AGGREGATE SPACE-TIME PERFORMANCE INDICATORS FOR SIMULATION-BASED BUILDING EVALUATION PROCEDURES

A. Mahdavi[1], P. Mathew[1], K.P. Lam[2]
1) Department of Architecture, Carnegie Mellon University, USA
2) School of Architecture, National University of Singapore

ABSTRACT

Computational modeling of building performance can generate extensive amounts of data. For this data to be useful, it must effectively interface with the informational requirements and procedural constraints of the building delivery process. Toward this end, this paper specifically explores the potential of aggregate space-time performance indicators.

1. INTRODUCTION AND BACKGROUND

In the past, much research has been undertaken to develop sophisticated simulation tools for building performance analysis. These advanced (mostly dynamic) tools can generate an extensive set of numeric data describing the space-time distribution of performance indicators. Comparatively less research has been conducted to explore how these potentially massive quantities of data should effectively interface with the informational requirements and procedural constraints of the building design and evaluation practice. Various approaches have been suggested to cope with this problem, a few of which are briefly described below:

- conservative data transformation: computed performance data are typically numeric and thus less convenient for the development of a global sense of building and space behavior. Creative transformation of such numeric data in visually expressive formats can support the understanding and evaluation of building performance. In this case the intention is not reduce or manipulate the computed data *per se*, but to use data representations that are more accessible to human information processing.
- non-interpretative data reduction: the vast number of numeric data generated by tools capable of transient simulation may be reduced using simple selective methods or more complex statistical aggregation. Examples of such reductive methods are aggregation of hourly data on building energy performance into "typical day" or "monthly" result formats. In this case, the underlying data base is "manipulated" to create a manageable set of performance attributes. However, the nature of these generated aggregate indicators (temperature, thermal load, illuminance level, etc.) does not differ from the originally computed simulation results.
- interpretative data translation: physical performance data may be translated into indicators of occupancy evaluation, such as those applied in the thermal comfort domain. In this case, the intention is to support the evaluation and decision making process through the derivation of intuitive measures of occupancy-relevant building quality based on physically defined indicators of building performance.

This paper primarily focuses on approaches to non-interpretative data reduction, arguing that more systematic research efforts are needed to formulate and test methods that allow for meaningful and effective aggregation of space-time performance indicators for simulation-based building evaluation procedures. Such indicators must satisfy two basic requirements. They must strategically reduce the simulated performance base data to the extent that designs can be effectively evaluated, compared, and further developed. At the same time, they must ensure that the reductive approach does not eliminate the responsiveness of the indictors to the complexity of and parametric changes in design. In this paper,

- some existing and new aggregate thermal performance indicators in time domain are reviewed regarding their potential for and effectiveness in decision support. This review includes not only simple statistical (e.g. cumulative) indicators known from the context of prescriptive standards as well as methods for time aggregation of simulation results, but also more sophisticated (combined geometric/energetic indicators) such as LEK and LEK_{eq} (see section 2).
- a detailed case study from the visual performance area (lighting distribution) is provided to demonstrate a new aggregate performance indicator in space domain. Again, the hierarchy of aggregation levels is discussed starting with traditional indicators of light distribution uniformity inside

spaces. Next, more sophisticated uniformity indicators are discussed, which address some of the shortcomings of the first generation reductive uniformity indicators, i.e. their unsatisfactory behavior in view of the local deviations of light levels. Finally, a new entropic light uniformity level is introduced to overcome the problems of the second generation indicators, i.e. their indifference toward the various spatial configurations (adjacency relations) of light levels in a room.

2. ON INDICATORS OF THERMAL PERFORMANCE

In the domain of thermal performance, prescriptive requirements pertaining to building fabric (particularly building envelope) such as maximum permissible U-values as well as simple and cumulative measures of energy performance (such as area-related or volume-related peak and annual loads) have been in use for a long time. Recent developments on both accounts demonstrate how *a)* the inherently dynamic behavior of building in the time domain, and *b)* certain aspects of building geometry may be reflected in new aggregate performance indicators.

Interpretative Cumulative Indicators

Transient simulations typically generate performance results (energy use, space temperatures, etc.) for every time step throughout the simulation period. Where target (desired) levels are known (e.g. a certain space temperature, or zero energy use), secondary (interpretative) indicators may be developed that incorporate the cumulative deviation from those target levels, with or without application of weights to various degrees of deviation. Such interpretative performance indicators allow for the comparison of various design alternatives and facilitate code compliance checking. An example of such a cumulative indicator is the temperature deviation factor (TDF) that captures the deviation of the predicted maintained space temperature from the preferred space temperature (Mahdavi 1997). This performance indicator (practically an average cumulative temperature deviation) is defined as follows:

$$TDF = \sum_{i=1}^{n} \frac{w \cdot \left(\frac{|t_p - t_i|}{t_p}\right)}{n} \cdot 100 \quad [\%] \qquad eq.1$$

Here t_p stands for the preferred space temperature, t_i represents the space temperature at time step *i*; *n* is the total number of time steps; and *w* is a weighting variable to penalize larger deviations of the maintained temperature from the target space temperature.

Topologically Enriched Energy Performance Indicators

Establishing criteria for the heat transfer through building components is as such a hallmark of the prescriptive approach to building quality assurance. However, there have been continuous attempts to arrive at related requirements and derivative performance indicators involving a more conclusive aggregation of information needed for building evaluation. For example, a procedure has been proposed and implemented that aggregates information on thermal characteristics of the building envelope with a simple descriptor of the building's geometry, namely "characteristic length" l_c, which is the ratio of building volume V_B to building envelope area A_B (Panzhauser 1993, Mahdavi et al. 1996). This has led to the establishment of LEK values (Lines of European k-values, cp. Figure 1) which allow for the definition of the thermal insulation of building envelopes (expressed in terms of envelope's mean U-value) while considering the building envelope's geometry (expressed in terms of envelope's characteristic length):

$$LEK = 300 \cdot U_m \cdot (2 + l_c)^{-1} \qquad eq.2$$

Despite this informational enrichment (in view of the concurrent consideration of both thermal characteristics of building envelope and its geometry), LEK still retains a prescriptive nature which diminishes its value as a true thermal *performance* indicator. Furthermore, LEK obviously does not consider the effects of solar and internal gains. To arrive at an indicator that would achieve this while retaining the benefit of LEK (in view of geometry description), LEK_{eq} has been proposed (Fantl et al. 1996). Once the heating energy need (q_h) of a building and the relevant heating degree days (DD_h) are known, LEK_{eq} can be calculated according to the following equation:

$$LEK_{eq} = 100 \cdot q_h \cdot l_c \cdot (0.024 \cdot DD_h \cdot (2 + l_c)) \qquad eq.3$$

The important point in the above formulation is that q_h itself can be derived based on advanced transient energy simulation. Thus, the single-number indicator LEK_{eq} involves a twofold enrichment in that it includes topologically meaningful geometric information and can embody detailed information on building's energy use derived from sophisticated energy simulation routines.

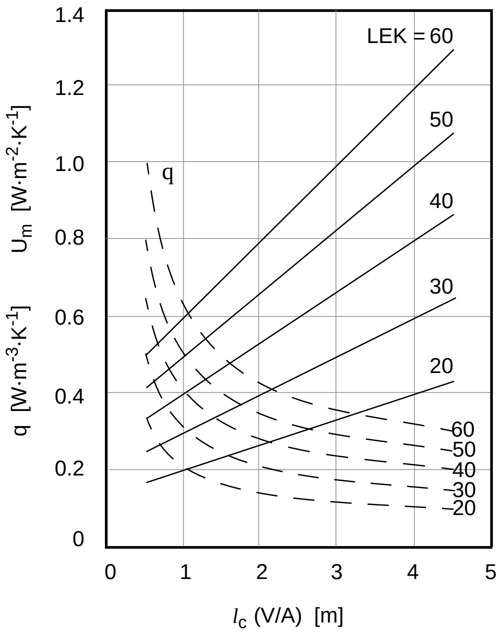

Figure 1. LEK-Diagram (Lines of European k-values) with corresponding volume-specific transmission heat loss values (Mahdavi et al. 1996)

3. A NEW LIGHT DISTRIBUTION UNIFORMITY INDICATOR

We now consider the problem of description of spatial distribution of light, as it represents a particularly good example for the development of a set of indictors that, despite their single-number format, can provide successively higher level of critical information. Uniformity indicators have been in use to describe the degree of uniformity of the illuminance or luminance levels for various applications (e.g. architectural lighting, lighting of sport facilities, road lighting). Numerical attributes of these indicators have been used as *a)* prescriptive definitions of required (or desirable) degrees of uniformity, *b)* simple ("compressed") representations of actual light measurement results, and *c)* descriptors of computer simulation output. We describe in the following (without the intention of exhaustive coverage) examples from three generations of uniformity indicators as space aggregates of visual performance.

First Generation

In IES 1993 (pp. 888), illuminance uniformity is discussed in the context of emergency, safety, and security lighting. Required levels of illuminance uniformity are defined in terms of "illuminance uniformity ratio":

$$\text{illuminance uniformity ratio} = \frac{E_{avg}}{E_{min}} \quad [-] \qquad eq.4$$

where E_{avg} is the average illuminance and E_{min} is the minimum illuminance.

In IES 1993 (pp. 525-526), a "uniformity ratio" is used to describe requirements pertaining to ceiling luminance in the context of indirect lighting. The uniformity ratio is defined as the "ratio of the brightest area of the ceiling ... to the darkest area of the ceiling, ... in other words, the ratio of the maximum to the minimum".

In DIN and CIE literature (DIN 5044, Hentschel 1982, pp. 196 and 224, Hochstädt and Kuloge 1969, pp. 99A-101A) the length-related (U_1) and the total (U_0) luminance distribution uniformity indicators ("Gleichmäßigkeitszahlen") are used for road lighting design purposes:

$$U_1 = \frac{L_{min}}{L_{max}} \quad [-] \qquad eq.5$$

$$U_0 = \frac{L_{min}}{L_m} \quad [-] \qquad eq.6$$

where L_{min} is the minimum luminance, L_{max} is the maximum luminance, and L_m the average luminance. In Hentschel 1982 (pp. 234) illuminance distribution uniformity requirements ("Gleichmäßigkeit") are given for sport stadiums based on recommendations in LiTG 1969 and LiTG 1967. The relevant definition is in this case:

$$\text{uniformity} = \frac{E_{min}}{E_m} \quad [-] \qquad eq.7$$

where E_{min} is the minimum (horizontal) illuminance and E_m is the average (horizontal) illuminance.

The above reviewed indicators involve, per definition, numeric values of light levels at a single point. For example, in order to derive the uniformity factor for the illuminance on a horizontal plane (e.g. task surface) in a space according to the above definitions, the minimum illuminance levels must be identified and applied in the computation. The question is, if and how the reliability of the so derived uniformity indicator might be affected due to the uncertainties involved in obtaining the individual (actually measured or computationally simulated) illuminance level at a certain point.

Second Generation

In response to the critical point raised above, a number of statistically more elaborate indicators have been proposed. One of these proposals (Mahdavi 1994, Mahdavi et al. 1995) was inspired by the definition of turbulence intensity in ventilation and thermal comfort domain (ASHRAE 1993, Fanger et al. 1987). Turbulence intensity (T_u) is defined as the ratio of the standard deviation of measured air velocities (v_{SD}) during a certain time period to the average value of these measurements (v_m) over the same time period:

$$T_u = \frac{v_{SD}}{v_m} \cdot 100 \qquad [-] \qquad \textit{eq.8}$$

Mahdavi's proposed new uniformity factor was defined analogous to the above relationship by applying three modifications. First, in the place of velocity in equation 8, a photometric term such as illuminance was used. Second, instead of dealing with the changes of the parameter in the time domain (time-dependent velocity measurements), fluctuations were defined in the space domain (location-dependent illuminance values). Finally, an algebraic modification was applied to insure that uniformity factors can only have values between 0 and 1. The result was the following definition for the illuminance distribution uniformity factor (U):

$$U = \frac{E_m}{E_m + E_{SD}} \qquad [-] \qquad \textit{eq.9}$$

where E_{SD} is the standard deviation and E_m the average value of the illuminance levels.

A comprehensive comparative statistical analysis of this indicator and two conventional uniformity indices (Mahdavi et al. 1995) demonstrated that: *a)* the proposed uniformity factor has a suitable range for the characterization of a wide range of possible light distribution patterns in architectural spaces (including day-lit rooms) and allows for cross-configuration and cross-space comparisons; *b)* it is relatively stable despite the uncertainties in obtaining individual readings (or computations) of illuminance or luminance levels; *c)* it is less affected by the resolution of the measurement/simulation grid; *d)* it does not "overreact" to minor (locally restricted) variations in illuminance (or luminance) distribution pattern. Furthermore, Mahdavi recently proposed to apply this indicator (eq. 9) toward the solution of the cloud cover description problem in daylighting applications. Recent initial studies involving the measured sky luminance distribution in Singapore appear to suggest an interesting new possibility to specify the sky's cloud cover as a function of the numeric attribute of the sky luminance uniformity indicator.

However, as with all second generation indicators, the uniformity indicator of equation 9 has a clear limitation, despite its obvious advantages compared to the conventional ones. It is indifferent to the specific topological pattern of adjacent illuminance (or luminance) patterns. For example, the fields a and b in figure 2 (which may be thought of as task surfaces with simulated illuminance levels) have obviously entirely different distribution patterns, yet yield identical uniformity attributes no matter if first or second generation indicators are applied.

300	150	300	150
150	300	150	300
300	150	300	150
150	300	150	300

A

300	300	150	150
300	300	150	150
300	300	150	150
300	300	150	150

B

Figure 2. Demonstrative spatial distribution patterns for which a second generation uniformity indicator yields an identical numeric attribute

<u>The Third Generation</u>

In response to this problem and inspired by the entropy notion in thermodynamics, Mahdavi 1996a proposed the concept of a single-number "entropic distribution index" (EDI). In this paper, instead of providing a detailed mathematical formulation of EDI, we provide an illustrative thermal analogy that leads to establishing relative entropic uniformity attributes for a few simple illuminance distribution patterns. Consider the dark-bright illuminance patterns A to E in figure 3. We represent these as low-high temperature zones in a space with an analogous geometry. Assuming adiabatic enclosure, we apply the detailed transient energy simulation tool SEMPER-NODEM (Mahdavi 1996b, Mahdavi and Mathew 1995) to compute for each case the time that is needed to move from the initial state to the thermal equilibrium state.

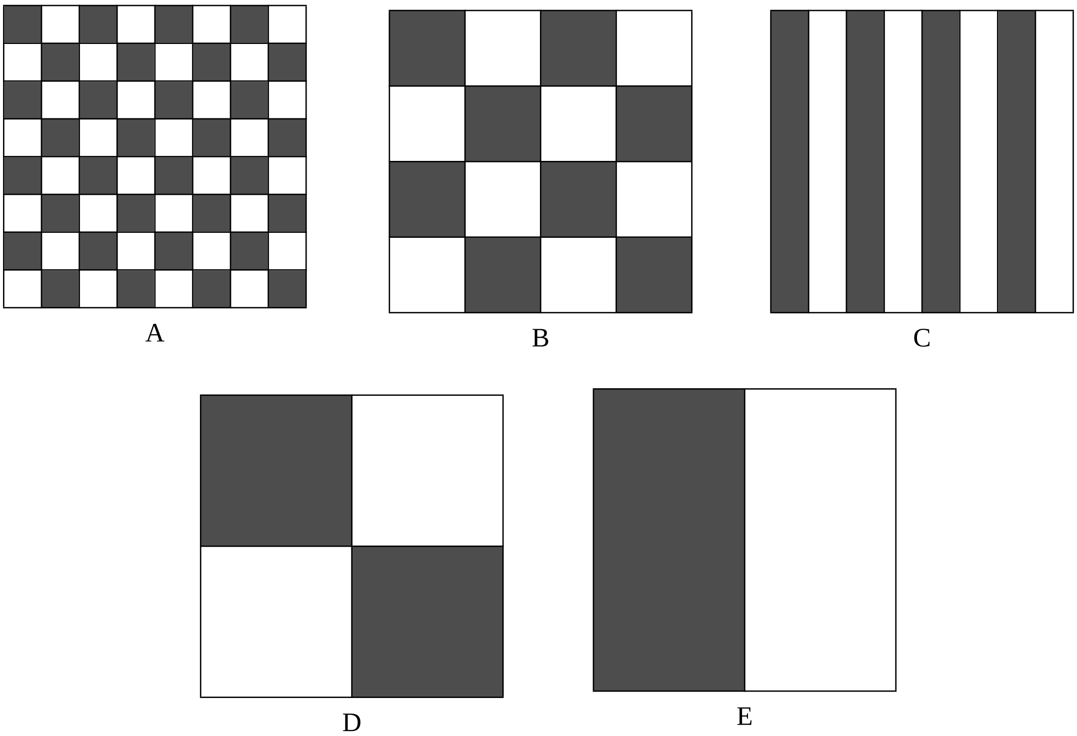

Figure 3. Five demonstrative spatial distribution patterns for which a third generation uniformity indicator yields different numeric attributes

The conjecture is that the longer the time taken to reach equilibrium, the lower the uniformity of the pattern. To arrive at a uniformity ranking, we first represented these times relative to the shortest equilibrium time among all patterns. The inverse of this relative time provides an entropic correlate to the visual uniformity of the patterns. We have used the numeric results of this procedure to rank the patterns A to E according to their degree of uniformity (cp. table 1). Table 1 clearly demonstrate the sensitivity of the proposed new entropic light distribution uniformity index (visual EDI) to the topological distribution of individual (simulated or measured) light levels.

Distribution pattern	**Uniformity rank**
A	I
B	II
C	III
D	IV
E	V

Table 1: Uniformity ranking of five demonstrative distribution patterns (cp. figure 3) derived based on the numeric attributes of Entropic Uniformity Indicator

4. CONCLUSION

In this paper, we specifically discussed some existing and new examples of aggregate space-time performance indicators for simulation-based building evaluation purposes in the thermal and visual (lighting) domains. We demonstrated that such carefully formulated aggregate indicators can strategically reduce the computational performance data, while conserving salient information on buildings' complex space-time behavior. Needless to say, as there is no one unique method to represent and communicate the typically extensive computationally generated building performance simulation results, such aggregate indicators do not represent a substitute for other numeric and graphic means of data representation, but should be applied in tandem with those.

REFERENCES

ASHRAE (1993): ASHRAE Handbook Fundamentals. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Atlanta, GA.
DIN 5044: Straßenbeleuchtung, Richtlinien.

Fanger, P. O. - Melikov, A. - Hanzawa, H. - Ring, J. (1987): "Air turbulence and sensation of drought." Energy and Buildings.

Fantl, K. - Panzhauser, E. - Wunderer E. (1996): Der Österreichische Energieausweis für Gebäude, Research Report 1365, Austria.

Hentschel, H. (1982): Licht und Beleuchtung; Theorie und Praxis der Lichttechnik. Dr. Alfred Hüthig Verlag Heidelberg.

Hochstädt, E. - Kuloge, R. (1969): Auswertung von projektierten Straßenbeleuchtungsanlagen hinsichtlich ihrer Leuchtdichtegleichmäßigkeit. Lichttechnik 21, Nr. 9.

IES (1993): Lighting Handbook; Reference & Application. 8th Edition. Illuminating Engineering Society of North America.

LiTG (1967): LiTG-Fachausschuß "Sportstätten-beleuchtung": Beleuchtung für Fußball, Handball und Rugby. Lichttechnik 19, Nr. 9.

LiTG (1969): LiTG-Fachausschuß "Sportstätten-beleuchtung": Beleuchtung von Sportstätten für das Farbfernsehen. Lichttechnik 21, Nr. 11.

Mahdavi, A. (1997): Toward a Simulation-Assisted Dynamic Building Control Strategy. Proceedings of the Fifth International Conference of the International Building Performance Simulation Association. Prague, Czech Republic.

Mahdavi, A. (1996a): An Entropic Uniformity Indicator. Report No. DOA-96-08-01. Department of Architecture, Carnegie Mellon University, Pittsburgh, PA.

Mahdavi, A. (1996b): Computational Support for Performance-based Reasoning in Building Design. Proceedings of the CIB-ASTM-ISO-RILEM International Symposium, "Applications of the Performance Concept in Building". Tel Aviv, Israel. Vol. 1, pp. 4-23 - 4-32.

Mahdavi, A. (1994): A New Light Distribution Uniformity Descriptor. CBPD Internal Document, No. 9410-01. Department of Architecture, Carnegie Mellon University, Pittsburgh, PA.

Mahdavi, A. - Mathew, P. (1995): Synchronous Generation of Homologous Representation in an Active, Multi-Aspect Design Environment. Proceedings of the Fourth International Conference of the International Building Performance Simulation Association (IBPSA) (Ed.: Mitchell, J.W. - Beckman, W. A.). Madison, Wisconsin. pp. 522 - 528.

Mahdavi, A. - Brahme, B. - Mathew, P. (1996): On the Applicability of the "LEK" Procedure for the Energy Analysis of Cooling-Dominated Commercial Buildings, Energy and Environment, Vol. 31, No. 5, pp. 409-415.

Mahdavi, A. - Prankprakma, P. - Berberidou, L. (1995): On Numeric Indicators of Light Distribution Uniformity. Proceedings of The 1995 IESNA Annual Conference, New York. pp. 385 - 394.

Panzhauser, E. (1993): Endenergie für Raumwärme, in: K. Masil, K. Fantl, E. Panzhauser, eds., Potential der thermischen Gebäudesanierung in Österreich (Austrian Institute for Economic Research).