# Environmental Comfort Criteria: Weighting and Integration

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**Abstract:** This paper presents an integration method for evaluating environmental quality in office buildings based on a series of interviews with 50 experts in the field of environmental quality in the built environment. A structured questionnaire was completed by experts during the interviews. The categories of environmental quality considered in this evaluation include lighting comfort, acoustic comfort, thermal comfort, and acceptable indoor air quality. Each category includes a set of performance criteria. Sixty-five performance criteria covering the evaluation of environmental quality in office buildings were extracted from the interviewed experts. The development of this integration method for assessing the environmental quality of built environments is described and an illustration of its application is presented.

## INTRODUCTION

Good quality environments result from appropriately combining a variety of building systems. The performance of those systems must be compatible with the activities required to be performed by the occupants. Environmental quality in one office building would not necessarily be identical to the environmental quality in another similar building in every detail, but there are constants that help determine the quality level of environmental comfort in almost all office buildings. There are degrees or levels of environmental comfort. Most offices could be better than they are now. The question is not, ''Why improve office quality?'' People simply work better in a quality environment. The question should be, ''Why not improve the quality of office environments?'' Knowing how to achieve this requires a method to evaluate office environmental quality (Vischer 1989).

## ENVIRONMENTAL QUALITY CATEGORIES (EQCs)

Environmental quality in office buildings refers to the provision of lighting comfort, acoustic comfort, thermal comfort, and acceptable indoor air quality (IAQ) for its occupants, and avoidance of performance debilitation in the capabilities of office workers (Davis 1986; Manning 1987).

The assessment of environmental quality in offices is broken down into relevant performance criteria within the categories of lighting comfort, acoustic comfort, thermal comfort, and IAQ. Sixty-five criteria covering the assessment of environmental quality in office buildings were extracted from experts during the interviews. Two kinds of experts were selected. The benchmarks for selecting experts included experience of at least 15 years in the field of specialization (e.g., lighting design), substantial practical contribution to the related field, and comprehensive understanding of the interdisciplinary relationships with the related fields (e.g., designing of acoustics, thermal, and IAQ). A combination between theory and practice was considered while selecting potential experts. The experts interviewed totaled 50. There were 29 professionals and 21 academics. A structured questionnaire was developed to collect the necessary knowledge and data, preceded by a comprehensive overview of related literature in which initial ranges of comfort conditions for each performance were nominated in the questionnaire. The 65 performance criteria are arranged within the main four categories—lighting comfort, acoustic comfort, thermal comfort, and acceptable IAQ—as follows.

### Lighting Comfort

For lighting to be optimal, it must provide a comfortable and healthy visual environment that supports the activities of the occupants. The majority of people in service industries work in indoor environments—predominantly offices equipped with artificial lighting (Preiser et al. 1991). A well-designed visual environment is essential for perceiving space, form, color, and object of regard. Until the post–World War II period, prediction of daylight in interiors was mostly associated with law rather than with comfort and convenience (McMullan 1983; Steffy 1990).

Many criteria may be relevant to the design of a particular lighting system. Illustrated in Table 1 are the main criteria that need to be considered, as extracted from the interviewed experts.

### Acoustic Comfort

The objectives of good acoustic design are to enhance wanted sounds and attenuate unwanted sounds (noise). People prefer to work in an environment that is quiet but not totally free of sound. People use sound for orientation, awareness, and masking to provide speech privacy. People in offices need to communicate easily (with each other and on the telephone), without the strain of shouting to be heard or the stress of believing that all conversation is overheard. Most offices are designed to standard acoustic specifications that do not respond to this wide variation in requirements (Vischer 1989).

The acoustic environment in an occupied space is the result of the sound arriving at the space from engineering services, adjacent zones, and external environment, and from sound generated within the occupied space such as voices, human activities, entertainment devices, and machinery. They all generate small rapid variations in pressure about the static atmospheric pressure and propagate through the air as sound waves. To evaluate the environmental quality of an office space from the acoustics point of view, the acoustic criteria illustrated in Table 2 should be considered.

### Thermal Comfort

Thermal comfort is the state of mind that expresses satisfaction with the thermal environment. It is achieved by the balance of heat exchange between the occupant and the environment and is a function of the occupant's activity level.

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TABLE 1. Set of Criteria To Be Considered in Lighting Design and Used To Evaluate Lighting Comfort in Office Buildings

| Number | Criterion | Description |
|---|---|---|
| 1 | EELG | Illuminance (E) for Electric Light in General areas |
| 2 | EELT | Illuminance (E) for Electric Light in Typing areas |
| 3 | EELF | Illuminance (E) for Electric Light in Filing areas |
| 4 | DFW | Daylight Factor on Workstation |
| 5 | DFWA | Daylight Factor over Whole area |
| 6 | DPEL | Direction and Position of Electric Light |
| 7 | RMEAE | Ratio of Minimum (E) to Average (E) in office area |
| 8 | REW | Ratio of (E) at Workstation |
| 9 | ALWAEHW | Average Luminance of any Wall to Average (E) in Horizontal Workplace |
| 10 | RETAT | Ratio of (E) on Task area to Around Task area |
| 11 | DSLVSR | Directional Strength of Light (Vector/Scalar Ratio) |
| 12 | CCTL | Correlated Color Temperature of Light |
| 13 | CRL | Color Rendering of Light |
| 14 | GIL | Glare Index of Light |
| 15 | DRTDFLW | Direct Ratio of Total Downward Flux from Luminaries directly incident on Workstation |
| 16 | FCPS | Reflectance (F) of Ceiling Paint Surface |
| 17 | FWPS | Reflectance (F) of Wall Paint Surface |
| 18 | FWGF | Reflectance (F) of Window Glass Finishing |
| 19 | FFFS | Reflectance (F) of Floor Finishing Surface |
| 20 | FEFS | Reflectance (F) of Equipment and Furnishing Surfaces |
| 21 | FIB | Reflectance (F) of Immediate Background |

TABLE 2. Set of Criteria To Be Considered in Acoustic Design and Used to Evaluate Acoustic Comfort in Office Buildings

| Number | Criterion | Description |
|---|---|---|
| 1 | BNL | Background Noise Level |
| 2 | RT | Reverberation Time |
| 3 | INGF | Impact Noise Generated from adjoining Floors |
| 4 | GNHVAC | Generated Noise from HVAC |
| 5 | SILW | Speech Interference Level in the Workplace Area |
| 6 | SILT | Speech Interference Level in Typing area |
| 7 | STC | Sound Transmission Class for walls, partitions, floors, and ceiling |
| 8 | ISI | Impact Sound Insulation of walls, partitions, and ceilings |
| 9 | NIC | Noise Isolation Class |
| 10 | DSSLBNL | Difference between Speech Sound Level and Background Noise Level |
| 11 | TIR | Time interval between Initial sound and its Reflection received by ear |
| 12 | TAWG | Total Area of Window Glazing |
| 13 | SAWM | Sound Absorption of Wall Materials |
| 14 | SACM | Sound Absorption of Ceiling Materials |
| 15 | SAFM | Sound absorption of Floor Materials |

Thermal comfort variables include conductive, radiative, and evaporative balances between the occupant and the environment and the rate of air movement over the skin (Fisk 1981). A human being is said to be thermally comfortable when he or she cannot say whether cooler or warmer surroundings would be preferred.

Sometimes it is thought that an adequate coverage of the design requirements for thermal comfort would consist simply of a schedule of required air temperature, air movement, and possibly relative humidity, but unfortunately, this is not completely true (Fisk 1981). Radiation can be significant. The major criteria, extracted from experts, that influence thermal comfort are illustrated in Table 3.

## IAQ

Acceptable IAQ is defined as air in which there are no contaminants at harmful concentrations and with which a substantial majority of the people are satisfied. The main criteria that IAQ depends on are shown in Table 4.

## INTEGRATED EVALUATION OF ENVIRONMENTAL QUALITY IN OFFICE BUILDINGS

Buildings should be designed to provide good quality environments to support the activities of their occupants. A major function of office buildings is to provide a comfortable environment defined conventionally in terms of specific factors laid down by regulatory bodies. Traditionally, these have been treated as independent of one another, although the designer typically tries to solve the individual problems by an integrated approach (Griffiths et al. 1987; de Dear and Brager 1998).

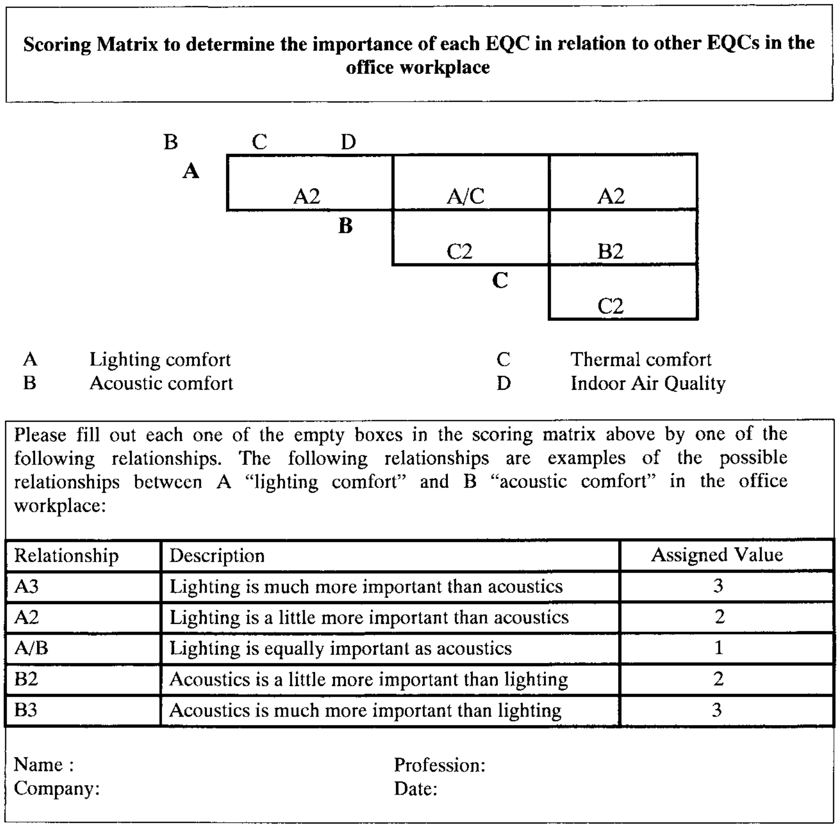
A method of making an integrated assessment of environmental quality in office buildings would be useful for designers to evaluate the quality of their completed projects in a postoccupancy evaluation. The procedures followed to develop the integrated assessment are based upon the four main categories and the 65 performance criteria presented earlier. The

TABLE 3. Set of Criteria To Be Considered in HVAC Design and Used to Evaluate Thermal Comfort in Office Buildings

| Number | Criterion | Description |
|---|---|---|
| 1 | ATW | Air Temperature in Winter |
| 2 | ATS | Air Temperature in Summer |
| 3 | MRTW | Mean Radiant Temperature in Winter |
| 4 | MRTS | Mean Radiant Temperature in Summer |
| 5 | RHW | Relative Humidity in Winter |
| 6 | RHS | Relative Humidity in Summer |
| 7 | AMW | Air Movement in Winter |
| 8 | AMS | Air Movement in Summer |
| 9 | ATIS | Average Temperature of Internal Surfaces |
| 10 | TS | Temperature Shifts |
| 11 | MIRTHMRT | Maximum Increase in Radiant Temperature on Head over Mean Radiant Temperature |
| 12 | FT | Floor Temperature |
| 13 | ATHF | Air Temperature between Head and Feet |
| 14 | HRL | Heat Recovered from Light |
| 15 | FTS | Frequency of Temperature Shifts |

TABLE 4. Set of Criteria To Be Considered in Evaluating IAQ in Office Buildings

| Number | Criterion | Description |
|---|---|---|
| 1 | AER | Air Exchange Rate (fresh air makeup) |
| 2 | ACH | Air Change per Hour |
| 3 | AFE | Air Filtration Efficiency |
| 4 | AME | Air Mixing Efficiency |
| 5 | EERA | Efficiency of Entrainment of Room Air by primary stream outside zone of occupancy |
| 6 | OSA | Odors from Smoking Areas |
| 7 | OB | Odors from Bathrooms |
| 8 | OK | Odors from Kitchenette |
| 9 | CDIA | Carbon Dioxide in Indoor Air in general office area |
| 10 | CMIA | Carbon Monoxide in Indoor Air in general office area |
| 11 | NDIA | Nitrogen Dioxide in Indoor Air in general office area |
| 12 | SDIA | Sulphur Dioxide in indoor Air in general office area |
| 13 | FIA | Formaldehyde in Indoor Air in general office area |
| 14 | OIA | Ozone in Indoor Air in general office area |


**Scoring Matrix to determine the importance of each EQC in relation to other EQCs in the office workplace**



| | | | |
|---|---|---|---|
| A | Lighting comfort | C | Thermal comfort |
| B | Acoustic comfort | D | Indoor Air Quality |

Please fill out each one of the empty boxes in the scoring matrix above by one of the following relationships. The following relationships are examples of the possible relationships between A "lighting comfort" and B "acoustic comfort" in the office workplace:

| Relationship | Description | Assigned Value |
|---|---|---|
| A3 | Lighting is much more important than acoustics | 3 |
| A2 | Lighting is a little more important than acoustics | 2 |
| A/B | Lighting is equally important as acoustics | 1 |
| B2 | Acoustics is a little more important than lighting | 2 |
| B3 | Acoustics is much more important than lighting | 3 |

Name : Profession:
Company: Date:

**FIG. 1.** Paired Comparison Form (Completed during Interview with One Selected Expert)

method presented in this paper is an integration of the four categories of environmental quality described as follows:

1. Determine the assigned weight for each EQC in relation to the other categories (global importance assessment).
2. Determine the assigned weight for each environmental quality performance criterion in relation to other performance criteria within its category (local importance assessment).
3. Determine the comfort ranges for each performance criterion and its corresponding attribute value.

## Weighting of EQCs

Data were collected through interviews with two kinds of professionals (21 academics and 29 practitioners) who are experts in lighting comfort, acoustic comfort, thermal comfort, and IAQ. Their input was used to determine the weight of each environmental category for the office workplace in an office building. A paired comparison method (David 1988) was used to determine the weights by comparing the importance of each EQC to other EQCs in an office workplace. An example of a completed paired comparison formed by one of the interviewed experts is shown in Fig. 1.

Experts' inputs in the scoring matrix were used to calculate the row score, assigned weight, and rank for each EQC. The types of relationships between each pair of environmental quality factors (EQFs) are assigned related values as shown in Fig. 1. The assigned values help determine the importance of each EQF in relation to other EQCs in an office workplace. The estimation of the importance of each EQF commences by calculating the row score for that EQF. The row score of a certain EQF is calculated by counting the assigned values that reflect its relationships to all EQCs in the scoring matrix. For instance in Fig. 1, the relationships between lighting comfort A, acoustic comfort B, thermal comfort C, and IAQ D are A2, A/C, and A2, respectively, where A2 indicates that lighting is a little more important and A/C indicates that it is equally important. The row score of lighting comfort A is 5 [(A2 + A/C + A2) = (2 + 1 + 2) = 5].

The assigned weight is calculated by converting the highest row score to 10 in a 10-point scale, and the rest of the row scores are accordingly converted using the same ratio. At this stage, EQCs are ranked based on their assigned weights. An example is shown in Table 5. The assigned weights calculated from the 50 expert inputs were collated and statistical analyses were carried out using the SPSS (Statistical Package for Social Sciences). For example, the means of the assigned weights of EQFs in the office workplace indicated that lighting comfort has the highest weight (9.56 on a 10-point scale), as shown in Table 6. Other weights are thermal comfort, 6.35; IAQ, 6.61; and acoustic comfort, 5.56. From these results, the final function that integrates the weights of lighting, acoustic, thermal,

**TABLE 5.** Calculation of Row Scores, Assigned Weights, and Ranks for EQCs

| Label | EQFs | Row score | Assigned weight | Rank |
|---|---|---|---|---|
| A | Lighting comfort | 5 | 10 | 1 |
| B | Acoustic comfort | 2 | 4 | 2 |
| C | Thermal comfort | 5 | 10 | 1 |
| D | IAQ | 0 | 0 | 3 |

**TABLE 6.** Calculation of Weighted Average of EQCs

| EQFs | Mean | Weighted average |
|---|---|---|
| Lighting comfort | 9.56 | $\{(9.56/27.78)\cdot 10\} = 3.44$ |
| Acoustic comfort | 5.26 | $\{(5.26/27.78)\cdot 10\} = 1.89$ |
| Thermal comfort | 6.35 | $\{(6.35/27.78)\cdot 10\} = 2.29$ |
| IAQ | 6.61 | $\{(6.61/27.78)\cdot 10\} = 2.38$ |
| Total | 27.78 | 10.00 |

and IAQ was derived (Table 6) to give the final percentage of achievement of environmental quality in the evaluated office building. The conversion of the mean to a weighted average for each EQC from the total 10-point scale is illustrated in Table 6. The comparison of the means of weighted averages of EQFs of office buildings is illustrated in Fig. 2.

The final function of the environmental quality evaluation is in the following form:

$$TEQE = \{(3.44 \cdot \text{lighting}) + (1.89 \cdot \text{acoustics}) + (2.29 \cdot \text{thermal}) + (2.38 \cdot \text{IAQ})\}$$

where $TEQE$ = total environmental quality evaluation.

## Weights of Each Environmental Quality Performance Criterion

A separate questionnaire was prepared and filled out by experts during the interviews for each criterion within the four categories: lighting comfort, acoustic comfort, thermal comfort, and acceptability of IAQ. There are two types of knowledge to be extracted from collected data: the influential effect of each performance criterion used to evaluate each EQC in an office workplace and the scales to be used to evaluate each criterion.

For instance, data were collected from 10 experts in thermal comfort to determine the influential effect of each thermal comfort performance criterion. Table 7 shows how the influential effect ‘‘expected value’’ was calculated for one criterion of thermal comfort (air temperature in winter). The severity index has also been calculated. The severity index is the conversion of the expected value (influential effect) to a percentage of the maximum possible score. The assigned weight of each criterion is calculated by converting its expected value(in relation to the total of all expected values of all criteria in a single EQC (e.g., thermal comfort) on a 100-point scale.

$$\text{assigned weight} = \{(E_x/E_x) \cdot 100\}$$

where $E_x$ = expected value of thermal comfort criteria.

For example, the total expected values of all thermal comfort criteria was 46, and the assigned weight of the ‘‘air temperature in winter’’ is $(3/46) \cdot 100 = 6.52$. Similarly, the expected value, severity index, and assigned weight were calculated for the 65 variables covering all EQCs. The assigned weights for each performance criterion of the 65 criteria of environmental quality are shown in Table 8.

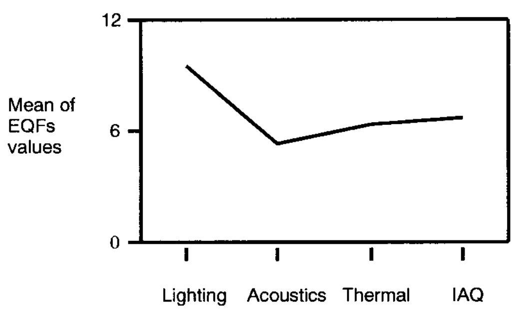



**FIG. 2.** Comparison of Mean Weighted Averages of EQCs

**TABLE 7.** Calculation of Expected Value and Severity Index for Air Temperature in Winter as One Performance Criterion of Evaluating Thermal Comfort

| EXPERTS' INPUTS | | | |
|---|---|---|---|
| Number of experts | Input | | Ratio of response |
| $n$ | Effect | Score | $P_x = n/t$ |
| 3 | EI | 4 | 3/10 |
| 4 | MI | 3 | 4/10 |
| 3 | I | 2 | 3/10 |
| 0 | SI | 1 | 0 |
| 0 | N | 0 | 0 |

Note: EI = extremely influential; MI = major influential; I = influential; SI = somewhat influential; and N = not influential; $n$ refers to number of inputs for each type of influential effect and $t$ refers to total number of inputs. Expected value $E_x = (P_x \cdot \text{score}) = 3$. Severity index $S_i = \{(E_x)/4 \cdot 100\} = 75\%$.

## Comfort Ranges of EQC and Their Attribute Values

The comfort ranges for environmental quality performance criteria vary from three to five ranges for each criterion (very comfortable, comfortable, reasonably comfortable, somewhat uncomfortable, and uncomfortable) in which each range has a corresponding attribute value of 10, 8, 6, 4, and 2, respectively. For instance, the comfort ranges of background noise level for conversational speech are <45, >45–<60, and >60 dB, which correspond to comfortable, reasonably comfortable, and uncomfortable, and their score values are 10, 6, and 2, respectively.

## Using Integrated Assessment Method for Evaluating Environmental Quality in Office Buildings

The integrated assessment method developed in this paper can be used manually to calculate the overall percentage of environmental quality for postoccupancy evaluation of the built environment in office buildings. The procedures for carrying out this evaluation are explained in the following steps:

1. Select an EQC to start the evaluation (e.g., acoustic comfort).
2. Evaluate the acoustic comfort by testing the office building to each of the acoustic comfort criteria as follows:
   a. Select the appropriate comfort range for each criterion that relates to the measurements taken of the office building design under assessment (e.g., find out what is the background noise level achieved in that office building and select the appropriate range that matches it). Assign the corresponding attribute value to the selected comfort range.
   b. Find out the assigned weight for that criterion, background noise level, from Table 8.
   c. Multiply the assigned weight of that criterion by the corresponding attribute value.
   d. Carry out the evaluation for all criteria of acoustic comfort from (a)–(d).
   e. Calculate the percentage of acoustic comfort achieved from a 100-point scale by finding the total of the assigned weights multiplied by their score values.
3. Carry out the evaluation for other EQCs: lighting comfort, thermal comfort, and acceptability of IAQ, as done in Step 2 above.
4. Apply the calculated percentages of EQCs achieved in the final formula to calculate an overall percentage of environmental quality in the office building under evaluation.

The integrated assessment method described above was used computationally in developing an expert system model to evaluate the environmental quality of office buildings (Reffat and Harkness 2000).

**TABLE 8.** Assigned Weights of 65 Performance Criteria of Environmental Quality

| Lighting | | Acoustic | | Thermal | | IAQ | |
|---|---|---|---|---|---|---|---|
| Criterion | Assigned Weight | Criterion | Assigned Weight | Criterion | Assigned Weight | Criterion | Assigned Weight |
| EELG | 6.0 | BNL | 6.8 | ATW | 6.52 | AER | 7.89 |
| EELT | 2.0 | RT | 4.5 | ATS | 6.52 | ACH | 7.89 |
| EELF | 2.0 | INGF | 6.8 | MRTW | 6.52 | AFE | 7.89 |
| DFW | 4.0 | GNHVAC | 6.8 | MRTS | 6.52 | AME | 7.89 |
| DFWA | 4.0 | SILW | 6.8 | RHW | 6.52 | EERA | 7.89 |
| DPEL | 4.0 | SILT | 9.10 | RHS | 6.52 | OSA | 10.53 |
| RMEAE | 6.0 | STC | 6.8 | AMW | 6.52 | OB | 7.89 |
| REW | 8.0 | ISI | 6.8 | AMS | 6.52 | OK | 7.89 |
| ALWAEHW | 6.0 | NIC | 6.8 | ATIS | 6.52 | CDIA | 7.89 |
| RETAT | 6.0 | DSSLBNL | 6.8 | TS | 8.7 | CMIA | 5.26 |
| DSLVSR | 4.0 | TIR | 9.10 | MIRTHMRT | 8.7 | NDIA | 5.26 |
| CCTL | 4.0 | TAWG | 4.55 | FT | 6.52 | SDIA | 5.26 |
| CRL | 4.0 | SAWM | 4.55 | ATHF | 6.52 | FIA | 5.26 |
| GIL | 8.0 | SACM | 9.10 | HRL | 4.35 | OIA | 5.26 |
| DRTDFLW | 6.0 | SAFM | 4.55 | FTS | 6.52 | | 100.0 |
| FCPS | 6.0 | | 100.0 | | 100.0 | | |
| FWPS | 4.0 | | | | | | |
| FWGF | 4.0 | | | | | | |
| FFFS | 4.0 | | | | | | |
| FEFS | 4.0 | | | | | | |
| FIB | 4.0 | | | | | | |
| | 100.0 | | | | | | |

## CONCLUSIONS

This paper presents an integrated assessment method that may be applied to evaluate the postoccupancy environmental quality in office buildings. The method enables weighting to be assigned to the overall contribution of each criterion of comfort. This approach may also be used during the process of designing. It could provide means of predicting the environmental quality of buildings prior to construction and occupancy. The same model may be used in both designing and postoccupancy phases. Comparing the overall assessment at the postoccupancy phase to the assessment made at the designing phase could facilitate identification of discrepancies.

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