Designation: E1765 – 16

Standard Practice for Applying Analytical Hierarchy Process (AHP) to Multiattribute Decision Analysis of Investments Related to Projects, Products, and Processes[1]

This standard is issued under the fixed designation E1765; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

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, product, and process alternatives. Investment 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/product's/process' total overall desirability when making capital investment decisions.[3] Projects include design, construction, operation, and disposal of commercial and residential buildings and other engineered structures.[4] Products include materials, components, systems, and equipment.[5] Processes include procurement, materials management, work flow, fabrication and assembly, quality control, and services.

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 among project/product/process alternatives are: a construction projects's building alternatives whose nonmonetary attributes are location/accessibility, site security, maintainability, quality of the sound and visual environment, and image to the public and occupants; building products based on their economic and environmental performance; and sustainability-related issues for key construction processes that address environmental needs, while considering project safety, cost, and schedule.

1.3 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

[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.

Current edition approved March 1, 2016. Published March 2016. Originally approved in 1995. Last previous edition approved in 2011 as E1765 – 11. DOI: 10.1520/E1765-16.

[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. *Software to Support ASTM E1765: Standard Practice for Applying Analytical Hierarchy Process (AHP) to Multiattribute Decision Analysis of Investments Related to Buildings and Building Systems*, MNL 29, ASTM, 1998.

[4] Projects also include analytical studies that identify alternative means for achieving organizational objectives as well as research and development activities that support the deployment of new products and processes.

[5] Typical construction-related products for each product type are: (*1*) materials—concrete; (*2*) components—structural steel members; (*3*) systems—heating, ventilating, and air-conditioning system; and (*4*) equipment—heat pump.

2. Referenced Documents

2.1 *ASTM Standards:*[6]

E631 Terminology of Building Constructions
E833 Terminology of Building Economics
E917 Practice for Measuring Life-Cycle Costs of Buildings and Building Systems
E964 Practice for Measuring Benefit-to-Cost and Savings-to-Investment Ratios for Buildings and Building Systems
E1057 Practice for Measuring Internal Rate of Return and Adjusted Internal Rate of Return for Investments in Buildings and Building Systems
E1074 Practice for Measuring Net Benefits and Net Savings for Investments in Buildings and Building Systems
E1121 Practice for Measuring Payback for Investments in Buildings and Building Systems
E1480 Terminology of Facility Management (Building-Related)
E1557 Classification for Building Elements and Related Sitework—UNIFORMAT II
E1660 Classification for Serviceability of an Office Facility for Support for Office Work
E1661 Classification for Serviceability of an Office Facility for Meetings and Group Effectiveness
E1662 Classification for Serviceability of an Office Facility for Sound and Visual Environment
E1663 Classification for Serviceability of an Office Facility for Typical Office Information Technology
E1664 Classification for Serviceability of an Office Facility for Layout and Building Factors
E1665 Classification for Serviceability of an Office Facility for Facility Protection
E1666 Classification for Serviceability of an Office Facility for Work Outside Normal Hours or Conditions
E1667 Classification for Serviceability of an Office Facility for Image to the Public and Occupants
E1668 Classification for Serviceability of an Office Facility for Amenities to Attract and Retain Staff
E1669 Classification for Serviceability of an Office Facility for Location, Access and Wayfinding
E1670 Classification for Serviceability of an Office Facility for Management of Operations and Maintenance
E1671 Classification for Serviceability of an Office Facility for Cleanliness
E1679 Practice for Setting the Requirements for the Serviceability of a Building or Building-Related Facility, and for Determining What Serviceability is Provided or Proposed
E1692 Classification for Serviceability of an Office Facility for Change and Churn by Occupants
E1693 Classification for Serviceability of an Office Facility for Protection of Occupant Assets
E1694 Classification for Serviceability of an Office Facility for Special Facilities and Technologies
E1700 Classification for Serviceability of an Office Facility for Structure and Building Envelope
E1701 Classification for Serviceability of an Office Facility for Manageability
E2114 Terminology for Sustainability Relative to the Performance of Buildings
E2320 Classification for Serviceability of an Office Facility for Thermal Environment and Indoor Air Conditions
E2432 Guide for General Principles of Sustainability Relative to Buildings

2.2 *Adjuncts:*

Discount Factor Tables Adjunct to Practices E917, E964, E1057, E1074, and E1121[7]

2.3 *ASTM Software Product:*

MNL 29 Software to Support ASTM E1765: Standard Practice for Applying Analytical Hierarchy Process (AHP) to Multiattribute Decision Analysis of Investments Related to Buildings and Building Systems[6]

3. Terminology

3.1 *Definitions*—For definitions of general terms related to building construction used in this practice, refer to Terminology E631; for general terms related to building economics, refer to Terminology E833; and for general terms related to whole buildings and facilities, refer to Terminology E1480. For definitions of general terms related to sustainability relative to the performance of buildings, refer to Terminology E2114.

4. Summary of Practice

4.1 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.

4.2 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.

4.3 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.

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

5. Significance and Use

5.1 The AHP method allows you to generate a single measure of desirability for project/product/process alternatives

[6] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[7] Available from ASTM International Headquarters. Order Adjunct No. ADJE091703.

with respect to multiple attributes (qualitative and quantitative). By contrast, life-cycle cost (Practice E917), net savings (Practice E1074), savings-to-investment ratio (Practice E964), internal rate-of-return (Practice E1057), and payback (Practice E1121) methods all require you to put a monetary value on benefits and costs in order to include them in a measure of project/product/process worth.

5.2 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.

5.3 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).

5.4 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.

5.5 The AHP method is well-suited for application to a variety of sustainability-related topics. Guide E2432 states when applying the concept of sustainability, it is necessary to assess and balance three dissimilar, yet interrelated general principles—environment, economic, and social—based on the best information available at the time the decision is made. Use AHP for pairwise comparisons among environmental attributes, among economic attributes, and among social attributes, and for establishing relative importance weights for each attribute and for each of the three general principles to which the attributes are attached. Use the AHP-established relative importance weights to select the preferred project/product/process from among the competing alternatives.

5.6 Potential users of AHP include architects, developers, owners, or lessors of buildings, real estate professionals (commercial and residential), facility managers, building material manufacturers, equipment manufacturers, product and process engineers, life cycle assessment experts, and agencies managing building portfolios.

6. Procedure

6.1 To carry out a MADA analysis using AHP, follow this procedure:[8]

6.1.1 Identify the elements of your problem to confirm that a MADA analysis is appropriate (see 6.2),

6.1.2 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 6.3),

6.1.3 Construct a decision matrix summarizing available data on the performance of each alternative with respect to each leaf attribute (see 6.4),

6.1.4 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 6.5),

6.1.5 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 6.6), and

6.1.6 Compute the final overall desirability score for each alternative (see 6.7).

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

6.2.1 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.

6.2.2 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.

6.2.3 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.

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

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

[8] Paragraphs 6.1 – 6.4 are common to many MADA methods. Paragraphs 6.5 – 6.7 pertain specifically to the AHP method.

6.3.1.1 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.

6.3.1.2 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.

6.3.1.3 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.

6.3.2 Fig. 2 covers attribute sets and leaf attributes.

6.3.2.1 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.

6.3.2.2 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.

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

6.4.1 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.

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

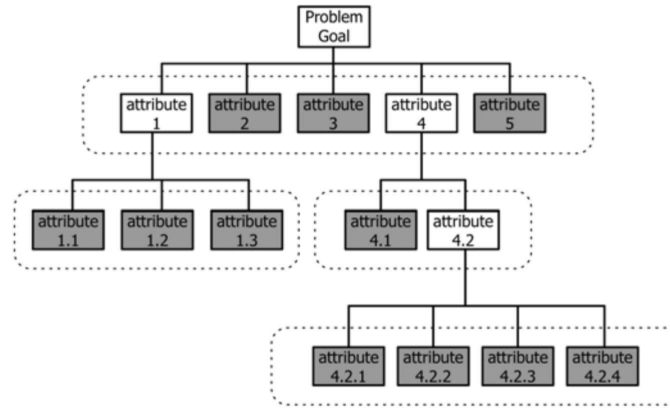

FIG. 2 A Hierarchy Illustrating Attribute Sets and Leaf Attributes

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

6.4.2 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.

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

6.4.4 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.

6.4.5 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.

6.5 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.

6.5.1 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.

6.5.2 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.

6.5.3 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?"

6.5.3.1 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."[9]

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

6.5.3.3 For verbally mediated judgments, have the decision maker answer each question with a verbal expression selected

[9] 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

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.

6.6 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 6.3.2.1.) Use the same MPC approach that was described in 6.5 for making a series of pairwise comparisons.

6.6.1 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?"

6.6.2 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 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.

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

6.6.3.1 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."

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

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.

6.6.3.3 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.

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

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

6.7.1 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.

$$\lambda_{max} e^* = M e^* \quad (1)$$

6.7.2 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.

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

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.

6.7.3 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.

6.7.3.1 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.

6.7.3.2 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.

6.7.3.3 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

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.

inconsistent is your set of pairwise comparisons.

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

$$D_a = \sum_{i=1}^{L} r_a(i)w(i) \quad (3)$$

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.

7. List of Selected Attributes for Evaluating Office Buildings

7.1 Table 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 Table 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.

7.2 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 18 published standard classifications developed by Subcommittee E06.25. These attributes focus on rating building serviceability and performance (see Practice E1679). The remaining attributes are drawn from the E06.81 Subcommittee standards and focus on evaluating the economic performance of investments in buildings and building systems. These economics standards include one standard classification, four standard practices, and one adjunct.

TABLE 4 Attributes for Building-Related Decisions

Attribute		ASTM Reference Standard
Level One (Col. 1)	Level Two (Col. 2)	(Col. 3)
Work Function	Support for office Work	E1660
	Meetings and Group Effectiveness	E1661
	Typical Office Information Technology	E1663
	Special Facilities and Technologies	E1694
Environmental/Ergonomic Support	Sound and Visual Environment	E1662
	Thermal Environment and Indoor Air Conditions	E2320
Flexibility and Space Planning	Change and Churn by Occupants	E1692
	Layout and Building Factors	E1664
Security and Continuity of Work	Protection of Occupant Assets	E1693
	Facility Protection	E1665
	Work Outside Normal Hours or Conditions	E1666
Image, Amenities and Access	Image to Public and Occupants	E1667
	Amenities to Attract and Retain Staff	E1668
	Location, Access and Wayfindig	E1669
Property Management and Regulation	Structure, Envelope and Grounds	E1700
	Manageability	E1701
	Management of Operations and Maintenance	E1670
	Cleanliness	E1671
Building Economics	First Cost Considerations	E1557
	Operations and Maintenance Cost Considerations	Discount Factor Tables
	Economic Measures	E917, E1074
		E964, E1057

7.3 The list of attributes shown in Table 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.

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

7.5 Some of the attributes, such as property management and regulation and building 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 Table 4 or add new attributes to make the decision model fit the type of facility being evaluated.

8. Typical Building-Related AHP Applications

8.1 There are four common types of AHP building-related choice decisions: (*1*) choosing among buildings, (*2*) choosing among building components or elements,[10] (*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.

8.2 *Residential Example*[11]—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.

8.2.1 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. 4 displays the hierarchy of attributes. The house-hunting client visits the houses with the highest AHP scores.

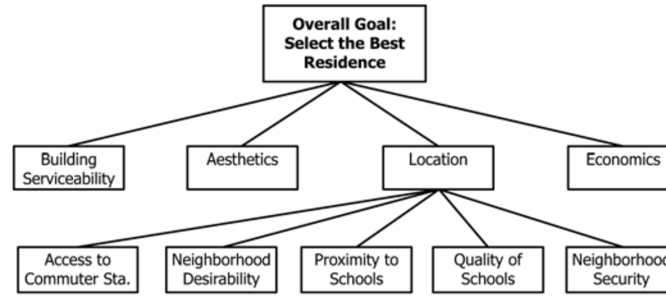

FIG. 4 An Example Hierarchy for the Problem of Selecting a Residence

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

8.3 *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.

8.3.1 The association selects several attributes from Table 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. 5 displays a hierarchy made up of these attributes.

8.4 *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

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

[10] See Classification E1557 for a classification of building elements.

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

building," cost is still a consideration. The architect decides to use AHP to make the material choices that will best satisfy the clients' needs.

8.4.1 Fig. 6 displays a hierarchy made up of the attributes that the clients identified: environmental impacts, economics, building serviceability, and operation and maintenance.

8.5 *Choosing the Location*[12]—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.

8.5.1 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. 7.

9. Case Illustration

9.1 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.

9.2 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

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

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.

9.3 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);

(4) Construct a decision matrix containing available data on the performance of each alternative with respect to each leaf attribute (see Fig. 8 and Fig. 9);

(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.

9.3.1 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.

9.3.2 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.

[12] 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.

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

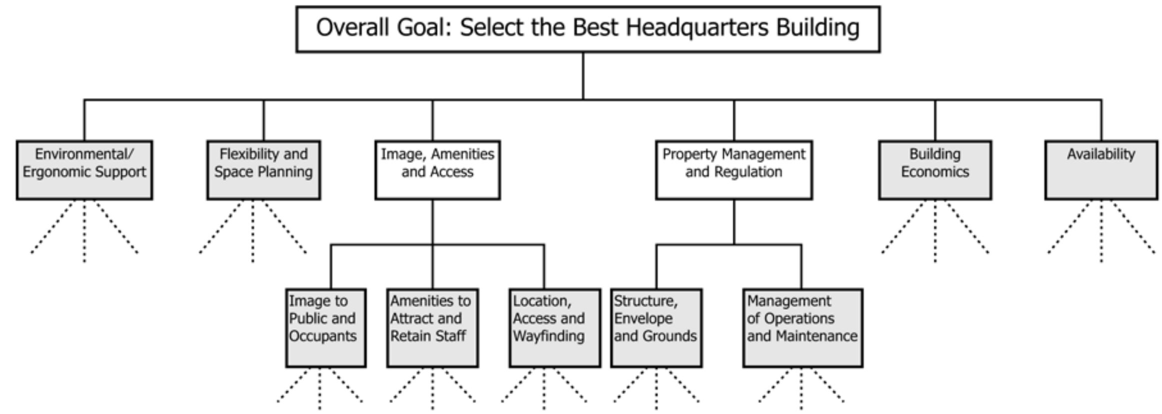

FIG. 8 Hierarchy for the Example Building Selection Problem, with Leaf Attributes Shaded

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. 9 Decision Matrix Description of Attributes by Property

9.3.3 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. 8. Note that image, amenities, and access, as well as flexibility and space planning, all emerge ultimately as important attributes.

9.3.4 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.

9.3.5 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. 8 (the leaf attributes are shaded in Fig. 8; the three alternatives are shown as dashed lines).[13]

9.3.6 The team makes a decision matrix to clarify what data they have on each subattribute. Fig. 9 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.

9.3.7 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. 10-18 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. 10, for example, Property C scores higher on environmental/ergonomic support than any other property.

9.3.8 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. 8 that two sets of subattributes require comparison. The results of these inter-comparisons are shown for image, amenities, and access in Fig. 19, and for property management and regulations in Fig. 20. 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. 21 the "derived priorities" are the attribute weights that indicate the relative importance of the attributes with respect to the goal.

[13] The ASTM software product, MNL 29, was used to construct the hierarchy and work this problem.

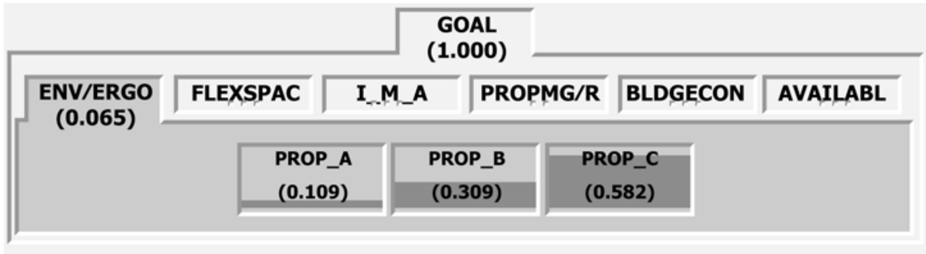

FIG. 10 Scores of Alternatives with Respect to Environmental/Ergonomic Support

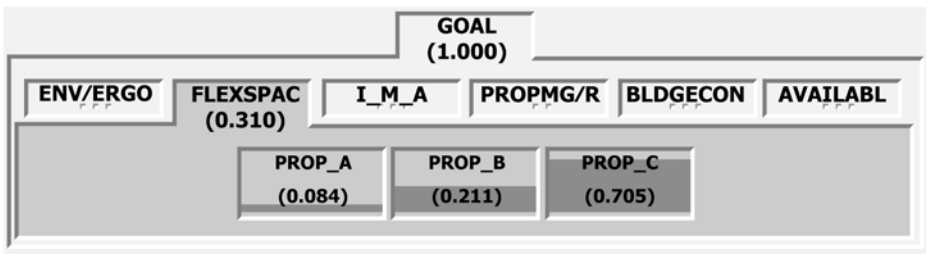

FIG. 11 Scores of Alternatives with Respect to Flexibility and Space Planning

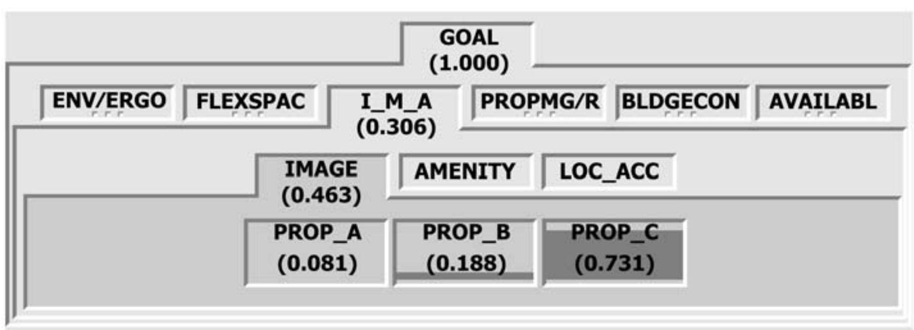

FIG. 12 Scores of Alternatives with Respect to Image to Public and Occupants

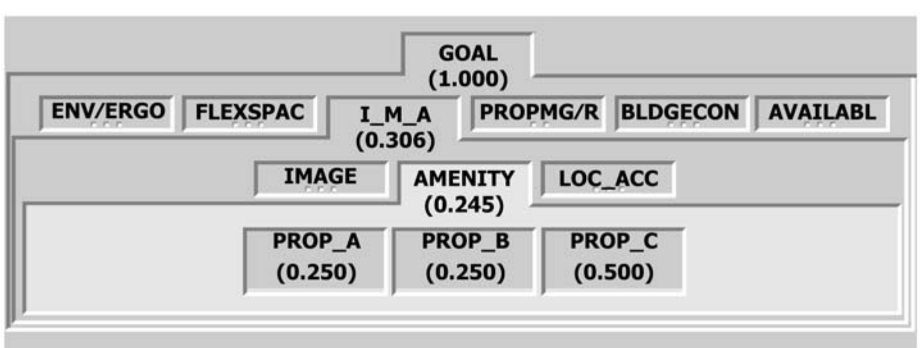

FIG. 13 Scores of Alternatives with Respect to Amenities to Attract and Retain Staff

9.3.9 The last step is to use the computer program to calculate a final overall desirability score for each alternative. Fig. 22 shows Property C to be the best building for the company.

10. Applications

10.1 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.

10.2 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.

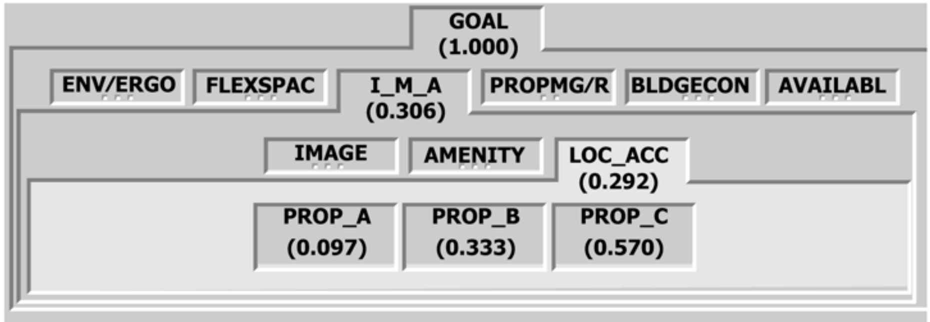

FIG. 14 Scores of Alternatives with Respect to Location, Access and Wayfinding

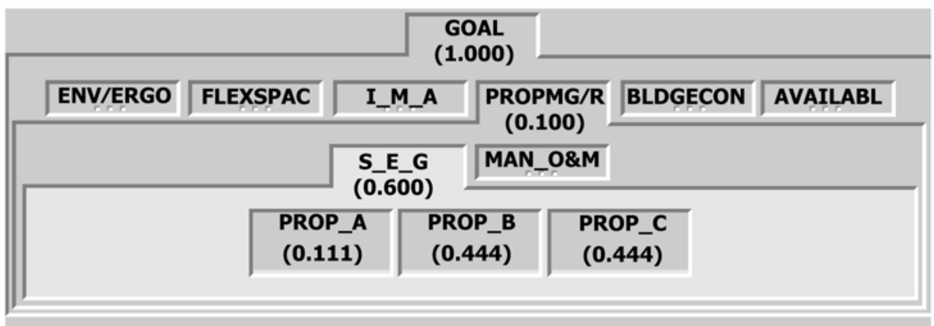

FIG. 15 Scores of Alternatives with Respect to Structure, Envelope and Grounds

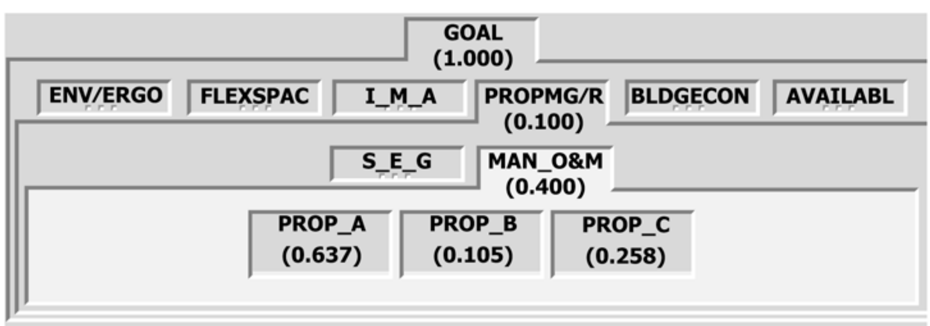

FIG. 16 Scores of Alternatives with Respect to Management of Operations and Maintenance

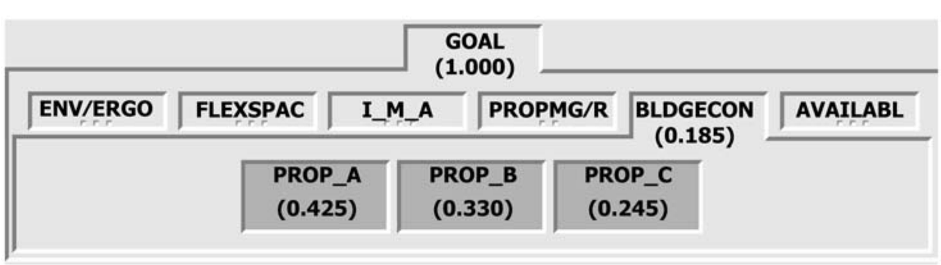

FIG. 17 Scores of Alternatives with Respect to Building Economics

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

10.4 Appendix X1 identifies relative importance weights for BEES (Building for Environmental and Economic Sustainability) that several groups of users have developed through application of the AHP process for use in evaluating 12 selected environmental impacts and explains how the AHP process was used to generate the weights for the environmental attributes.

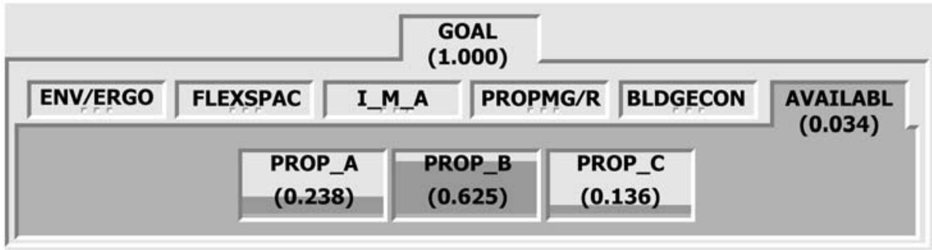

FIG. 18 Scores of Alternatives with Respect to Availability

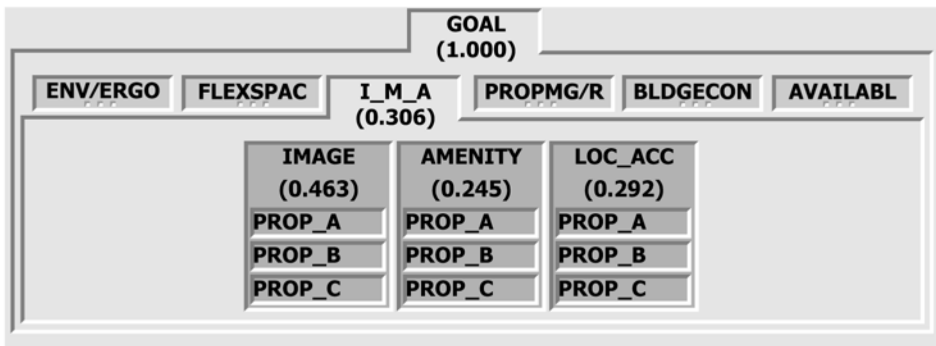

FIG. 19 Level Two Attribute Weights: Image, Amenities and Access

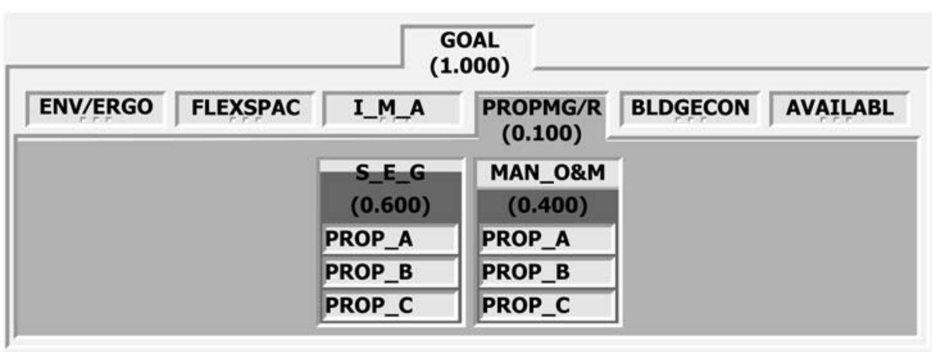

FIG. 20 Level Two Attribute Weights: Property Management and Regulation

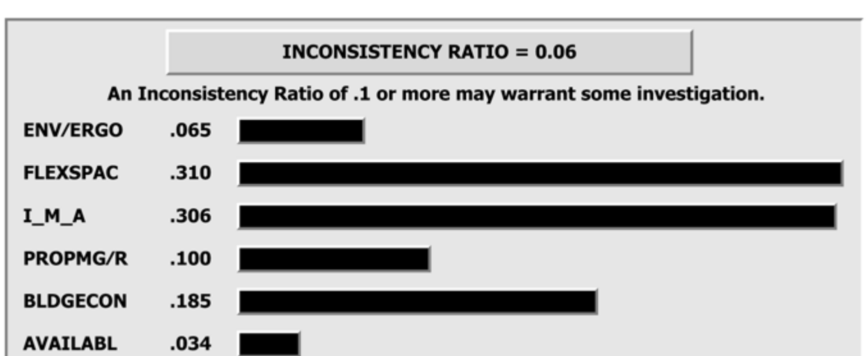

FIG. 21 Level One Attribute Weights

11. Limitations

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

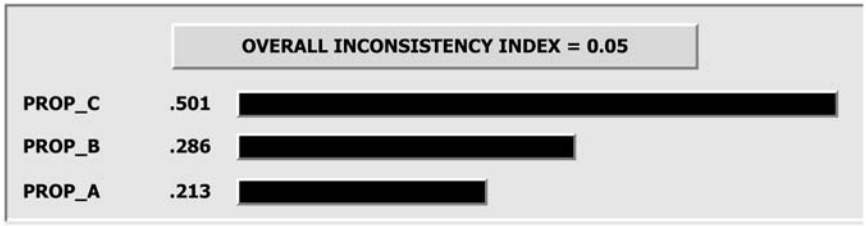

FIG. 22 Final Desirability Scores

11.2 Some analysts assert that the final desirability scores produced by AHP are somewhat arbitrary.[14]

12. Keywords

12.1 analytical hierarchy process; building economics; decision analysis; economic evaluation methods; engineering economics; hierarchical methods; investment analysis; multi-attribute decision analysis; multiple criteria decision analysis; multiple objective decision analysis; operations research methods; sustainability

[14] See, for example, Dyer, J., "Remarks on the Analytical Hierarchy Process," *Management Science*, Vol 39, No. 3, 1990, p. 254.

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 6.7.4).

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.

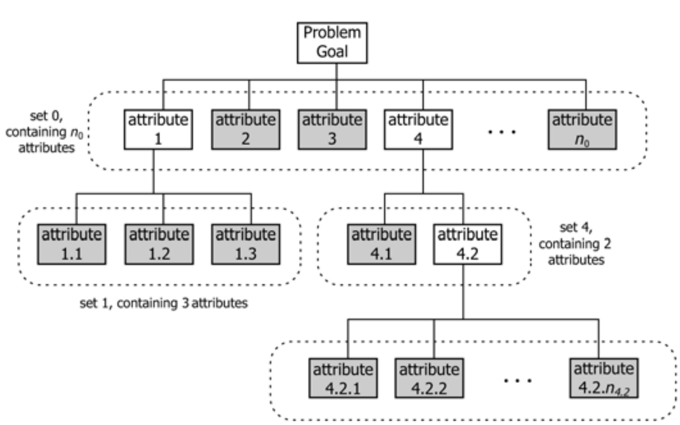

FIG. A1.1 A Hierarchy Illustrating the Attribute Labeling Convention

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.

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

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

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

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.

$$w(i) = \Pi_w[label(i)] \quad (A1.3)$$

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

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

A1.5 Based on the equations and notation presented in this annex, the equation for the desirability score of Attribute *a* (Eq 3 of 6.7.4) generalizes to Eq A1.5, where *L* is the total number of leaf attributes in the hierarchy.

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

APPENDIX

(Nonmandatory Information)

X1. ATTRIBUTE WEIGHTS IN BEES (BUILDING FOR ENVIRONMENTAL AND ECONOMIC SUSTAINABILITY)

X1.1 *Problem*—Building choices with respect to whole buildings and building-related products entail tradeoffs between economic and environmental objectives. This AHP standard provides a methodology for structuring an analysis of building-related alternatives in order to rate them with a numerical score that identifies their relative desirability according to the stakeholder's personal weights of relative importance assigned economics and various environmental attributes. The standard also describes how to determine those relative attribute weights. Governments, industry, and vested interests often want to know what importance weights they might assign attributes in an analysis that would be acceptable to different classes of stakeholders without trying to derive those weights themselves in every application. Whereas an individual user might be satisfied to come up with their own importance weights, others, such as product manufacturers, would like to have industry-and customer-acceptable weights, especially in measuring the relative importance of environmental and economic attributes. It is particularly important that the same weights be used, for example, when building products from different manufacturers are being evaluated by a given consumer trying to determine which is the most desirable. Thus users of AHP who are evaluating products based on economic and environmental objectives need relative importance weights for the economic and environmental attributes that will be representative of and acceptable to the population of product users.

X1.2 *Objective*—This appendix identifies relative importance weights that several groups of users have developed through application of the AHP process for use in evaluating 12 selected environmental impacts. These weights have been used in the BEES (Building for Environmental and Economic Sustainability) methodology[15] and software tool.[16] The BEES decision-support software helps decision makers choose among buildings and building-related products in a way that optimizes tradeoffs between environmental considerations and cost effectiveness. This appendix provides relative importance weights as a resource for those who need environmental weights as inputs in applying AHP (through BEES or other tools) in determining optimal building-related choices when multiple environmental attributes are being considered. A second objective of the appendix is to explain how the AHP process was used to generate the weights for the environmental attributes. A third objective is to calculate and interpret the overall performance score that combines environmental and economic attributes.

X1.3 *Importance Weights for Environmental Attributes*—Three alternative sets of environmental importance weights are provided. One is based on a set of equal weights. The second is based on an Environmental Protection Agency (EPA) Science Advisory Board study. The third was developed through a structured judgment process that was undertaken by a BEES Stakeholder Panel at a 2006 meeting at the National Institute of Standards and Technology. It is important to note that the three alternative sets of environmental importance weights are examples of sets that might be used if deemed appropriate by the user. They are not the only sets, nor are they necessarily the best sets, for all categories of users.

X1.3.1 *Equal Weights* If the user preferred equal weights in measuring the relative importance of the 12 selected impact categories, the weight would be 8.3 % (100/12 = 8.3) for each of the 12 categories. See Table X1.1 for a listing of the 12

TABLE X1.1 Relative Importance Weights for 12 Impact Categories of Equal Importance

Impact Category	Relative Importance Weight (%)
Global Warming	8.3
Acidification	8.3
Eutrophication	8.3
Fossil Fuel Depletion	8.3
Indoor Air Quality	8.3
Habitat Alteration	8.3
Water Intake	8.3
Criteria Air Pollutants	8.3
Smog	8.3
Ecological Toxicity	8.3
Ozone Depletion	8.3
Human Health	8.3

[15] Lippiatt, B.C., *BEES 4.0: Building for Environmental and Economic Sustainability Technical Manual and User Guide*, NISTIR 7423, Gaithersburg, MD: National Institute of Standards and Technology, 2007.

[16] Available from National Institute of Standards and Technology (NIST), 100 Bureau Dr., Stop 1070, Gaithersburg, MD 20899-1070, http://www.bfrl.nist.gov/oae/software/bees.

Impact Categories and equal Environmental Weights.

X1.3.2 *EPA Science Advisory Board (SAB) Weights*—EPA's SAB developed verbal importance weights first in 1990 and then again in 2000.[17]

X1.3.2.1 The following criteria were used to develop the list of important environmental impact categories:

(1) The spatial scale of the impact,

(2) The severity of the hazard,

(3) The degree of exposure, and

(4) The penalty for being wrong.

X1.3.2.2 Ten of the twelve BEES impact categories were included in the SAB lists of relative importance:

(1) Highest-Risk Problems—Global warming, habitat alteration.

(2) High-Risk Problems—Indoor air quality, ecological toxicity, human health.

(3) Medium-Risk Problems—Ozone depletion, smog, acidification, eutrophication, criteria air pollutants.

X1.3.2.3 The SAB's verbal importance rankings, such as "highest risk," were translated by the BEES developer into numerical importance weights using this guide for AHP. The following numerical comparison scale for environmental impacts was developed using the AHP methodology:

1	Two impacts contribute equally to the objective (in this case environmental performance).
3	Experience and judgment slightly favor one impact over another.
5	Experience and judgment strongly favor one impact over another.
7	One impact is favored very strongly over another, its dominance demonstrated in practice.
9	The evidence favoring one impact over another is of the highest possible order of affirmation.
2, 4, 6, 8	When compromise between values of 1, 3, 5, 7, and 9 is needed.

X1.3.2.4 Through the AHP process of pairwise comparison, numerical comparison values were assigned to each possible pair of environmental impacts. Relative importance weights were then derived by computing the normalized eigenvector of the largest eigenvalue of the matrix of pairwise comparison values. Table X1.2 and Table X1.3 list the pairwise comparison values assigned to the verbal importance rankings and the resulting SAB importance weights computed for the 12 impacts, respectively. Note that the pairwise comparison values were assigned through an iterative process based on the background and experience of NIST researchers in applying the AHP technique.

[17] United States Environmental Protection Agency, Science Advisory Board, Reducing Risk: Setting Priorities and Strategies for Environmental Protection, SAB-EC-90-021, Washington, D.C., September 1990, pp. 13-14; and United States Environmental Protection Agency, Science Advisory Board, Toward Integrated Environmental Decision-Making, EPA-SAB-EC-00-011, Washington, D.C., August 2000.

TABLE X1.2 Pairwise Comparison Values for Deriving Impact Category Importance Weights

Verbal Importance Comparison	Pairwise Comparison Value
Highest vs. Low	6
Highest vs. Medium	3
Highest vs. High	1.5
High vs. Low	4
High vs. Medium	2
Medium vs. Low	2

TABLE X1.3 Relative Importance Weights Based on EPA Science Advisory Board Study

Impact Category	Relative Importance Weight (%)
Global Warming	16
Acidification	5
Eutrophication	5
Fossil Fuel Depletion	5
Indoor Air Quality	11
Habitat Alteration	16
Water Intake	3
Criteria Air Pollutants	6
Smog	6
Ecological Toxicity	11
Ozone Depletion	5
Human Health	11

X1.3.3 *BEES Stakeholder Panel Weights* Users of BEES wanted a close match of impact categories and their intended application of BEES, which is environmentally preferable purchasing. In order to develop such a weight set, NIST assembled a volunteer stakeholder panel that met at its facilities in Gaithersburg, Maryland for a full day in May 2006. To convene the panel, invitations were sent to individuals representing one of three "voting interests:" producers (for example, building product manufacturers), users (for example, green building designers and private and public sector organizations concerned about environmental issues and the public's perception of them as "socially responsible" entities), and life-cycle assessment (LCA) experts. Nineteen individuals participated in the panel: seven producers, seven users, and five LCA experts. These "voting interests" were adapted from the groupings that ASTM International employs for developing voluntary standards. The panelists established the weight sets based on their personal and professional understanding of the various impact categories and their personal assignments of value to those respective categories.[18] The panel represented specific voting interests or stakeholders. Users of such weights, however, might want a different set of voting interests to best represent the population whose interests they wished to capture. The objective here is to show how the weights were determined using the AHP process and show one possible set for one possible mix of voting interests.

X1.3.3.1 The BEES Stakeholder Panel was led by Dr. Ernest Forman, founder of the AHP firm Expert Choice Inc. Dr. Forman facilitated panelists in weighting the BEES impact categories using the AHP pairwise comparison process. Thirteen Impact Categories were evaluated. Cancerous and Non-cancerous effects were judged separately to enable a more refined assessment of these two constituents of the Human Health impact. The other 11 were the same as those used in the SAB list. The panel weighted all impacts in the Short Term

[18] Readers interested in the methodology used to select panelists and to generate assignment of values to the 12 environmental attributes are referred to (Lippiatt, 2007).

(0 years to 10 years), Medium Term (10 years to 100 years), and Long Term (>100 years). One year's worth of U.S. flows for each pair of impacts was compared with respect to their contributions to environmental performance. For example, for an impact comparison over the Long Term, the panel was evaluating the effect that the current year's U.S. emissions would have more than 100 years hence.

X1.3.3.2 Once the panel completed pairwise comparisons of impacts for the three time horizons, its judgments were synthesized across these time horizons. Note that when synthesizing judgments across voting interests and time horizons, all panelists were assigned equal importance, while the short, medium, and long-term time horizons were assigned by the panel to carry 24 %, 31 %, and 45 % of the weight, respectively.

X1.3.3.3 The environmental impact importance weights developed through application of the AHP technique at the facilitated BEES Stakeholder Panel event are shown in Table X1.4. These weights reflect a synthesis of panelists' perspectives across all combinations of stakeholder voting interest and time horizon.

X1.3.3.4 The three figures below display in graphical form the BEES Stakeholder Panel weights. Fig. X1.1 displays the synthesized weight set; Fig. X1.2 the weights specific to panelist voting interest; and Fig. X1.3 the weights specific to time horizon. The AHP user is free to interpret results using any of the weight sets displayed in Figs. X1.1-X1.3 by entering them as a user-defined weight set in an analysis of building alternatives.

X1.4 Importance Weights in the BEES Overall Score Calculation

X1.4.1 The BEES overall performance measure synthesizes the environmental and economic results into a single score, as illustrated in Fig. X1.4.

X1.4.2 Measuring the economic performance is more straightforward than measuring the environmental performance; it does not require the use of weighting techniques. BEES follows the ASTM standard method for life-cycle costing of building-related investments.[19] In the BEES model, economic performance is measured over a 50-year study period for all assessed products. For consistency, the BEES model evaluates the use stage of environmental performance over the same 50-year study period.

X1.4.3 There are two cost categories associated with the economic score. First costs are the cost of the product in the initial year of analysis. Future costs (for example, replacement costs) are converted to their equivalent present value through the use of discount rates. As a default, the BEES model computes life-cycle costs using a real rate of 3.0 %, the 2006 rate mandated by the U.S. Office of Management and Budget for most Federal projects.[20] The economic score component simply sums across the first cost and discounted future costs.

X1.4.4 Before combining the environmental and economic performance scores, each is placed on a common scale by dividing by the sum of the corresponding scores across all alternatives under analysis. Effectively, this process rescales each of the economic and environmental performance scores in terms of its share of all scores, placing each on the same, relative scale of 0 to 100.

X1.4.5 Economic and environmental scores are combined into an overall score by weighting each by their relative importance and taking a weighted average. The default weighting in BEES is set to 50-50 between the two scores. The user is able to specify the relative importance weights used to combine environmental and economic performance scores.

X1.5 How to Interpret the BEES Overall Score

X1.5.1 The BEES overall performance scores do not represent absolute performance. Rather, they represent proportional differences in performance, or relative performance, among competing alternatives. Consequently, the overall performance score for a given building alternative can change if one or more competing alternatives are added to or removed from the set of alternatives under consideration.

X1.5.2 Among competing alternatives, the lowest overall score is preferred, so long as the alternatives remain the same, as described above. Though, since they are relative scores, no conclusions may be drawn by comparing overall scores across building categories (for example, exterior wall finishes as compared to roof coverings). Among competing alternatives within a given building category (for example, different types of roof coverings), the one with the lowest environmental score is the most desirable with reference to the goal of least environmental impact. Environmental scores remain absolute regardless of the addition or removal of alternatives and are comparable across building categories.

TABLE X1.4 Relative Importance Weights Based on BEES Stakeholder Panel Weights

Impact Category	Relative Importance Weight (%)
Global Warming	29
Acidification	3
Eutrophication	6
Fossil Fuel Depletion	10
Indoor Air Quality	3
Habitat Alteration	6
Water Intake	8
Criteria Air Pollutants	9
Smog	4
Ecological Toxicity	7
Ozone Depletion	2
Human Health	
Cancerous Effects	8
Noncancerous Effects	5

[19] E917-05 Standard Practice for Measuring Life-Cycle Costs of Buildings and Building Systems ASTM International, Standard Practice for Measuring Life-Cycle Costs of Buildings and Building Systems, ASTM Designation E917-05, West Conshohocken, PA, 2002.

[20] U.S. Office of Management and Budget (OMB) Circular A-94, Guidelines and Discount Rates for Benefit-Cost Analysis of Federal Programs, Washington, D.C., October 27, 1992 and OMB Circular A-94, Appendix C, Washington, D.C., January 2007.

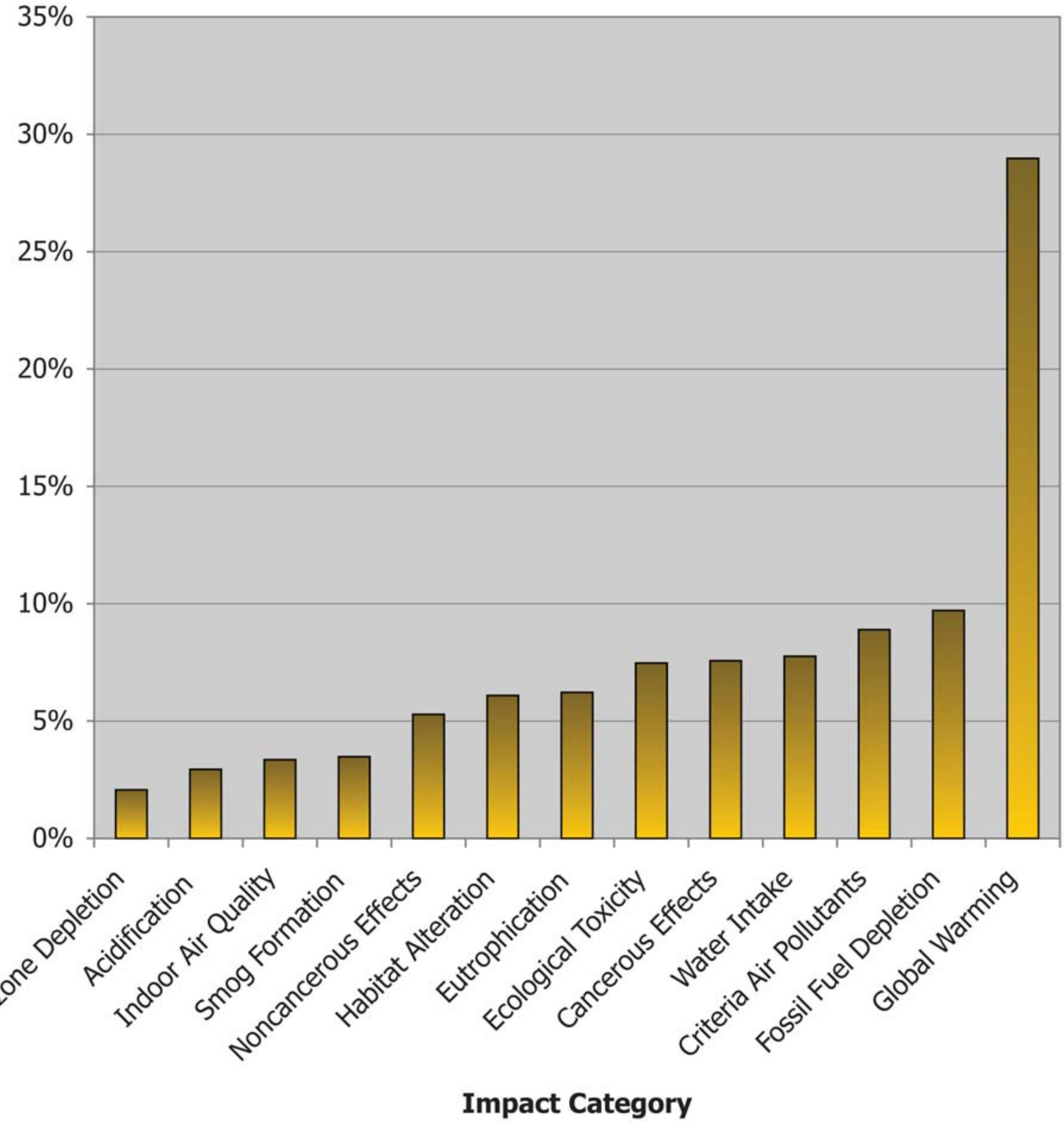

FIG. X1.1 Relative Importance Weights Based on BEES Stakeholder Panel Weights

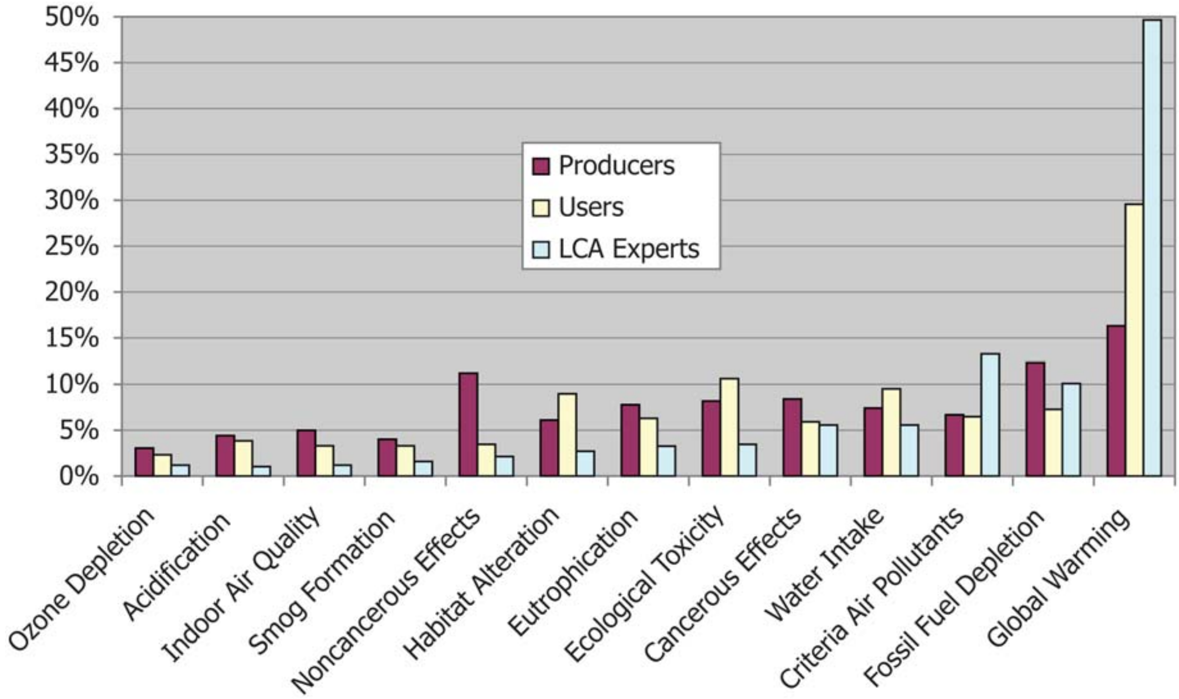

FIG. X1.2 Relative Importance Weights by BEES Stakeholder Voting Interest

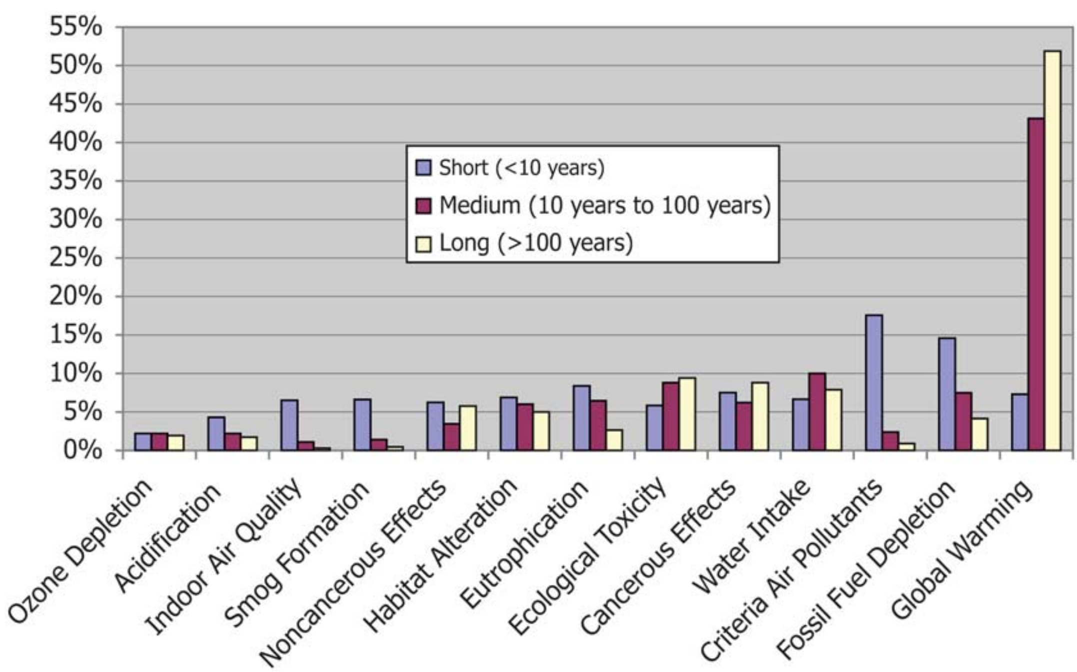

FIG. X1.3 Relative Importance Weights Based on BEES Stakeholder Time Horizons

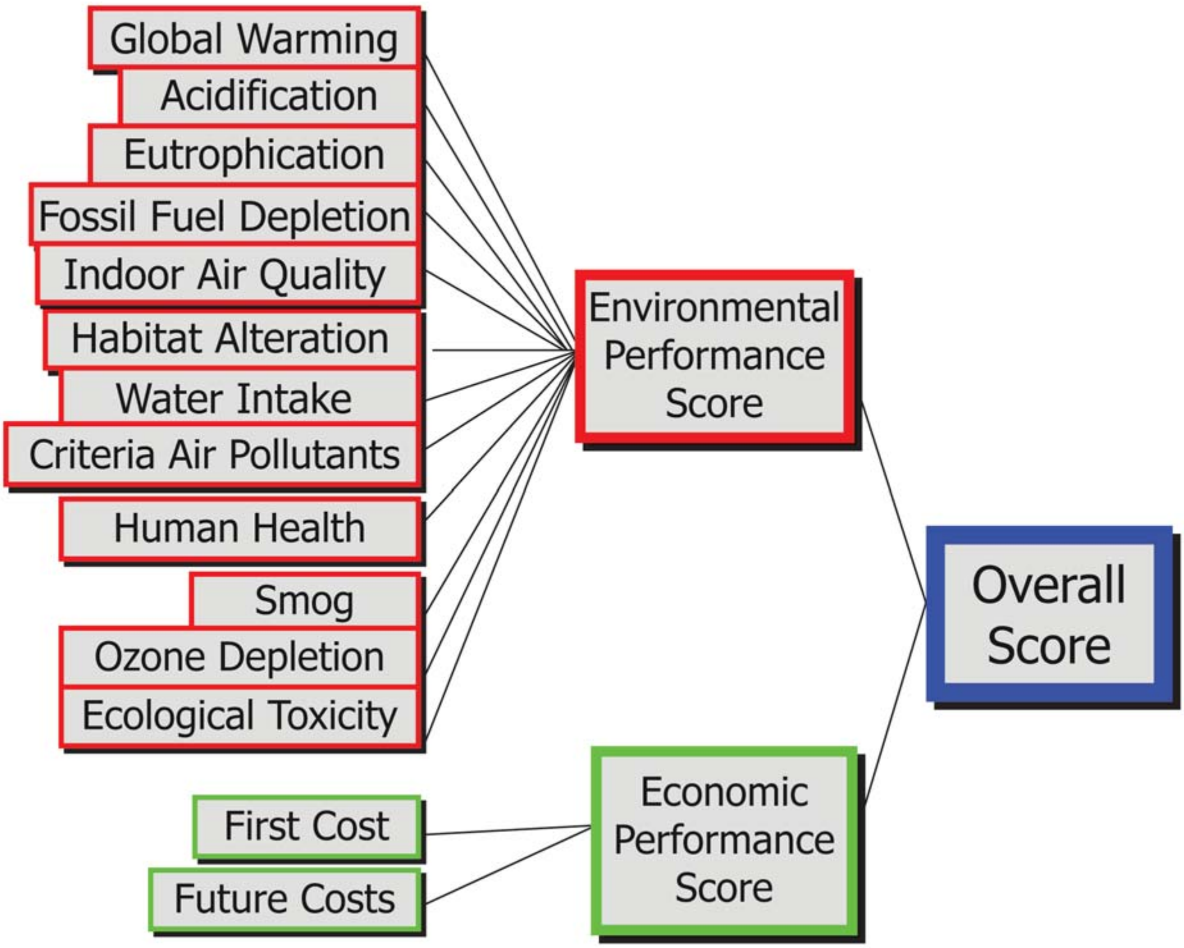

FIG. X1.4 Deriving the BEES Overall Performance Score