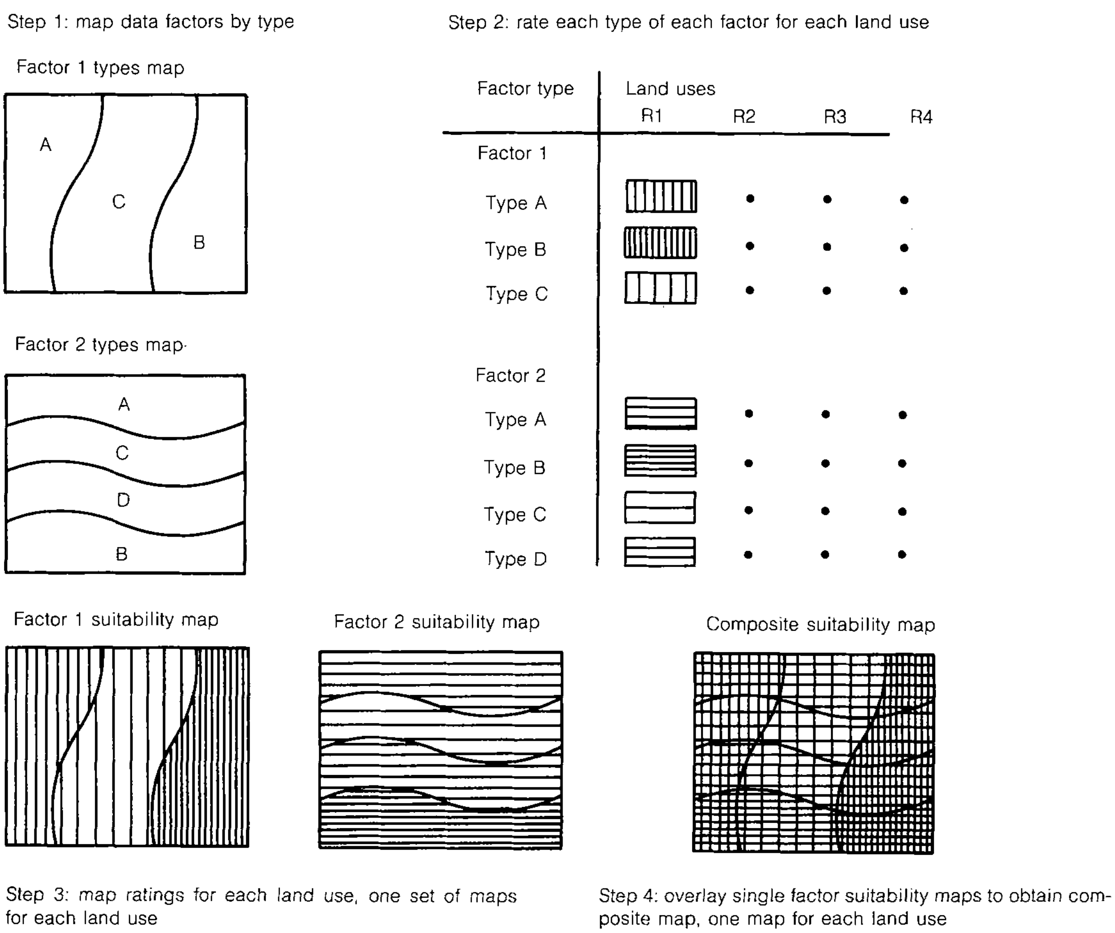
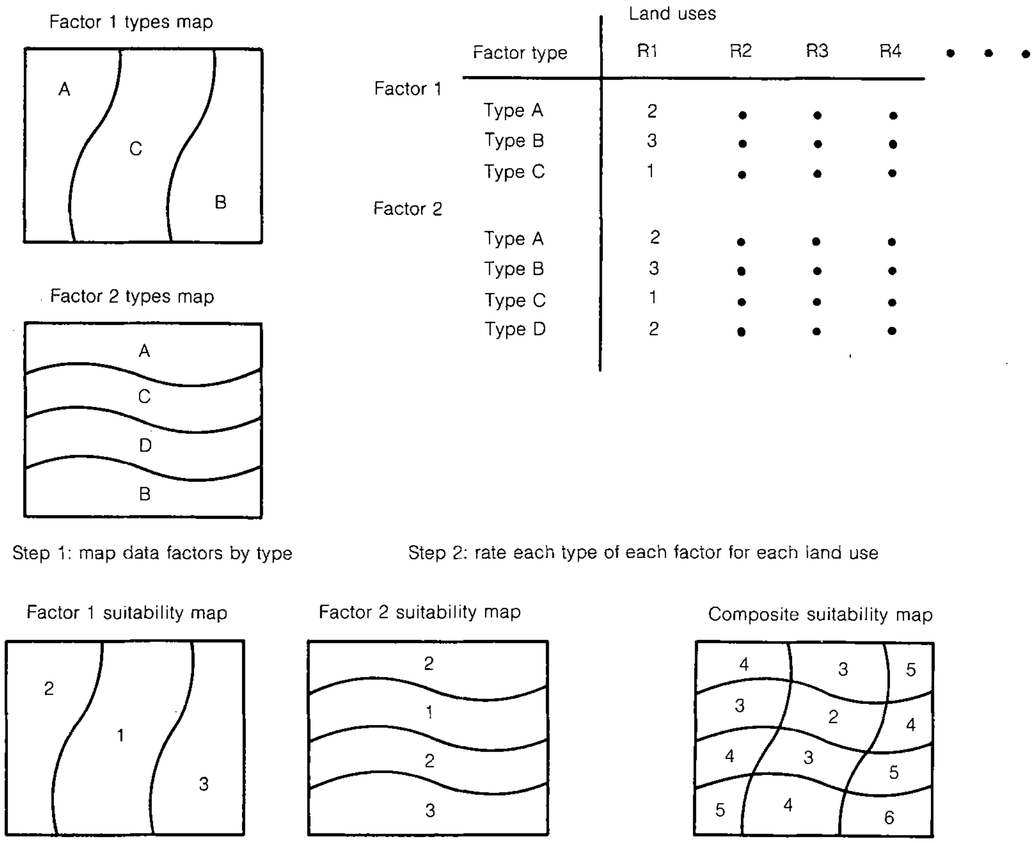


Figure 3. Ordinal combination method with numerical index



Step 1: map data factors by type

Step 2: rate each type of each factor for each land use

Step 3: map ratings for each land use, one set of maps for each land use

Step 4: overlay single factor suitability maps to obtain composite, one map for each land use

ferent subsurface or a slope of 5 percent on well-drained soil over clay might be quite acceptable. The suitability may be a nonlinear and nonseparable (i.e., multiplicative) function of the combination of types; it is not, in general, simply the sum of the suitabilities of the individual types.

Ordinal combination is *not* a good method for generating suitability maps because of the implied addition of ordinal scale numbers and because of the implied independence of factors.

Linear combination method

The most frequent response to this understanding of the measurement assumptions of the ordinal combination method has been to play the weighting game. The usual procedure is illustrated in Figure 4. The types within each factor are rated on separate interval scales. Then a multiplier—often identified as an *importance* weight—is assigned for each factor as shown in step 2. The ratings for each type are multiplied by the weight for the factor. The suitability rating for a particular region is then the sum of the multiplied ratings, or in mathematical terms, the linear combination. The effect of multiplication by the weights is merely to change the unit of measure of the ratings on each factor by the ratio of the multipliers so that all of the ratings are on the same interval scale (e.g., if one factor is in dollars and another in cents, then the first would be multiplied by 1 and the second by 0.01 to put both in dollars). The ratings can then be added. Thus, the units of measure for suitability with respect to each factor can be made equivalent after rating the types for each factor individually on interval scales with different measurement units.

Rating procedures. A straightforward explanation of the linear combination method is given by Ward and Grant (1971), although (or because) the example is entirely artificial as is the one here. Each type of each factor is assigned an interval rating from one to nine, where nine is most preferred. Each of the factors is then assigned a weight. The information is then combined by the standard formula for a weighted average: the sum of the products of the ratings multiplied by the respective weights for each factor, divided by the sum of the weights.

$$\text{Rating} = \frac{w_1 r_1 + w_2 r_2 + \cdots + w_n r_n}{w_1 + w_2 + \cdots + w_n}.$$

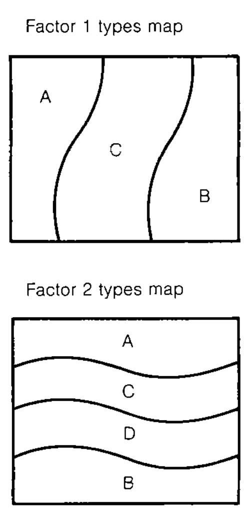
A *1* is the minimum rating permitted in the Ward and Grant example, suggesting that a system visualized as ordinal is being scaled by multiplication and addition. One therefore must assume, as is indicated implicitly, that *1* represents zero, and signifies no amenities and all costs (see appendix). The weights are merely relative proportions among the units in which the suitability within each factor was measured in the first place. One must be wary of using units of measure resulting in single factor ratings of 4, 6, and 8 with an importance of 1, versus ratings using units resulting in 2, 3, and 4 with an importance of 2. This ambiguity occurs in the Ward and Grant example. The importance weights are not independent of the units used to measure suitability in terms of the individual factors.

Another alternative is to transform the set of rating values for each factor to a range that is common for all factors. For example, a transformation of the form $r_i' = r_i / r_i^{\max}$, where $r_i^{\max}$ is the maximum rating for any type for factor one, would transform all ratings for the factor to the range zero to one. This transformation expresses the ratings in an interval unit that makes all factors equally influential in determining the resultant variation in suitability among regions. This transformation makes the use of importance weights more comprehensible in that it eliminates any differences attributable to the unit of measure used for a particular factor. It is then possible to (re)introduce these differences through importance weighting without the ambiguity found in the Ward and Grant example.

Another rating scheme, which is equivalent to a linear combination, is familiar to many as a method frequently used in grading examinations. First, a total possible suitability (test score) of 100 is divided among various factors (questions) so each is worth a certain proportion of the total. Each type (answer) of each factor (question) is then rated as to its suitability (quality) relative to the proportion of the total score assigned to the factor (question). For example, one might assign (receive) a 7 out of a possible 10 on a factor (question). The scores for each factor (question) are then summed to get a total score for a site (exam). The total score is usually expressed as a percentage of the maximum possible score. This procedure has been proposed for environmental impact assessment (Battelle 1971). A procedure based on the proportional scoring concept is also used by Lyle and von Wodtke (1974).

The result of the weighted combination is a single measurement scale with a common unit. Some people find it easier to evaluate all the types of all the individual factors directly in a common unit rather than devising separate units of measure and weights

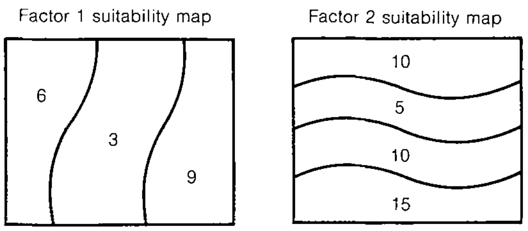
Figure 4. Linear combination method



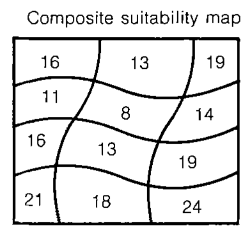
Step 1: map data factors by type

Factor types	Land uses R1	R2	R3	R4	• • •
Factor 1 weight	3				
Type A	2	•	•	•	
Type B	3	•	•	•	
Type C	1	•	•	•	
Factor 2 weight	5				
Type A	2	•	•	•	
Type B	3	•	•	•	
Type C	1	•	•	•	
Type D	2	•	•	•	

Step 2: rate each type of each factor and weight each factor for each land use



Step 3: map ratings for each land use, one set of maps for each land use



Step 4: overlay single-factor suitability maps to obtain composite, one map for each land use

for each factor. One way of initiating such an evaluation is to choose an arbitrary value, say 100, for the suitability of a certain type (e.g., Drummer-Flannagan soil) of a certain factor (soils) for a certain land use (e.g., row crop agriculture). All other evaluations are then made with reference to this standard, using the unit implied. The dollar is one unit of valuation that people are used to applying to a wide, but still limited, range of options. Therefore, another useful evaluation procedure is to express suitabilities by factor directly in estimated dollar units (Hopkins 1975).

Although some people do not believe that such all-inclusive ratings can exist, the same thing is being accomplished through the weights in the usual linear combination method. The protection of not understanding exactly what the ultimate ratings will be has simply been removed. Freeman (1970) has provided a straightforward explanation of the necessity of valuation in making choices (see also Hopkins, et al. 1973). One can do the valuation explicitly or implicitly, but any choice among alternatives with respect to a set of factors implies a relative valuation of factors at least sufficient to make that choice.

Independence of factors. The linear combination method corrects the measurement problems of the ordinal combination method, but the problem of handling interdependence among the factors still remains. The linear combination method cannot deal with the situation where the relative suitability for a given land use of a type on one factor depends on the type on any of the other factors. Despite its inability to handle interdependence among the factors, the linear combination approach is still frequently used, as implied for example by the discussion of weighted overlays in Steinitz, Parker, and Jordan (1976). There are three possible justifications for continued use of the linear combination method.

First, the factors might be known to be independent because they had been derived through factor analysis or some similar statistical technique that generates independent factors. This possibility, and the need for independent factors as inputs to a cluster analysis of regions, was recognized in the Rice Center (1974) study. The researchers implemented it, however, only to the extent of using human judgment to identify independent factors. Durfee (1972) has discussed the potential for application of factor analysis, but it has not been applied to justify using a linear combination method in determining suitabilities. Limited experimental experience suggests that, because of the data requirements and difficulty of interpretation, using factor analysis to identify factors is not worthwhile for most suitability analyses.

The second possible justification is that linear combination, though highly imperfect, is the best method available in the sense that the benefits from any alternative method would not exceed the cost of applying that alternative. The rules of combination method described below can handle interdependence and requires no transformation to numerical values. Therefore, the linear combination method cannot be justified as the best available method.

The third possible justification is that the factors typically used such as bedrock geology, surface geology, ground water, surface water, soils, slope, vegetation, and existing land use can be deductively determined to be independent. Although examples of interdependence among these factors are harder to identify than some people might expect, there are many. Recall the above case of slope, subsurface, and soils. Another example would be adding the amenity for residential use of an existing tree canopy and subtracting the cost of artificial drainage required because of soil conditions. Installation of the artificial drainage and the resulting change in water table would eliminate the vegetation canopy. Therefore there is interdependence among the factors: the value of the vegetation type depends on the soil type.

Although interdependence among the frequently used factors does exist, not all factors are interdependent. In addition, some factors that affect several types of costs and impacts, such as soils, may be interdependent with respect to some of these costs or impacts but not others. It is certainly acceptable to use a linear combination for particular instances where it can be empirically or deductively shown to be correct. For example, costs for constructing a foundation to compensate for poor soil conditions are independent of the vegetation cover type. Therefore the construction costs could be subtracted from the vegetation amenity value.

The linear combination of factors should be viewed as a particular case. It is only one of an infinite number of possible functions for combining factors. The linear combination method can not be applied appropriately across the board to all combinations of factors. Of course, some factors are independent; but the point is that many land use suitability studies have used the linear combination method to apply to all factors, as if the method were inherently correct without regard to observable interdependence among factors.

Nonlinear combination method

Interdependence among the factors could be handled if the combination equation were not linear. If the appropriate relationships among the factors are known and can be expressed as mathematical functions, the nonlinear combination method is ideal. Instead of a linear combination (weighted addition) as in deriving step 4 in Figure 4, the ratings of types are plugged into the nonlinear functions and results are obtained analytically for all factors combined.

The only difference from Figure 4 is that the combination equation to get from step 3 to step 4 contains a nonlinear relationship instead of addition. However, this method is not likely to be possible for studies of the kind under consideration, because the relationships required to deal with the full range of costs and impacts are not known.

Although Storie (1933) proposed a nonlinear (multiplicative) index of soil factors for agricultural production, he provided little convincing evidence for the functional form chosen. Voelker (1976) presented a rating index for site costs with a nonlinear relationship between percent coverage of vegetation and a previously computed index that is a function of soil and slope. He reported iterative, judgmental fitting of the index, but this is just one of many required relationships. The most frequently used nonlinear combination functions are the standard equations for computing runoff and soil loss for given combinations of types of land cover, slope, and watershed shape. Although these equations are certainly useful, they apply only to specific components of an overall suitability rating.

Most nonlinear equations that are widely used generate suitabilities regarding generation of impact, runoff for example, rather than suitabilities for land uses. As discussed at the beginning of this article, such impact suitability maps may be inputs to land suitability maps, but they constitute only one factor in the broader level of analysis that is required. The nonlinear combination method overcomes the problem of interdependence among factors, but so far it has not been operationally useful for generating overall land use suitabilities.

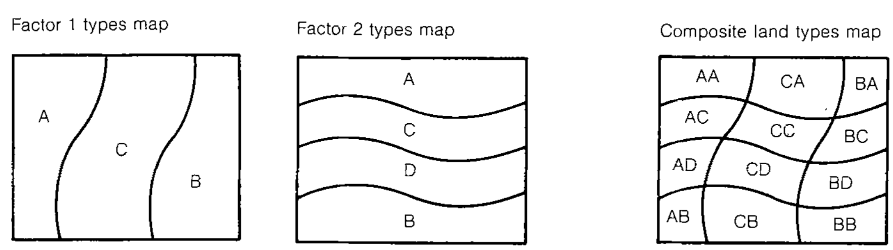
Explicit identification of regions

One way to avoid the problem of interdependence among the factors is to first identify homogeneous regions explicitly. The homogeneity of regions does not depend on the independence of factors. Given the homogeneous regions, the suitability ratings for each region can be determined by implicit judgment concerning the combinations of types that then define the regions.

Factor combination method

A straightforward modification of the gestalt method allows one to deal with interdependence among the factors but with a tremendous loss of efficiency compared to the methods described in the previous section. Figure 5 describes the same artificial problem

Figure 5. Factor combination method

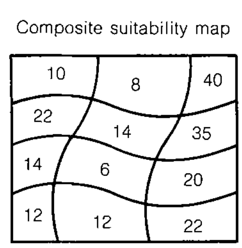


Step 1: map data factors by type

Step 2: intersect factor types maps to obtain composite

Regions	Land uses R1	R2	R3	R4
AA	10.0	•	•	•
AB	12.0	•	•	•
AC	22.0	•	•	•
AD	14.0	•	•	•
BA	40.0	•	•	•
BB	22.0	•	•	•
BC	35.0	•	•	•
BD	20.0	•	•	•
CA	8.0	•	•	•
CB	12.0	•	•	•
CC	14.0	•	•	•
CD	6.0	•	•	•

Step 3: rate each region for each land use



Step 4: map suitability ratings for each land use, one map for each land use

used for illustration previously, but in this case the order of steps 2 and 3 is reversed. Step 2 now consists of combining type maps for each of the factors to obtain a composite map of regions that are homogeneous with respect to all factors. No rating is implied; this map is merely a complete logical intersection or factor combination of the boundaries of the regions from each factor map. It is equivalent to a very complex Venn diagram in set theory.

Step 3 is now the derivation of the suitability ratings table. Instead of a list of factors and types for each, the vertical axis identifies all the regions that occur on the map. It is thus equivalent to the table for the gestalt method in Figure 1, except that an explicit procedure has been used for deriving the homogeneous regions from the individual factors. One can now evaluate the suitability for each land use relative to each specific combination of types, without having to consider the general relationships among individual factors as in the linear combination and nonlinear combination methods. It is evident that, just as in the gestalt method, implicit judgments are used to determine the suitabilities. The determination of homogeneous regions has been made explicit; the determination of suitabilities has not.

The *Plan for the Valleys* by Wallace-McHarg Associates (1964) is a simple example of this method. Two factors, forest cover and topography, were used to generate five combinations: valley floors, unforested valley walls, forested valley walls, forested plateau, and unforested plateau. By implication, forest cover did not apply to any valley floor areas on the site. Management principles were prescribed for each region (see also McHarg 1969, pp. 79ff.).

Factor combination is suitable for studies involving only a few factors; a larger number of factors makes infeasible the determination of suitability ratings for each combination. The most time consuming part of a real study is identifying the ratings to go into each box in the suitability table. It is thus desirable to minimize the number and difficulty of evaluations. Note that the table for the linear combination procedure in Figure 3 requires suitability ratings for various activities on each type within each factor. This number (seven in this example) equals the sum of the types over all factors for each activity. For the factor combination method, however, the table includes a row for each homogeneous region that actually occurs on the site. This number has an upper bound (twelve in this example) that is equal to the product of the number of types for each factor. The potential number of combinations is enormous—if one dealt with ten factors each having ten types, the number of possible homogeneous regions to be rated would be 10^{10} or one billion. For the same set of factors the table for the linear combination approach would require assigning ratings to only 100 types.

This tremendous difference in the required number of evaluations is reduced by mapping the homogeneous regions first. Most of the possible combinations will not occur on a real site due to spatial correlation among the ecological factors. In one unpublished study carried out in this fashion by the present author, approximately 5 percent of the possible combinations actually occurred. However, if accessibility relationships among existing and potential activities were one of the factors, this percentage would be much greater. Even with the potential reduction of regions by mapping to determine those that actually exist, the suitability table for the factor combination procedure may be unwieldly, especially for large, diverse study areas. The factor combination method has the further disadvantage that the rating of regions in terms of suitability relies entirely on implicit judgment for the transformation of the types in the combination into a rating for the combination as a whole.

Cluster analysis

Cluster analysis, used in the Rice Center (1974) study, also explicitly identifies homogeneous regions by successively pairing the most similar sites or groups of sites, based on an index of similarity across the set of factors. The process is stopped at some predetermined acceptable level of diversity within the clusters, resulting in a set of regions, each with a profile showing the range of types for each factor. As in the factor combination method, this profile still must be transformed into some aggregate rating by implicit judgment. The clustering does, however, serve to reduce explicitly the combinations of types to be considered.

One of the most interesting potentials of the cluster analysis method is the possibility of using the statistical measures of variation on factors within clusters as measures of suitability. Diversity within a homogeneous region is often a more useful measure of suitability for particular uses than a modal type or a specified range. For example, a region with diverse slopes makes a good site for a planned unit development; a region with all flat land or all steep slopes does not. However used, cluster analysis requires great care in interpretation and significant costs for computation. Cluster analysis can not be justified unless expected results are significantly better than from other methods; this case has not yet been demonstrated.

Suitabilities by logical combination

Rules of combination is a useful label for a class of methods that is, in a sense, a compromise between the nonlinear combination method and the factor combination method. The rules assign suitabilities to *sets* of combinations of types rather than to single combinations and are expressed in terms of verbal logic rather than in terms of numbers and arithmetic. It is then not necessary to evaluate each combination separately as in the factor combination method; nor is it necessary to find a precise mathematical statement of the relationships among factors as in the nonlinear combination method. In addition, the process of determining suitabilities is more explicit than in the factor combination method and can deal with interdependence. A final method, *hierarchical combination*, could be viewed as a special case of rules of combination. However, because it is an important case, with general properties of its own, hierarchical combination is treated separately.

Rules of combination method

A simple, clearcut example of the rules of combination method is given by Kiefer (1965). After mapping the factors, he rates the types within the factors in a process equivalent to step 2 in Figure 3. He then states the general rule that the rating of the worst factor in a given region overrides the rating of all other factors. The rating of the worst factor is thus assigned as the rating of the combination of types for the given region, though often with exceptions. Kiefer, for instance, identifies sets of combinations that are to be rated by different rules, such as "a land unit rating 'optimum' in all factors except soil class and rating 'satisfactory' in soil class should be given an overall rating of 'optimum'" (p. 113). Instead of a linear combination to map step 2 into steps 3 and 4 as in Figure 3, the verbally expressed rules determine the composite ratings for the map in step 4.

The early warning system (Patri, Streatfield, and Ingmire 1970, Ingmire and Patri 1971) uses the rules of combination approach in deriving the "critical factor" map for rock and soil dynamics, which is essentially a suitability map for the likelihood of geologic activity. Rules of the following sort were used to define suitability levels.

> This broad category includes all cells which are scored in excess of 10% slope and are of a high erosion hazard category. They are outside of critical formations and expansive soil zones. They may include all but "active" and "major" faults (Patri, Streatfield, and Ingmire 1970, p. 132).

Although McHarg's work is usually associated with the ordinal combination method described in Figure 2, many of his studies are more accurately described in terms of rules of combination. A frequently used graphic procedure begins by following the factor combination method illustrated in Figure 5. Each of the factor maps is drawn with nominal data types. A code sheet is made by placing a piece of tracing paper on each of the factor maps in succession, outlining areas bounding each type and identifying them with a sequential code of letters or numbers as illustrated for the two-factor case in step 2 of Figure 5. This paint-by-number sheet is then printed as a base map for drawing suitability maps for various land use activities. However, instead of developing suitabilities through implicit judgment of each of the combinations at this stage, as in the factor combination method, a set of explicit rules of combination is developed. The map of step 4 is then colored to show suitability for a particular use by applying the rules to each combination on the coded base map. The only difference from Figure 5 is that rules are used to generate the ratings in step 3. The Medford study (Juneja 1974) provides a well-documented example of this approach, although the rules of combination follow a very simplistic and rigid form. The general rule used is not specific to the set of combinations, nor does it have any very convincing basis in terms of the natural relationships among factors. A single rule of this type is unlikely to be valid for the many different factors and land uses, because it is unlikely that the natural relationships involved will be so nearly the same.

A set of simple rules for the example of interdependence among slope, soil permeability, and subsurface material demonstrates the handling of interdependence among factors and the relationships of rules to the natural system being described. Assume that there are two slope types, greater than 25 percent and less than 25 percent; two soil types, well-drained and poorly drained; and two subsurface materials, clay and not clay. Then high suitability would include regions with slopes less than 25 percent or regions with slopes greater than 25 percent and poorly drained soil or regions with greater than 25 percent and not clay subsurface. Low suitability would include regions with slopes greater than 25 percent, well drained soil, and clay subsurface. These rules cover all of the eight possible combinations of the three factors. In contrast to the Medford study rules, these rules have a logic based in the understanding of the natural system being described rather than a single set of relationships repeated for all combinations regardless of the specific types and factors being combined.

Rules of combination can be applied to construct the composite suitability ratings map without having to deal with each possible combination individually. If the rules are stated explicitly, they can be used to generate maps directly without compiling a suitability table for all possible combinations. This is an obvious saving of effort compared to the factor combination approach. In addition, such rules are explicit and thus subject to scrutiny. The rules, if carefully devised, can also handle interdependence among factors.

Hierarchical combination

A more structured approach to rules of combination is based on the work of Alexander (1964). The basic concept is that a composite rating can be generated hierarchically. First, the combinations of types from each subset of strongly interdependent factors are rated for suitability as combinations, which thus permits consideration of interdependence among the factors within each subset. Then higher order combinations of the combinations from these subsets of factors are rated, with each lower order combination now treated as an integrated whole. This sequence of hierarchical combinations is repeated until a rating is achieved that includes all relevant factors. In this approach a combination of types in a subset is evaluated only once, rather than being evaluated each time it appears as part of a combination of types for all factors. The increase in efficiency over evaluating all possible combinations depends on the number of relatively independent subsets of factors that can be identified. Alexander and Manheim (1962) applied this concept in a somewhat different fashion for the location of a highway corridor.

A hierarchical method also was used for the impact models in the Honey Hill study (Murray, et al. 1971). However, the purpose for doing so and the criteria for carrying out the process do not seem to match the mathematical properties of the procedure. The evaluator was restricted to a set of three factors of his choice and was told to rate the combinations resulting from the two *least important* factors first; then these combinations (pairs) were combined with the *most important* factor. To handle interdependence it would be more appropriate to combine the two factors with the greatest *interdependence* first. The third factor would then, by implication, be interdependent only with the combinations of the first two factors. Regardless of the stated intentions in the Honey Hill study, this hierarchical combination is in effect what the logical properties of the procedure actually accomplish.

The neat three-by-three structure of the Honey Hill procedure has the appearance of a superficial gimmick with little realization of its logical basis. There is no inherent reason why one should be limited in all cases to three levels of three factors, nor to considering variation among only three sets of land uses. It is highly unlikely that knowledge of various impacts would happen to fit this rigid three-by-three framework. These comments, which also apply to some of the simplistic rules of combination described in the previous section, are not intended to denigrate the importance of the format in which data are presented for manipulation; the format should not, however, override the logic of the manipulations.

Table 1. Summary comparison of methods

Method	Handles interdependence of factors	Explicit identification of regions	Explicit determination of ratings	Additional comments	Example
Gestalt	Yes	No	No		Hills (1961)
Mathematical combination					
Ordinal combination	No	Yes	Yes	Involves invalid mathematical operations	McHarg (1969) pp. 31–41
Linear combination	No	Yes	Yes		Ward and Grant (1971)
Nonlinear combination	Yes	Yes	Yes	Required functional relationships generally not known	Voelker (1976) pp. 49 ff.
Identification of regions					
Factor combination	Yes	Yes	No	Requires a very large number of evaluative judgments	Wallace-McHarg (1964)
Cluster analysis	Yes	Yes	No		Rice Center (1974)
Logical combination					
Rules of combination	Yes	Yes	Yes		Kiefer (1965)
Hierarchical combination	Yes	Yes	Yes		Murray, et al. (1971) pp. 131–74

Comparison, integration of methods

A comparison of some important characteristics of the eight general methods—gestalt, ordinal combination, linear combination, nonlinear combination, factor combination, cluster analysis, rules of combination, and hierarchical combination—is presented in Table 1. Because of the complementary characteristics of several of the methods, it is useful to apply more than one method in carrying out a land suitability analysis. This summary and comparison outlines circumstances in which the various methods are appropriate either alone or in conjunction with other methods.

Recommended methods

For simple, small, land resource inventories, the gestalt method is quite acceptable if qualified field personnel are available. A typical application would be a site visit, enhanced by making notes on aerial photographs, to determine land suitabilities for a small planned unit development. The disadvantage of the gestalt method is the implicit identification of regions and determination of ratings. It would be difficult to convince others of the validity of the suitability results if, for example, a change in zoning were required.

The three mathematical combination methods are either invalid or insufficient by themselves. The ordinal combination method is invalid and should not be used because of its assumptions and its inability to handle interdependence. The linear combination method should not be used as a general method for developing suitability maps because of its inability to handle interdependence. For particular sets of factors that can be shown to be independent, however, it is perfectly appropriate and relatively easy to use. The nonlinear combination method is generally insufficient by itself because the required mathematical relationships for the full range of costs and impacts are not known.

The factor combination and cluster analysis methods do not include explicit means for determining suitability ratings. The factor combination method is sometimes useful when an analyst is not sufficiently familiar with an area to make gestalt judgments to identify land types. If the study is otherwise relatively simple, it may then be reasonable to make implicit judgments as to the relative suitabilities of the regions. Although cluster analysis has been used in a few research studies for reducing the number of suitability evaluations required, it has not yet been shown to be worthwhile compared to the costs and benefits of using other methods.

For most studies, the best approach is to use the linear and nonlinear combination methods as a first stage, followed by rules of combination. First, incorporate the relationships among factors for which mathematical functions, either linear or nonlinear, are known by using the particular functions that apply. For example, soil loss and runoff can be computed from nonlinear relationships of soil type, vegetation cover, and slope. Also, certain construction costs associated with soil characteristics, vegetation, and slope can be summed as a linear combination to yield a construction cost figure. This preliminary stage yields additional factors—in this example soil loss, runoff, and construction costs. These new factors can then be combined with each other and the original factors (exclusive of their contribution to soil loss, runoff, and construction costs) using rules of combination. This second stage considers costs and impacts for which precise mathematical relationships are not known and yields an overall suitability rating for a land use. Extensive research projects at Harvard (Landscape Architecture Research Office 1974), the University of Massachusetts (Fabos and Caswell 1977) and Oak Ridge National Laboratories (Voelker 1976) include examples of the general approach of using linear, nonlinear, and rules of combination for appropriate components of a suitability analysis.

The approach just described involves a hierarchical sequence of combinations. First, a set of relationships is used to yield a new factor, runoff. Other relationships are used to yield other new factors such as soil loss. Then these new factors (or a subset of them) are combined. In this combination of new factors the relationships that yielded the runoff are *not* considered. The relationships between runoff and the other new factors are considered at the more general level. Hierarchy is a pervasive structure in thinking and accumulating knowledge (Simon 1969). It is therefore inherent in any complex procedure for generating suitability maps.

Interpretation of land suitability maps

No matter how obtained, land suitability maps provide information only about the supply of land at various levels of suitability for different uses. It is not possible to make evaluative, predictive, or normative statements about allocations of several uses to sites without also making some assumptions about the relative demands for the alternative uses. The necessity of dealing with both supply and demand in order to consider questions of land resource allocation is basic to land resource economics (Barlowe 1972). Gold (1974) has presented the argument for simple, artificial examples in the context of land suitability analysis. Some land suitability studies pretend, or at least appear to pretend, to yield immediate implications for allocation of land uses without recourse to explicit assumptions about relative demand for various land uses. It is on this point that the land suitability inventory work of the past two decades must be integrated with other land use modeling and analysis, which has been developed primarily in the context of economic analysis. Many experiments already have been conducted in pursuit of analytical models capable of considering not only transportation and demand assumptions but also the site variations and environmental effects. (See, for example, Schlager 1965; Southeastern Wisconsin Regional Planning Commission 1968, 1969, 1973; Hopkins 1973; Landscape Architecture Research Office 1974; Hopkins 1975).

This taxonomy of methods points up the inappropriateness of the frequently cited ordinal combination method, the limitations of the linear and nonlinear combination methods, and the advantages of the general class of methods called rules of combination. It is hoped that the attempt to draw meaningful distinctions among frequently used methods will provide a basis on which further development of land suitability analysis techniques can take place.

Appendix.
Measurement scales for land suitability analysis

It is possible to manipulate numbers using any rules one might concoct as long as mathematical properties are not inferred from the numbers for which the conditions are not met. The book of readings edited by Maranell (1974) provides a wide ranging discussion of the general issue of measurement and scaling. This appendix is intended to clarify which conditions must be met to assure the validity of some simple numerical relationships usually assumed in making relative judgments for evaluation of suitabilities.

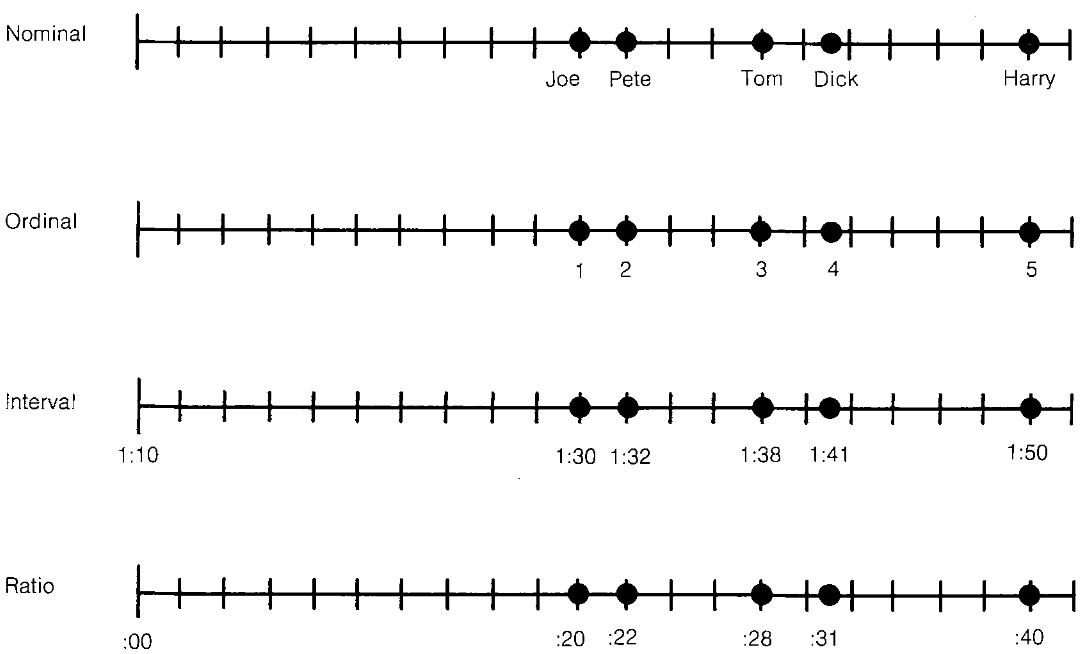
Perhaps the characteristics of the various measurement systems can be best understood by the example of a footrace illustrated in Figure A1. A *nominal* scale merely gives names to the elements, permitting only counting (five people ran the race) and perhaps some kinds of grouping (two males, three females). Soil types and land use types are examples of nominal identification in land suitability analysis.

An *ordinal* scale indicates the order in which people finished the race, permitting certain statements of preference, but none of the standard mathematical operations. Through the use of modern nonmetric, multidimensional scaling techniques, more information can be gained from ordinal data than was once thought possible. (See, for example, Green and Carmone 1970.) Hill and Tzamir (1972) have experimented with nonmetric scaling on a land use study in the context of evaluation. Rice Center for Community Design and Research (1974) has suggested some very preliminary ideas as to its use in land resource studies.

An *interval* scale—as meaured by a clock—indicates when each person finished the race in units of time, say one o'clock. This permits determining differences in meaningful units. Joe came in two minutes before Pete, which can be found by subtracting Joe's time from Pete's. These *differences* can be compared by multiplication or division. Joe was ⅓ as much before Pete as Pete was before Tom. Multiplication or division of the times themselves is, however, spurious. One does not know when the race started or how long anyone took to run it. On an interval scale one can say only how many units better or worse, *not* how many times or what percent better or worse. One can say that the interval between one pair of runners is twice that between another pair of runners, but not that one runner took twice as long. One special kind of multiplication is meaningful with respect to an interval scale. Multiplying all values of one interval scale by a constant has the effect of changing the unit in which measurement on that scale is expressed. One can multiply a time given in seconds by 1/60 and obtain time in minutes, which can then be compared to other times given in minutes.

A *ratio* scale—as measured by the stop watch—establishes a meaningful zero point, in this case the beginning of the race. It thus permits multiplication and division with numbers expressed on the ratio scale. Joe ran in half the time of Harry, which is found by dividing Joe's time by Harry's. Note from Figure A1 that adding or subtracting with the ordinal scale or multiplying and dividing with the interval scale would give meaningless results.

Figure A1. Comparison of representation of same data in different measurement systems



A statement of evaluation using numbers, say zero through nine, could occur in any of these measurement systems. The digits could be simply names or could represent a ratio number system with a meaningful zero, a scale divided into nine units, and positions expressed to the nearest unit. Note that the result of applying this latter measurement system to the results of a nine-person race would not be equivalent to a ranking of the participants. One cannot determine the type of measurement system used by simply observing the information, but only from the assumptions stated explicitly, or more often, implied by the mathematical operations performed. The argument is not against zero to nine, but against failure to realize and accept assumptions of the measurement system being used. If an inappropriate zero point is chosen, the measurement results can be quite meaningless, as in the case of stating that Harry took 1.22 times as long as Joe on the basis of the interval scale where the zero point is 12 noon, but the race began at 1:10 p.m.

An interval number system is sufficient to identify the suitability of land for a given use as long as an analyst infers no ratio relationships between values. It may still be preferable to use a ratio scale with a meaningfully defined zero, because it seems to lead to better comprehension of the evaluation process and its implications. Rather than relying only on additive differences in thinking about relative values, one can also think in terms of ratios of the values.

At the risk of belaboring an important point, the crux of the issue is often missed in the usual example where degrees Centrigrade is called an interval scale, having an arbitrary zero, and degrees Kelvin a ratio scale with an "absolute" zero. The kind of scale and the concomitant mathematical properties can only be determined by whether one wishes to think in terms of ratios of distance from the freezing point of water or from the cessation of molecular motion. Using a ratio scale does not imply that there is some absolute zero, but simply that the zero point being used is a meaningful reference point from which to think about ratio relationships.

The zero point of suitability can be positioned in at least three ways. One approach is to rate benefits as positive and costs and impacts as negative so that the zero point is where no costs and no benefits occur. A second approach is to assume that the zero point represents the occurrence of all costs and no benefits. The third approach considers the lack of a benefit to be a cost and thus multiplied by -1. Therefore, in this third approach, the zero point represents no costs occurring and all benefits occurring.

The *added cost* concept implies a fourth temporary positioning of the zero for obtaining evaluation ratings. In this case the ideal site in the region for a given use is assigned zero cost for that use and increments of cost are related to the ideal, as additional costs for lack of benefits or occurrence of costs or impacts. Care must be taken to add the base costs of the ideal, and therefore to deal in total costs and an appropriate ratio scale, before applying any cost-benefit ratio criteria to projects or alternatives.

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