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An American National Standard

Standard Practice for Applying Analytical Hierarchy Process (AHP) to Multiattribute Decision Analysis of Investments Related to Buildings and Building Systems[1]

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INTRODUCTION

The analytical hierarchy process (AHP) is one of a set of multi-attribute decision analysis (MADA) methods that considers nonmonetary attributes (qualitative and quantitative) in addition to common economic evaluation measures (such as life-cycle costing or net benefits) when evaluating project alternatives. Building-related decisions depend in part on how competing options perform with respect to nonmonetary attributes. This practice complements existing ASTM standards on building economics by incorporating the existing economic/monetary measures of worth described in those standards into a more comprehensive standard method of evaluation that includes nonmonetary (quantitative and nonquantitative) benefits and costs. The AHP is the MADA method described in this practice.[2] It has three significant strengths: an efficient attribute weighting process of pairwise comparisons; hierarchical descriptions of attributes, which keep the number of pairwise comparisons manageable; and available software to facilitate its use.[3]

1. Scope

1.1 This practice presents a procedure for calculating and interpreting AHP scores of a project's total overall desirability when making building-related capital investment decisions.[3]

1.2 In addition to monetary benefits and costs, the procedure allows for the consideration of characteristics or attributes which decision makers regard as important, but which are not readily expressed in monetary terms. Examples of such attributes that pertain to the selection of a building alternative (and its surroundings) are location/accessibility, site security, maintainability, quality of the sound and visual environment, and image to the public and occupants.

2. Referenced Documents

2.1 *ASTM Standards:*

E 631 Terminology of Building Constructions[4]

E 833 Terminology of Building Economics[4]

E 917 Practice for Measuring Life-Cycle Costs of Buildings and Building Systems[4]

E 964 Practice for Measuring Benefit-to-Cost and Savings-to-Investment Ratios for Buildings and Building Systems[4]

E 1057 Practice for Measuring Internal Rate of Return and Adjusted Internal Rate of Return for Investments in Buildings and Building Systems[4]

E 1074 Practice for Measuring Net Benefits for Investments in Buildings and Building Systems[4]

E 1121 Practice for Measuring Payback for Investments in Buildings and Building Systems[4]

E 1334 Practice for Rating the Serviceability of a Building or Building-Related Facility[4]

E 1480 Terminology of Facility Management (Building-Related)[4]

E 1557 Classification for Building Elements and Related Sitework—UNIFORMAT II[4]

E 1660 Classification for the Serviceability of an Office Facility for Support for Office Work[4]

[1] This practice is under the jurisdiction of ASTM Committee E06 on Performance of Buildings and is the direct responsibility of Subcommittee E06.81 on Building Economics.

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[2] For an extensive overview of MADA methods and a detailed treatment of how to apply two MADA methods (one of which is AHP) to building-related decisions, see Norris, G. A., and Marshall, H. E., *Multiattribute Decision Analysis: Recommended Method for Evaluating Buildings and Building Systems*, National Institute of Standards and Technology, 1995.

[3] This practice presents a stand-alone procedure for performing an AHP analysis. In addition, an ASTM software product for performing AHP analyses has been developed to support and facilitate use of this practice. *User's Guide to AHP/Expert Choice for ASTM Building Evaluation*, MNL 29, ASTM, 1998.

[4] *Annual Book of ASTM Standards*, Vol 04.11.

E 1661 Classification for the Serviceability of an Office Facility for Meetings and Group Effectiveness[4]
E 1662 Classification for the Serviceability of an Office Facility for Sound and Visual Environment[4]
E 1663 Classification for the Serviceability of an Office Facility for Typical Office Information Technology[4]
E 1664 Classification for the Serviceability of an Office Facility for Layout and Building Factors[4]
E 1665 Classification for the Serviceability of an Office Facility for Facility Protection[4]
E 1666 Classification for the Serviceability of an Office Facility for Work Outside Normal Hours or Conditions[4]
E 1667 Classification for the Serviceability of an Office Facility for Image to Public and Occupants[4]
E 1668 Classification for the Serviceability of an Office Facility for Amenities to Attract and Retain Staff[4]
E 1669 Classification for the Serviceability of an Office Facility for Location, Access, and Wayfinding[4]
E 1670 Classification for the Serviceability of an Office Facility for Management of Operations and Maintenance[4]
E 1671 Classification for the Serviceability of an Office Facility for Cleanliness[5]
E 1679 Practice for Setting the Requirements for the Serviceability of a Building or Building-Related Facility[5]
E 1692 Classification for the Serviceability of an Office Facility for Change and Churn by Occupants[5]
E 1693 Classification for the Serviceability of an Office Facility for Protection of Occupant Assets[5]
E 1694 Classification for the Serviceability of an Office Facility for Special Facilities and Technologies[5]
E 1700 Classification for the Serviceability of an Office Facility for Structure and Building Envelope[5]
E 1701 Classification for the Serviceability of an Office Facility for Manageability[5]

2.2 *ASTM Software Product:*
AHP/Expert Choice for ASTM Building Evaluation, Software to Support Practice E 1765.

3. Summary of Practice

3.1 This practice helps you identify a MADA application, describe the elements that make up a MADA problem, and recognize the three types of problems that MADA can address: screening alternatives, ranking alternatives, and choosing a final "best" alternative.

3.2 A comprehensive list of selected attributes (monetary and nonmonetary) for evaluating building decisions provides a pick list for customizing an AHP model that best fits your building-related decision. Three types of building decisions to which the list applies are choosing among buildings, choosing among building components, and choosing among building materials. Examples of these typical building-related decisions are provided.

3.3 A case illustration of a building choice decision shows how to structure a problem in a hierarchical fashion, describe the attributes of each alternative in a decision matrix, compute attribute weights, check for consistency in pairwise comparisons, and develop the final desirability scores of each alternative.

3.4 A description of the applications and limitations of the AHP method concludes this practice.

4. Significance and Use

4.1 The AHP method allows you to generate a single measure of desirability for project alternatives with respect to multiple attributes (qualitative and quantitative). By contrast, life-cycle cost (Practice E 917), net savings (Practice E 1074), savings-to-investment ratio (Practice E 964), internal rate-of-return (Practice E 1057), and payback (Practice E 1121) methods all require you to put a monetary value on benefits and costs in order to include them in a measure of project worth.

4.2 Use AHP to evaluate a finite and generally small set of discrete and predetermined options or alternatives. Specific AHP applications are ranking and choosing among alternatives. For example, rank alternative building locations with AHP to see how they measure up to one another, or use AHP to choose among building materials to see which is best for your application.

4.3 Use AHP if no single alternative exhibits the most preferred available value or performance for all attributes. This is often the result of an underlying trade-off relationship among attributes. An example is the trade-off between low desired energy costs and large glass window areas (which may raise heating and cooling costs while lowering lighting costs).

4.4 Use AHP to evaluate alternatives whose attributes are not all measurable in the same units. Also use AHP when performance relative to some or all of the attributes is impractical, impossible, or too costly to measure. For example, while life-cycle costs are directly measured in monetary units, the number and size of offices are measured in other units, and the public image of a building may not be practically measurable in any unit. To help you choose among candidate buildings with these diverse attributes, use AHP to evaluate your alternatives.

4.5 Potential users of AHP include architects, developers, owners, or lessors of buildings, real estate professionals (commercial and residential), facility managers, building material manufacturers, and agencies managing building portfolios.

5. Procedure

5.1 To carry out a MADA analysis using AHP, follow this procedure:[6]

5.1.1 Identify the elements of your problem to confirm that a MADA analysis is appropriate (see 5.2),

5.1.2 Determine the goal or objective of the analysis, select the attributes on the basis of which you plan to choose an alternative, arrange the attributes in a hierarchy, identify the attribute sets in the hierarchy, identify the leaf attributes in the hierarchy, and identify alternatives to consider (see 5.3),

[5] *Annual Book of ASTM Standards*, Vol 04.12.

[6] Paragraphs 5.1-5.4 are common to many MADA methods. Paragraphs 5.5-5.7 pertain specifically to the AHP method.

5.1.3 Construct a decision matrix summarizing available data on the performance of each alternative with respect to each leaf attribute (see 5.4),

5.1.4 Compare in pairwise fashion each alternative against every other alternative as to how much better one is than the other with respect to each leaf attribute (see 5.5),

5.1.5 Make pairwise comparisons, starting from the bottom of the hierarchy, of the relative importance of each attribute in a given set with respect to the attribute or goal immediately above that set in the hierarchy (see 5.6), and

5.1.6 Compute the final overall desirability score for each alternative (see 5.7).

5.2 Confirm that a MADA analysis is appropriate. Three elements are typically common to MADA problems.

5.2.1 MADA problems involve analysis of a finite and generally small set of discrete and predetermined options or alternatives. They do *not* involve the design of a "best" alternative from among a theoretically infinite set of possible designs where the decision maker considers trade-offs among interacting continuous decision variables. Selecting a replacement HVAC system for an existing building is a MADA problem. In contrast, the integrated design and sizing of a future building and its HVAC system is not a MADA problem.

5.2.2 In MADA problems, no single alternative is dominant, that is, no alternative exhibits the most preferred value or performance for all attributes. If one alternative is dominant, a MADA analysis is not needed. You simply choose that alternative. The lack of a dominant alternative is often the result of an underlying trade-off relationship among attributes. An example is the trade-off between proximity to the central business district for convenient meetings with business clients and the desire for a suburban location that is convenient for commuting to residential neighborhoods and relatively free of street crime.

5.2.3 The attributes in a MADA problem are not all measurable in the same units. Some attributes may be either impractical, impossible, or too costly to measure at all. For example, in an office building, energy costs are measurable in life-cycle cost terms. But the architectural statement of the building may not be practically measurable in any unit. If all relevant attributes characterizing alternative buildings can be expressed in terms of monetary costs or benefits scheduled to occur at specifiable times, then the ranking and selection of a building does not require the application of MADA.

5.3 Identify the goal of the analysis, the attributes to be considered, and the alternatives to evaluate. Display the goal and attributes in a hierarchy.

5.3.1 The following case example of a search for public office space illustrates how to organize and display the constituents of a hierarchy.

5.3.1.1 A state agency needs, within the next 18 months, office space for 300 workers. It seeks a location convenient to the state capitol building by shuttle. The agency seeks to minimize the travel time and will not accept travel times greater than 10 min. It also has telecommunications and computer infrastructure requirements that will exclude many buildings. The goal of the analysis is to find the best building for the agency.

5.3.1.2 The specification of a 10 min maximum travel time from the site to the capitol eliminates all buildings outside a certain radius. Having up to 18 months to occupy allows either the construction of a new building or the retrofitting of an existing building, either of which could be rented or leased. Telecommunications and computer infrastructure requirements will limit the search even more. These specifications help the analyst define the "attributes" and building "alternatives" for the MADA analysis.

5.3.1.3 Attributes selected for the hierarchy, displayed in Fig. 1, are occupancy availability (within 18 months); information technology (available telecommunications and computer support infrastructure); economics (life-cycle costs of alternative buildings, owned or leased); and location (how convenient to capitol building). The analyst works with the decision maker to make sure that all significant needs of the decision maker are covered by the hierarchy of attributes.

5.3.2 Fig. 2 covers attribute sets and leaf attributes.

5.3.2.1 A set of attributes refers to a complete group of attributes in the hierarchy which is located under another attribute or under the problem goal. There are four separate sets of attributes in the hierarchy displayed in Fig. 2. Each set is enclosed by dashed lines.

5.3.2.2 A leaf attribute is an attribute which has no attributes below it in the hierarchy. The eleven leaf attributes present in the hierarchy in Fig. 2 are shaded.

5.4 Construct a decision matrix with data on the performance of each alternative with respect to each leaf attribute.

5.4.1 Characterize your MADA problem with a decision matrix similar to Table 1. The decision matrix indicates both the set of alternatives and the set of leaf attributes being considered in a given problem, and it summarizes the "raw" data available to the decision maker at the start of the analysis. A decision matrix has a row corresponding to each alternative being considered and a column corresponding to each leaf attribute being considered. Each element of the matrix contains the available information about that row's alternative with respect to that column's attribute. Put quantitative data in the decision matrix if available; use nonquantitative data otherwise.

5.4.2 Table 1 is a hypothetical and simplified decision matrix for the problem of selecting the "best" heating system for a building. Note that the first column pertains to a monetary attribute: life-cycle costs. The next attribute, warranty period, is measured quantitatively, but not in monetary terms. The last attribute, familiarity with the technology, is characterized only qualitatively.

5.4.3 Include in the decision matrix and analysis only those attributes which the decision maker considers important and

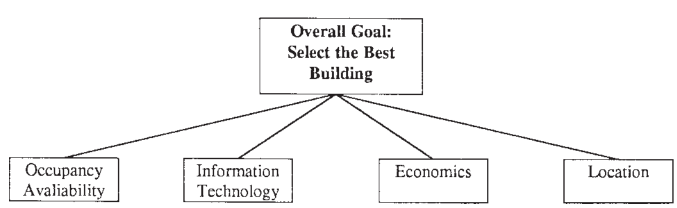

FIG. 1 An Example Hierarchy for the Problem of Selecting a Building

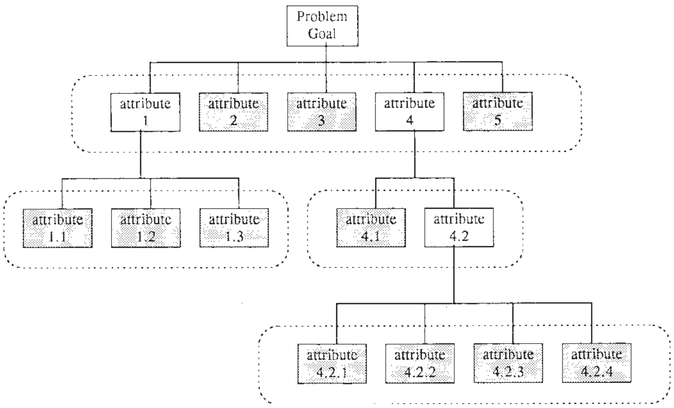

FIG. 2 A Hierarchy Illustrating Attribute Sets and Leaf Attributes

TABLE 1 Heating System Decision Matrix

	Leaf Attributes		
	Life-Cycle Cost, K$	Duration of Warranty, years	Familiarity with the Technology
Alternative 1	10	3	high
Alternative 2	15	1	medium
Alternative 3	20	10	low

which vary significantly among one or more alternatives. For example, heating capacity is clearly an important attribute of any heating system, but if the alternatives in Table 1 include only systems which match the capacity requirements of the building in question, then capacity is not a distinguishing attribute and is not to be included in the decision matrix or in the MADA analysis.

5.4.4 The MADA methods allow one to use the information in a problem's decision matrix together with additional information from the decision maker in determining a final ranking or selection from among the alternatives. For example, the decision matrix alone provides neither information about the relative importance of the different attributes to the decision maker, nor about any minimum acceptable, maximum acceptable, or target values for particular attributes.

5.4.5 For analytical and procedural simplicity, it is common practice when employing MADA to neglect both uncertainties and imprecision inherent in the decision matrix data as well as in the additional information about attributes and alternatives elicited from the decision maker. While there are ways to incorporate uncertainty and imprecision in MADA analyses, they are not addressed here.

5.5 Compare in pairwise fashion each alternative against every other alternative as to how much better one is than the other with respect to each leaf attribute. Repeat this process for each leaf attribute in the hierarchy. This and subsequent steps in the procedure describe the AHP method of performing MADA analysis.

5.5.1 The AHP summarizes the results of pairwise judgments in a matrix of pairwise comparisons (MPC), as shown in Fig. 3. For each pair of alternatives, the decision maker specifies a judgment about how much more desirable or how much better in terms of strength of preference one alternative is than the other with respect to the attribute in question. Each pairwise comparison requires the decision maker to provide an answer to the question, "Alternative 1 is how much more desirable than Alternative 2, relative to the attribute of interest?" This procedure is repeated for each leaf attribute in the hierarchy.

5.5.2 Note that the decision maker responds to questions about how much more desirable one alternative is than another. It helps responders if the question is framed this way, since all answers will result in a number greater than or equal to one. As shown in Fig. 3, however, the entries in the MPC always characterize the desirability of the row alternative versus the column alternative. Therefore, in cases where the column alternative is more desirable than the row alternative, the decision maker must answer the question, "How much more desirable is the column alternative than the row alternative?" In such cases, enter the reciprocal of the resulting number into the MPC.

5.5.3 There are three types of approaches for specifying pairwise comparison judgments in AHP: numerical, graphically mediated, and verbally mediated. Each method requires the decision maker to answer a series of questions of the form, "How much more desirable is Alternative 1 than Alternative 2 with respect to the attribute of interest?"

5.5.3.1 For the numerical approach, have the decision maker answer each question with a number, as in "Alternative 1 is *3* times as desirable as Alternative 2."[7]

5.5.3.2 For graphically mediated judgments, use an interactive software display to help the decision maker establish the degree of preference.

5.5.3.3 For verbally mediated judgments, have the decision maker answer each question with a verbal expression selected from Table 2 as in "Alternative 1 is moderately more desirable than Alternative 2." Then convert the verbal expressions to their numerical counterparts in Table 2. Be aware, however, that with verbal mediation, the final desirability scores for the alternatives are sensitive to the numerical scale underlying the approach.

5.6 Make pairwise comparisons of the relative importance of each attribute in a given set (starting with sets at the bottom of the hierarchy) with respect to the attribute or goal immediately above that set. (Attribute sets are defined in 5.3.2.1.) Use the same MPC approach that was described in 5.5 for making a series of pairwise comparisons.

5.6.1 Compare in pairwise fashion the relative importance of each attribute with respect to the attribute or goal above its set in the hierarchy. For each pair of attributes, the decision maker specifies a judgment about how much more important one attribute is than the other. Each pairwise comparison requires the decision maker to provide an answer to the question," Attribute 1 is how much more important than Attribute 2, relative to the attribute or goal above it in the hierarchy?"

5.6.2 Note that the decision maker responds to questions about how much more important one attribute is than another. It helps responders if the question is framed this way, since all

[7] Integer answers are not required. For example, it is appropriate to say Alternative 1 is 1.2 times as desirable as Alternative 2 if that is your best estimate of relative desirability.

	Alternative 1	Alternative 2	...	Alternative *j*	Alternative *k*	...	Alternative *n*
Alternative 1	1	Desirability of Alt. 1 versus Alt. 2	...	Desirability of Alt. 1 versus Alt. *j*	Desirability of Alt. 1 versus Alt. *k*	...	Desirability of Alt. 1 versus Alt. *n*
Alternative 2	Desirability of Alt. 2 versus Alt. 1	1	...	Desirability of Alt. 2 versus Alt. *j*	Desirability of Alt. 2 versus Alt. *k*	...	Desirability of Alt. 2 versus Alt. *n*
...	...	...	1	...	...	...	...
Alternative *j*	Desirability of Alt. *j* versus Alt. 1	Desirability of Alt. *j* versus Alt. 2	...	1	Desirability of Alt. *j* versus Alt. *k*	...	Desirability of Alt. *j* versus Alt. *n*
Alternative *k*	Desirability of Alt. *k* versus Alt. 1	Desirability of Alt. *k* versus Alt. 2	...	Desirability of Alt. *k* versus Alt. *j*	1	...	Desirability of Alt. *k* versus Alt. *n*
...	...	...	...	...	...	1	...
Alternative *n*	Desirability of Alt. *n* versus Alt. 1	Desirability of Alt. *n* versus Alt. 2	...	Desirability of Alt. *n* versus Alt. *j*	Desirability of Alt. *n* versus Alt. *k*	...	1

NOTE 1—A separate MPC comparing the alternatives is completed for each leaf attribute in the hierarchy. Within a given MPC, all comparisons of the desirability of Alternative *j* versus Alternative *k* are made with respect to the given leaf attribute of interest.

NOTE 2—Only the $n\ (n-1)/2$ shaded elements of the matrix (those above the matrix's diagonal) need to be filled in by the decision maker. The *n* diagonal elements are all equal to 1 by definition because each alternative is "exactly as desirable as itself." The $n\ (n-1)/2$ elements below the diagonal are equal to the reciprocals of the corresponding elements above the diagonal. This is because, for example, if Alternative 1 is twice as desirable as Alternative 2, then Alternative 2 must be half as desirable as Alternative 1.

FIG. 3 A Matrix of Paired Comparisons (MPC) Among Alternatives

TABLE 2 Verbal Expressions and Their Numerical Counterparts[A]

NOTE 1—Use numerical values that are intermediate between those listed in the" numerical counterpart" column when preferences are intermediate between those listed in the "verbal expression" column of the table. For these intermediate numerical values, use either integers or non-integers.

Verbal Expression	Numerical Counterpart
Equal importance of attributes/Equal desirability of alternatives	1
Moderate importance of one attribute over another/*Moderate* desirability of one alternative over another	3
Strong importance of one attribute over another/*Strong* desirability of one alternative over another	5
Very Strong importance of one attribute over another/*Very Strong* desirability of one alternative over another	7
Extreme importance of one attribute over another/*Extreme* desirability of one alternative over another	9

[A] This table comes from the *Expert Choice User's Guide*, Decision Support Software, Inc., Pittsburgh, PA, 1993.

answers will result in a number greater than or equal to one. Recall from Fig. 3, however, that the entries in an MPC always characterize the importance of each row attribute versus each column attribute. Therefore, in cases where the column attribute is more important than the row attribute, the decision maker shall answer the question, "How much more important is the column attribute than the row attribute?" In such cases, enter the reciprocal of the resulting number into the MPC.

5.6.3 Use numerical, graphically mediated, or verbally mediated judgments.

5.6.3.1 For example, in the numerical approach, have the decision maker answer each question with a number, as in "Attribute 1 is *2* times as important as Attribute 2."

5.6.3.2 For graphical judgments, use an interactive software display to help the decision maker establish the degree of preference.

5.6.3.3 For verbally mediated judgments, have the decision maker respond with a verbal expression selected from Table 2 as in" Attribute 1 is *moderately more important* than Attribute 2." Then convert the verbal expressions to their numerical counterparts in Table 2. Again be aware, however, that with verbal mediation the final desirability scores for the alternatives are sensitive to the underlying numerical scale underlying the approach.

5.6.4 Repeat the procedure for each set of attributes in the hierarchy.

5.7 Compute the final, overall desirability score for each alternative.

5.7.1 Obtain a vector of weights for each MPC using the principal eigenvector method. Find the principal eigenvector e^* which solves Eq 1, where M is the MPC of interest and λ_{max} is the principal eigenvalue of the matrix M.

$$\lambda_{max} e^* = M e^* \tag{1}$$

5.7.2 Normalize the eigenvector so that its elements sum to 1.0. To solve for the normalized principle eigenvector p, divide each of the n elements of the principal eigenvector e^* by the sum of the elements of e^*, as shown in Eq 2. The elements of the normalized principal eigenvector p are the weights derived from the MPC using the principal eigenvector method.

$$p = \left(\frac{1}{\sum_{i=1}^{n} e^*_i} \right) e^* \tag{2}$$

Use the AHP/Expert Choice for ASTM Building Evaluation software product or similar commercially available software to compute the principal eigenvector of each MPC. Simpler hand calculations which develop approximate solutions to Eq 1 do not reliably provide an accurate solution to the principal eigenvector problem.

5.7.3 Use the principal eigenvalue to calculate a heuristic check of consistency among the pairwise comparisons in a given MPC. Do a consistency check for each MPC in the problem both on comparisons among alternatives and among attributes.

5.7.3.1 Perfect consistency among pairwise comparisons is equivalent to perfect cardinal transitivity among the comparisons. That is, if Attribute 1 is twice as important as Attribute 2, and Attribute 2 is three times as important as Attribute 3, then perfect cardinal transitivity requires that Attribute 1 is six (two times three) times as important as Attribute 3.

5.7.3.2 Since the MPC has ones along its diagonal, then according to a theorem of linear algebra, its principal eigenvalue will be exactly equal to n if the pairwise comparisons are perfectly consistent, where n is the number of columns or rows in the square matrix. Also, if the pairwise comparisons deviate only slightly from perfect consistency, then the principal eigenvalue will deviate only slightly from n.

5.7.3.3 Use the difference between the principal eigenvalue λ_{max} and the order n of the matrix as the measure of inconsistency. Compare this difference with the average difference, as shown in the second column of Table 3, which would arise from purely random pairwise comparison values. The farther the difference $|\lambda_{max} - n|$ is from zero (that is, the closer to the difference resulting from random comparison values), the more inconsistent is your set of pairwise comparisons.

5.7.4 Compute the final desirability scores for each alternative, using Eq 3. The alternative with the highest desirability score is the preferred alternative.

$$D_a = \Sigma_{i=1}^{L} r_a(i) w(i) \tag{3}$$

TABLE 3 Values of $|\lambda_{max} - n|$ Resulting from Random Comparison Values[A]

Order of the Matrix (number of columns or rows)	Value of $|\lambda_{max} - n|$ Resulting from Random Comparison Values
3	1.16
4	2.7
5	4.48
6	6.2
7	7.92
8	9.87
9	11.6
10	13.41
11	15.1

[A] The numbers in this table are adopted from results published in Saaty's *The Analytic Hierarchy Process*, 1988, p. 21. They were derived assuming equal probability of integer comparison values over the closed interval from 1 to 9, enforcing reciprocity.

The quantity L is the number of leaf attributes in the hierarchy. The quantity $r_a(i)$ is the normalized "rating" of Alternative a with respect to Leaf Attribute i, which is equal to the *ath* element of the normalized principal eigenvector of the MPC from comparisons of the alternatives with respect to Leaf Attribute i. The quantity $w(i)$ is the composite weight of Leaf Attribute i. For simple hierarchies with only one set of attributes, $w(i)$ is equal to the *ith* element of the normalized principal eigenvector of the MPC from comparisons of the attributes with respect to the goal. For hierarchies with more than one set of attributes, compute $w(i)$ following the procedure described in Annex A1.

6. List of Selected Attributes for Evaluating Office Buildings

6.1 Fig. 4 contains a list of attributes and subattributes that decision makers typically find important in making building-related choices. The list gives building users a ready-made set of building attributes to choose from when using an AHP model to compare building alternatives. Because the list is intended to be comprehensive, it is arranged in a hierarchical fashion. Column 1 of Fig. 4 contains seven attributes (Level One in the hierarchy), and Col. 2 contains 21 subattributes (Level Two in the hierarchy). The Level One attributes represent broad categories; they are designed to help decision makers shape their decision problem in a parsimonious fashion (that is, without introducing an overly large number of attributes). Consequently, the Level One attributes help decision makers avoid unnecessary complexity which would make the decision hierarchy become unwieldy. The Level Two attributes provide traceability to one or more of ASTM's reference standards. The corresponding ASTM reference standard(s) for each Level Two attribute is listed in Col. 3.

6.2 The list of attributes is the product of a collaboration between two subcommittees of ASTM Committee E06 on Performance of Buildings. These subcommittees are ASTM Subcommittee E06.25 on Whole Buildings and Facilities and ASTM Subcommittee E06.81 on Building Economics. The majority of the attributes are based on the 17 published and one in-process standard classifications developed by Subcommittee E06.25. These attributes focus on rating building serviceability and performance. The remaining attributes are drawn from the E06.81 Subcommittee standards and focus on evaluating the

Attribute		ASTM Reference Standard (Col. 3)
Level One (Col. 1)	Level Two (Col. 2)	
Work Functions	Support for Office Work Meetings and Group Effectiveness Typical Office Information Technology Special Facilities and Technologies	E 1660 E 1661 E 1663 E 1694
Environmental/Ergonomic Support	Sound and Visual Environment Thermal Environment and Indoor Air	E 1662 In Balloting
Flexibility and Space Planning	Change and Churn by Occupants Layout and Building Factors	E 1692 E 1664
Security and Continuity of Work	Protection of Occupant Assets Facility Protection Work Outside Normal Hours or Conditions	E 1693 E1665 E1666
Image, Amenities and Access	Image to Public and Occupants Amenities to Attract and Retain Staff Location, Access and Wayfinding	E 1667 E 1668 E 1669
Property Management and Regulation	Structure, Envelope and Grounds Manageability Management of Operations and Maintenance Cleanliness	E 1700 E 1701 E 1670 E 1671
Building Economics	First Cost Considerations Operations and Maintenance Cost Considerations Economic Measures	E 1557 Building Maintenance, Repair, and Replacement Database (BMDB) for Life-Cycle Analysis E 917, E 1074, E 964, E 1057

FIG. 4 Attributes for Building-Related Decisions

economic performance of investments in buildings and building systems. These economics standards include one standard classification, four standard practices, and one adjunct.

6.3 The list of attributes shown in Fig. 4 provides the basis for a glossary of attributes in the ASTM software product, AHP/Expert Choice for ASTM Building Evaluation. The software product, designed to support this standard, provides a model-building feature that allows the decision maker to "slice" away those attributes not wanted to create a model of remaining attributes that best represent the decision maker's unique problem. The software product is quite flexible in that any attribute important to the decision maker, whether or not it is included in the glossary, can be added to the model structure.

6.4 The attributes apply primarily to office or commercial buildings. With some minor modifications, however the attributes are appropriate for evaluating residential choices.

6.5 Some of the attributes, such as property management and regulation and building and economics are also appropriate when using AHP to evaluate constructed facilities other than buildings. This includes dams, water supply and waste treatment facilities, transportation infrastructure, and other public works type projects. Alter the attributes cited in Fig. 4 or add new attributes to make the decision model fit the type of facility being evaluated.

7. Typical Building-Related AHP Applications

7.1 There are four common types of AHP building-related choice decisions: (*1*) choosing among buildings, (*2*) choosing among building components or elements,[8] (*3*) choosing among building materials, and (*4*) choosing the location for a business or household. The following sections illustrate for these four decision types how to identify the goal, select attributes, and display them in a hierarchy.

7.2 *Residential Example*[9]—A real estate company specializing in residential properties wants a computer-based decision tool to help clients select the "best" match between their individual housing wants and what is available on the multiple listing. An out-of-town client on a two-day house search comes to the real estate office and asks to be shown houses. The client wants a four-bedroom, three-bath, traditional home with a two-car garage in the suburbs that is reasonably accessible to a commuter train station on route to the central business district. The client wants a highly respectable, safe neighborhood and is willing to pay up to $200,000 for the house. An important consideration to the client is the quality of the public schools. Find the best house for the client.

7.2.1 An AHP analysis is appropriate here in two stages. First, the real estate salesperson uses AHP to help the client select that set of houses to visit. The client identified the following significant attributes: building serviceability (number of rooms and baths, capacity of garage); aesthetics (tastefully designed traditional home); location (accessibility to commuter station, desirability of neighborhood, proximity of good public schools); security; and economics (budget constraint). Fig. 5 displays the hierarchy of attributes. The house-hunting client visits the houses with the highest AHP scores.

7.2.2 The real estate salesperson does the AHP analysis a second time once the client has seen the selected houses and

[8] See Classification E 1557 for a classification of building elements.

[9] The choice-among-buildings decision for a commercial office building is illustrated in Section 8.

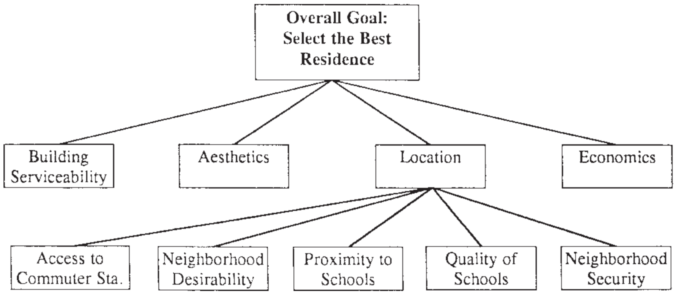

FIG. 5 An Example Hierarchy for the Problem of Selecting a Residence

has additional information for constructing a more detailed decision matrix. An AHP analysis with a graphical presentation of the score of each house helps satisfy homebuyers that they are selecting the house that is best for them.

7.3 *Choosing Among Components*—A trade association representing the heating and cooling equipment industry is choosing among three high-technology systems for retrofitting its office building. It wants to show the state of the art in its choice of equipment components, but at the same time it does not want to appear to its constituency as being uneconomic in its choice of a heating and cooling system. Furthermore, the association does not want the equipment to impair the existing successful operation and maintenance of the building. Help the trade association identify the best alternative among the candidate systems.

7.3.1 The association selects several attributes from Fig. 4 in evaluating the systems. In seeking to show the state-of-the-art in equipment, the association acknowledges that image to the owner is important. Economics was also pointed out. Maintaining successful building functions, smooth operation and maintenance, a high level of thermal environment and air quality, and a high standard of sound and visual environment are also important. Fig. 6 displays a hierarchy made up of these attributes.

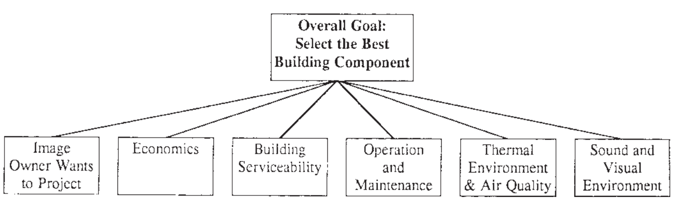

FIG. 6 An Example Hierarchy for the Problem of Selecting a Building Component

7.4 *Choosing Among Materials*—An architect is working with clients to select materials for a large office building. The clients tell the architect that they want a building made from materials that are friendly to the environment. The clients qualify their specifications, however, to say that they do not want the building's functions to be compromised by the design or choice of materials. They go on to say that, while they are willing to spend more money on materials to achieve a "green building," cost is still a consideration. The architect decides to use AHP to make the material choices that will best satisfy the clients' needs.

7.4.1 Fig. 7 displays a hierarchy made up of the attributes that the clients identified: environmental impacts, economics, building serviceability, and operation and maintenance.

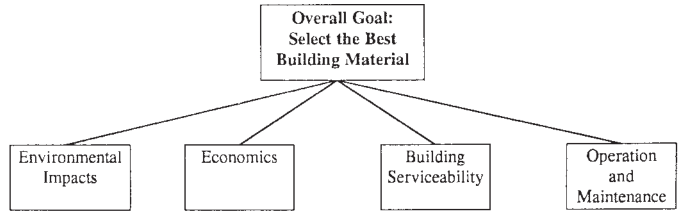

FIG. 7 An Example Hierarchy for the Problem of Selecting a Building Material

7.5 *Choosing the Location*[10]—A large corporation is seeking the best location in the United States for a new manufacturing plant. The search committee is seeking an area where there will be a continuing, abundant, sufficiently educated labor pool to staff an assembly line employing state-of-the-art technology. The company is looking for an area where the demand for labor is low, the community will offer incentives to a new company, new hires are expected to be loyal to the company, and where management can likely operate a non-union plant. Convenient and centrally located transportation nodes are also important. The major objective is to hold down costs and remain competitive with foreign manufacturers. Environmental and cultural amenities are also important, however, to attract a high-quality management team. The search committee uses AHP to find the best location.

7.5.1 The search committee identifies four attributes: economics (hold down costs to remain competitive); educational base for employees (ability to work in state-of-the-art factory); transportation (efficiently moving raw materials in and finished product out); and environmental and cultural amenities. The committee structures their location choice problem as shown in Fig. 8.

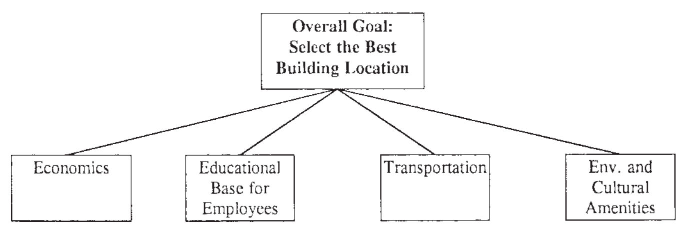

FIG. 8 An Example Hierarchy for the Problem of Selecting a Building Location

8. Case Illustration

8.1 This case illustrates how to apply AHP using a hypothetical example of a private company making a choice among existing buildings. The company gives the following description of its needs to a commercial realtor engaged to find appropriate space.

[10] There is a literature on location theory which investigates the factors that influence location decisions by businesses and households. See, for example, Schmenner, R. W., *Making Business Location Decisions* (Englewood Cliffs, NJ: Prentice-Hall, 1992).

8.2 The company conducts business inside and outside the United States. The headquarters building, which is too small because of staff growth, is in a large metropolitan area. Management wants to lease a building for the new corporate headquarters in a prominent location somewhere in the same metropolitan area. They want the style and location of the building to portray an upscale public image of a company that is modern and progressive. They also want a location that will be an attractant to the existing headquarters staff whom they hope will stay with the company after the move to the new building. Time is important because the lease on the existing headquarters building is up for renewal in six months.

(4) Construct a decision matrix containing available data on the performance of each alternative with respect to each leaf attribute (see Fig. 9 and Fig. 10);

(5) Construct the hierarchy;

(6) Make pairwise comparisons of each alternative against every other alternative as to how much preferable one is over the other with respect to each leaf attribute;

(7) Make pairwise comparisons, starting from the bottom of the hierarchy, of the relative importance of each attribute in a given set with respect to the attribute or goal above that set; and

(8) Compute the final overall desirability score for each alternative.

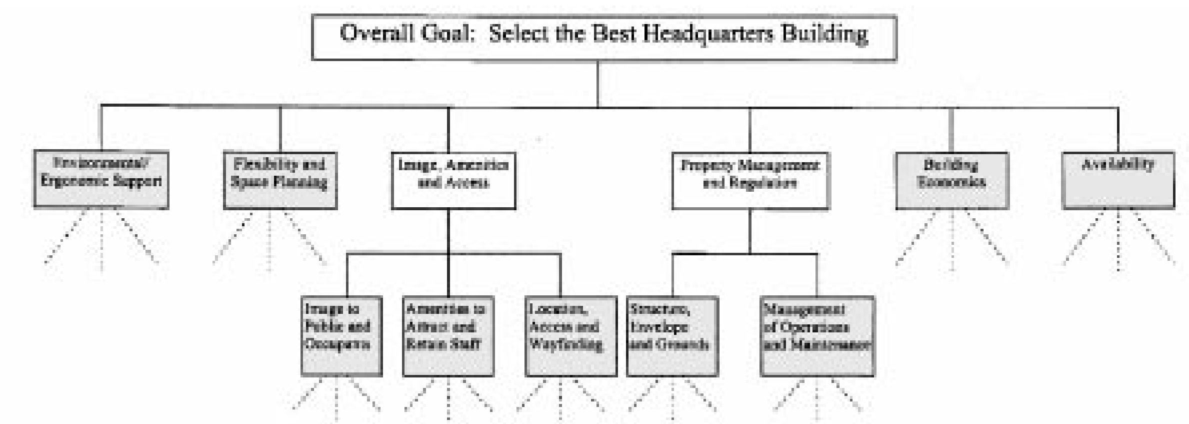

FIG. 9 Hierarchy for the Example Building Selection Problem, with Leaf Attributes Shaded

Attribute		Performance		
Level One	Level Two	Property A	Property B	Property C
Environmental/Ergonomic Support		Good	Very Good	Excellent
Flexibility and Space Planning		Fair	Good	Excellent
Image, Amenities and Access	Image to Public and Occupants	Fair	Good	Excellent
	Amenities to Attract and Retain Staff	Good	Good	Very Good
	Location, Access and Wayfinding	Fair	Very Good	Excellent
Property Management and Regulations	Structure, Envelope and Grounds	Good	Excellent	Excellent
	Management of Operations and Maintenance	Excellent	Good	Very Good
Building Economics		$4,500,000 per year	$5,800,000 per year	$7,800,000 per year
Availability		2 months	now	5 months

FIG. 10 Decision Matrix Description of Attributes by Property

8.3 To find the building that best suits the company's needs, the search firm decides to apply the AHP method in collaboration with the three-member property search committee of the company's board of directors. The steps, in order, are as follows:

(1) Define the goal of the building search;

(2) Identify important attributes and subattributes;

(3) Identify alternative buildings (called properties in the analysis);

8.3.1 The goal of the building search is to find the building that best suits the company's needs, as described by the company to the search firm.

8.3.2 An initial set of attributes that the company feels are most important was identified in the description of space needs. The initial set consisted of three attributes: (1) flexibility and space planning; (2) building aesthetics (image, amenities, and access); and (3) occupancy availability within six months, with sooner availability dates being preferred to later ones. The realty search firm gives the board of directors a questionnaire to see if there are other attributes that the company regards as important. The directors identify three more attributes: (1) economics (rent, utilities, and maintenance costs); (2) environmental/ergonomic support (sound and visual environment); and (3) property management and regulation. While yet additional attributes are considered, such as safety, meeting rooms, and thermal environment, the company is able to specify minimum requirements for these. So the search firm uses them as screening attributes only, and does not address them explicitly in the AHP. That is, the company expects any candidate property presented by the search firm to meet the constraint values of those additional attributes.

8.3.3 The AHP team, composed of the property committee of the board and the realty search firm, describe the problem using six attributes (and five subattributes) as shown in the hierarchy in Fig. 9. Note that image, amenities, and access, as well as flexibility and space planning, all emerge ultimately as important attributes.

8.3.4 Using the six AHP attributes and other constraint attributes to guide them, the search firm finds three building alternatives that they feel meet the company's needs: Properties A, B, and C.

8.3.5 Construct the AHP hierarchy from the goal by adding attributes and where appropriate their subattributes. Lastly, add the alternatives below each leaf attribute. The completed hierarchy is shown in Fig. 9 (the leaf attributes are shaded in Fig. 9; the three alternatives are shown as dashed lines).[11]

8.3.6 The team makes a decision matrix to clarify what data they have on each subattribute. Fig. 10 shows how the committee scored each alternative with respect to each attribute. Excellent is better than very good which is better than good with respect to all but the last two attributes. For these attributes, the fewer months until the property is available, the better and the lesser the annual economic cost, the better.

8.3.7 Starting from the bottom up, the committee makes pairwise comparisons of each alternative against every other alternative with respect to each leaf attribute in the hierarchy. Figs. 11-19 show the scores of alternatives with respect to each leaf attribute. A separate MPC was constructed for each leaf attribute. The "derived priorities" shown in each exhibit are the scores of the alternatives which the software calculated from each MPC. In Fig. 11, for example, Property C scores higher on environmental/ergonomic support than any other property.

8.3.8 The team then provides pairwise judgments of the relative importance of each subattribute with respect to the attribute above it in the hierarchy. Note from the hierarchy diagram in Fig. 9 that two sets of subattributes require comparison. The results of these inter-comparisons are shown for image, amenities, and access in Fig. 20, and for property management and regulations in Fig. 21. The company then provides pairwise judgments of how important each of the attributes is with respect to the goal of finding the best building. In Fig. 22 the "derived priorities" are the attribute weights that indicate the relative importance of the attributes with respect to the goal.

8.3.9 The last step is to use the computer program to calculate a final overall desirability score for each alternative. Fig. 23 shows Property C to be the best building for the company.

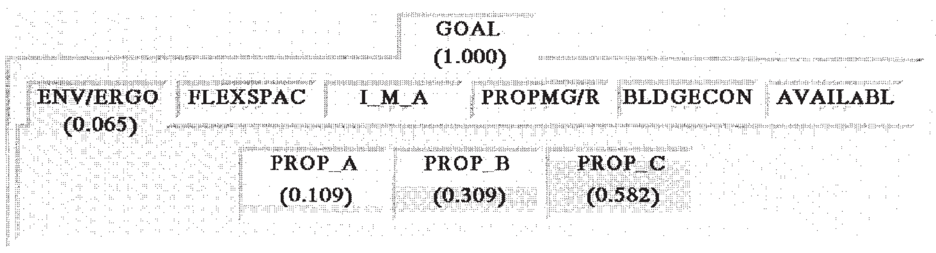

FIG. 11 Scores of Alternatives with Respect to Environmental/Ergonomic Support

[11] The ASTM software product, AHP/Expert Choice for ASTM Building Evaluation, was used to construct the hierarchy and work this problem.

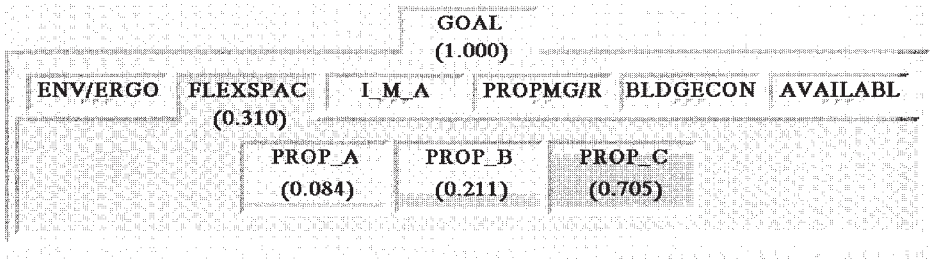

FIG. 12 Scores of Alternatives with Respect to Flexibility and Space Planning

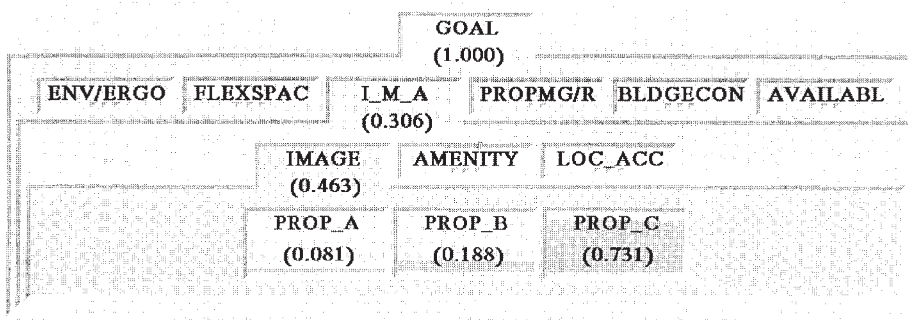

FIG. 13 Scores of Alternatives with Respect to Image to Public and Occupants

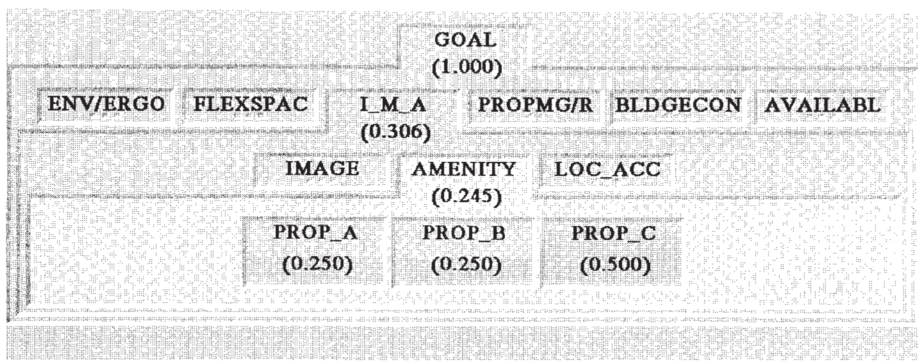

FIG. 14 Scores of Alternatives with Respect to Amenities to Attract and Retain Staff

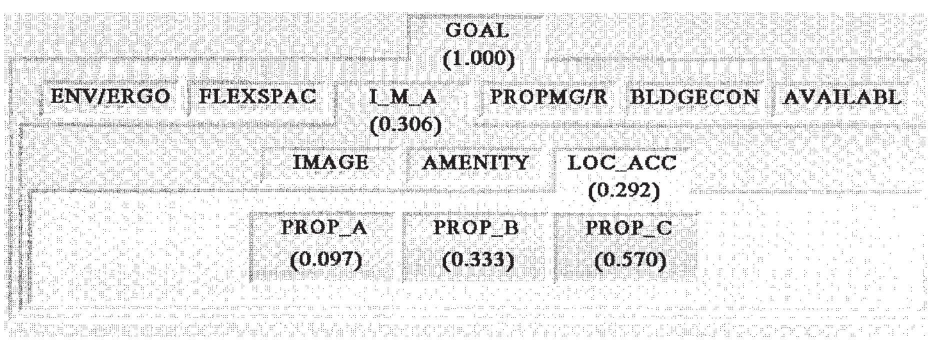

FIG. 15 Scores of Alternatives with Respect to Location, Access and Wayfinding

9. Applications

9.1 MADA methods allow decision makers in their investment decision making to consider multiple, conflicting, quantifiable (both nonmonetary and monetary), and nonquantifiable attributes of candidate alternatives.

9.2 The AHP, a well-tested MADA method, has an efficient attribute weighting process of pairwise comparisons and provides hierarchical descriptions of attributes, which keeps the number of pairwise comparisons manageable.

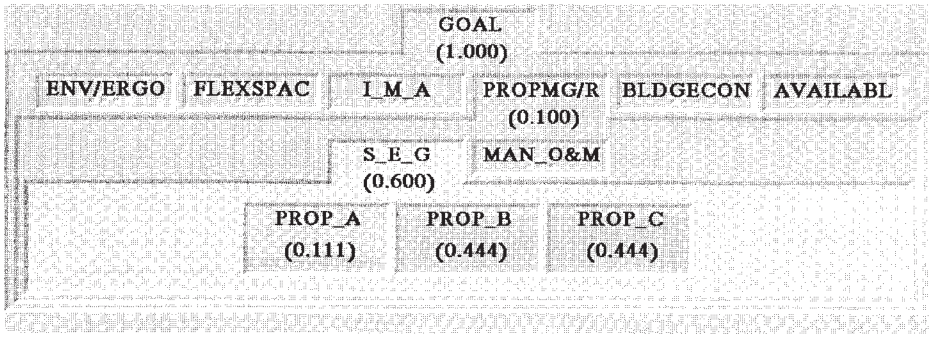

FIG. 16 Scores of Alternatives with Respect to Structure, Envelope and Grounds

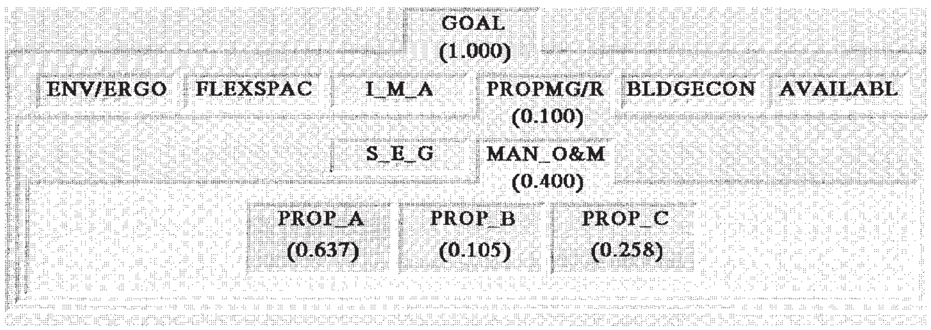

FIG. 17 Scores of Alternatives with Respect to Management of Operations and Maintenance

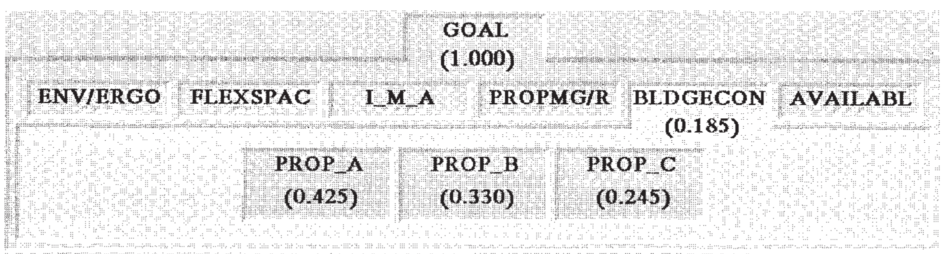

FIG. 18 Scores of Alternatives with Respect to Building Economics

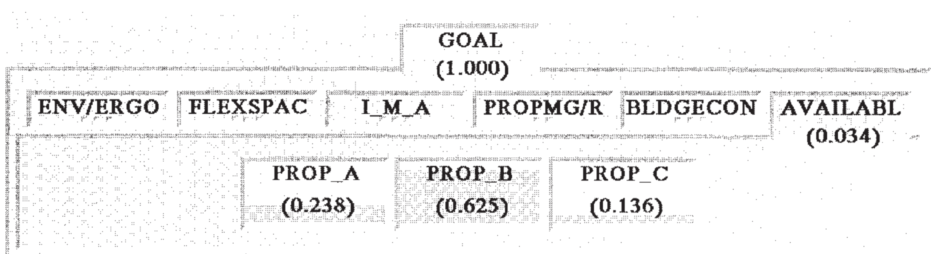

FIG. 19 Scores of Alternatives with Respect to Availability

9.3 The AHP is supported by commercially available, flexible, and user-friendly computer software.

10. Limitations

10.1 With the AHP approach to MADA, it is possible to have rank reversal among the remaining alternatives if one alternative is deleted from consideration.

10.2 Some analysts assert that the final desirability scores produced by AHP are somewhat arbitrary.[12]

[12] See, for example, Dyer, J., "Remarks on the Analytical Hierarchy Process," *Management Science*, 39(3), 1990, p. 254.

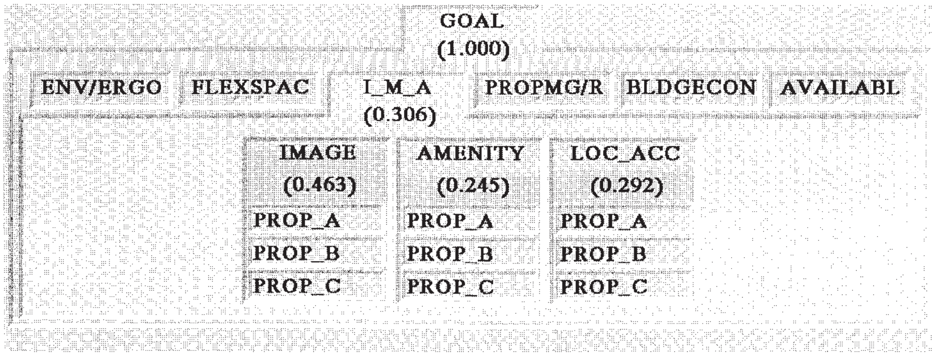

FIG. 20 Level Two Attribute Weights: Image, Amenities and Access

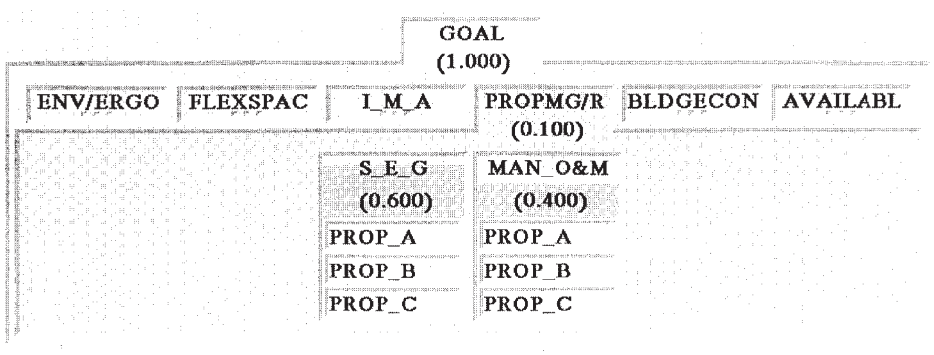

FIG. 21 Level Two Attribute Weights: Property Management and Regulation

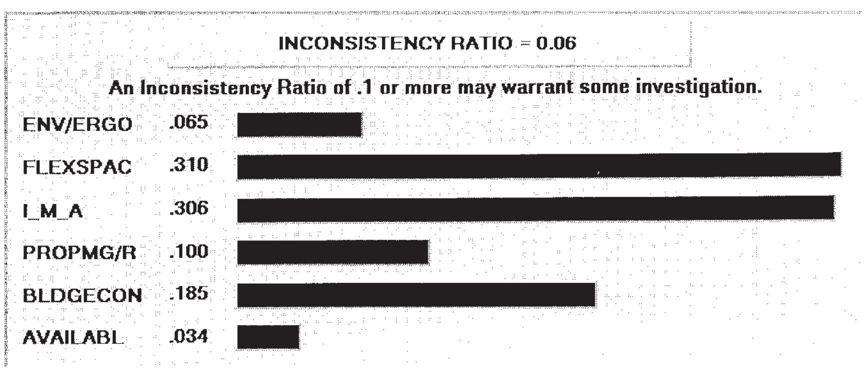

FIG. 22 Level One Attribute Weights

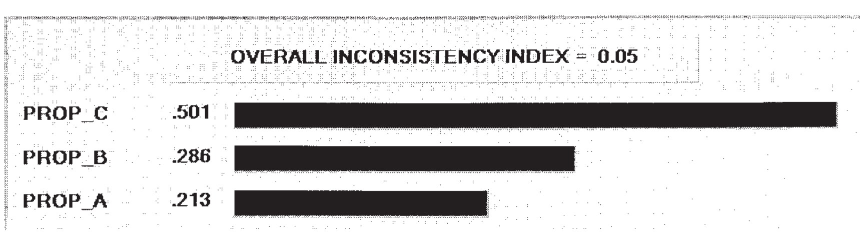

FIG. 23 Final Desirability Scores

11. Keywords

11.1 analytical hierarchy process; building economics; decision analysis; economic evaluation methods; engineering economics; hierarchical methods; investment analysis; multiattribute decision analysis; multiple criteria decision analysis; multiple objective decision analysis; operations research methods

ANNEX

(Mandatory Information)

A1. PROCEDURE FOR COMPUTING COMPOSITE WEIGHTS FOR LEAF ATTRIBUTES

A1.1 Use the method described in this annex to compute the composite weight, *w(i)*, for each Leaf Attribute *i* in a hierarchy. Then use the leaf attribute composite weights, together with the normalized "ratings," $r_a(i)$, of each Alternative *a* with respect to each of the *i* leaf attributes, to compute the final desirability scores for each alternative using Eq 3 (see 5.7.4).

A1.2 The general form of a hierarchy of attributes is displayed in Fig. A1.1. Each leaf attribute in the hierarchy is shaded, and each set of attributes is enclosed by dashed lines. The figure illustrates an attribute labeling convention which is used in this annex. The number used to refer to a particular attribute in the hierarchy is called the label of that attribute. There are three levels of sets in the hierarchy displayed in Fig. A1.1. To keep the size of the problem and the number of computations tractable, use no more than four levels of sets in a hierarchy.

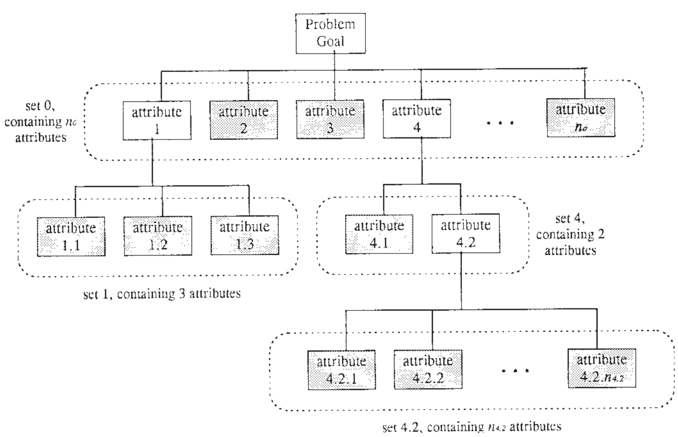

FIG. A1.1 A Hierarchy Illustrating the Attribute Labeling Convention

A1.3 Define the "product of weights" operator, Π_w, as an operator which returns the product of an attribute's normalized weight times the product of the normalized weights associated with all of the attributes located vertically above that attribute in the hierarchy. The argument of the product of weights operator is the label of the particular attribute within the hierarchy. Using the attribute labeling convention illustrated in Fig. A1.1, the product of weights operator is defined by Eq A1.1, where w_k refers to the normalized weight of Attribute *k* within its set.

$$\Pi_w = (w_k)(w_{k.l})(w_{k.l.m})(w_{k.l.m.n}) \tag{A1.1}$$

For example, Eq A1.1 specifies that the product of weights for Attribute 4.2.3 is given uniquely by the product:

$$\Pi_w[4.2.3] = (w_4)(w_{4.2})(w_{4.2.3}) \tag{A1.2}$$

A1.4 Determine the label of Leaf Attribute *i*, referred to as *label(i)*. Then, use Eq A1.3 to calculate the composite weight, *w(i)*, for each of the *i* leaf attributes in the hierarchy.

$$w(i) = \Pi_w[label(i)] \tag{A1.3}$$

For example, if Attribute 2.4.6.8 is the *j*th leaf attribute (and thus 2.4.6.8 is the label of the *j*th leaf attribute), then the composite weight, *w(j)*, for this leaf attribute is given by:

$$w(j) = \Pi_w[label(j)] = \Pi_w[2.4.6.8] = (w_2)(w_{2.4})(w_{2.4.6})(w_{2.4.6.8}) \tag{A1.4}$$

A1.5 Based on the equations and notation presented in this annex, the equation for the desirability score of Attribute *a* (Eq 3 of 5.7.4) generalizes to Eq A1.5, where *L* is the total number of leaf attributes in the hierarchy.

$$D_a = \sum_{i=1}^{L} r_a(i)\, \Pi_w[label(i)] \tag{A1.5}$$