# ACTIVE COMPUTATIONAL SUPPORT FOR CONCURRENT BUILDING ENVELOPE AND LIGHTING SYSTEM DESIGN

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## ABSTRACT

*This paper introduces an active computational tool to generate and comparatively evaluate integrated building envelope and interior lighting system designs. In this context, active computational support denotes the derivation of possible design schemes based on preliminary performance considerations. The "generate-and-test" method is adopted to realize this active system feature. The tool is intended to facilitate the comparative evaluation of the generated envelope and room-lighting schemes in view of daylight utilization potential, visual performance criteria, and energy consumption levels.*

## INTRODUCTION

Conventional lighting design support tools can be labeled as "passive," as they require complete and detailed design descriptions before performance analysis can be done. This represents a major drawback, particularly in view of the integrated building envelope and interior lighting system design strategies that aim at effective daylight utilization for building energy-use reduction (Mahdavi et al. 1994b; Ne'eman and Longmore 1973; Lynes et al. 1966). Given the interdependence of the design variables and contextual parameters involved (aperture size and shape, glazing transmittance, room size, proportions and reflective properties, time-dependent outdoor daylight levels), the convergence toward an appropriate design solution cannot be effectively supported by conventional simulation tools. Rather, systems are needed that would actively support the iterative translation of performance requirements (desirable illuminance values, appropriate light distribution, tolerable brightness contrast levels, reduced electrical energy use, etc.) into integrated building envelope and lighting design schemes.

## APPROACHES TO ACTIVE DESIGN SUPPORT

The concept of an active design support environment implies the derivation of preliminary envelope and room features, as well as possible lighting system designs based on a set of constraints associated with daylight availability, task requirements, and designers' preferences. Two possible strategies for providing active design support are the "bidirectional inference" approach and the "generate-and-test" approach.

A bidirectional simulation environment facilitates not only the evaluation of a given design solution in terms of its performance, but also the derivation of formal and semantic implications of performance criteria, thus allowing parallel design generation and performance evaluation. The bidirectional inference approach implies either an explicit (direct) transformation of performance requirements into corresponding design solutions or an implicit ("trial-and-error"-based) performance-driven convergence toward the desired state of the design solution (Mahdavi and Berberidou-Kallivoka 1993, 1994; Mahdavi 1993).

However, in this paper the focus is on the generate-and-test approach, which requires the generation of a matrix of potential design solutions based on logical and/or heuristic rules, the performance simulation of the generated design using conventional computational tools, the comparative evaluation of the results, and selection of desired solutions based on prespecified performance criteria/priorities (Mahdavi et al. 1993, 1994a).

Both approaches require the use of appropriate simulation algorithms for the computation of interior light levels. The next section provides a brief description of the computational modules adopted.

## THE COMPUTATIONAL BACKGROUND

### External Irradiance and Illuminance

A computational module (Mahdavi et al. 1994a) has been developed to predict solar irradiance on any arbitrarily oriented surface based on geographical data (longitude, latitude), time information, the Linke-turbidity

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factor, the Reitz diffuse radiation factor, and albedo, as well as the orientation of the receiving surface element. The module initially computes the ecliptical length, solar declination angle, and local solar and standard times. Adopting the horizontal coordinate system, the position of the sun is specified by the solar azimuth and altitude, which are computed using a unit vector pointing toward the sun. As the solar beam is subjected to atmospheric refraction, an adjusted altitude is adopted (Heindl and Koch 1976; Linke 1942; Reitz 1939).

The current implementation of the computational environment relies on "standard" tables (for example, Hopkinson et al. [1966]), as well as a limited set of original luminous efficiency data derived from simultaneous measurements of irradiance and illuminance (some examples are shown in Figures 1 and 2). Presently, the solar irradiance module models the direct solar contribution in considerable detail, but the underlying sky model is assumed to be isotropic. However, given the flexibility of the adapted data structure and the matrix-based description of the sky luminance distributions (described in the next section), no principal obstacle exists regarding the adaptation of more detailed modeling approaches in the future (as an example, Perez et al. [1992]).

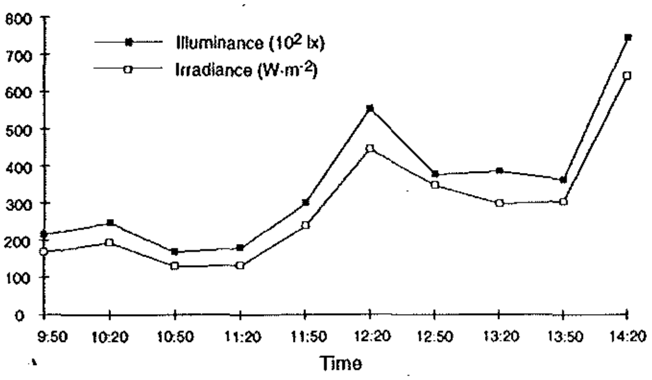

**Figure 1** *Comparative irradiance and illuminance measurements on a horizontal surface (Pittsburgh, Pa., Cathedral of Learning, October 29, 1993).*

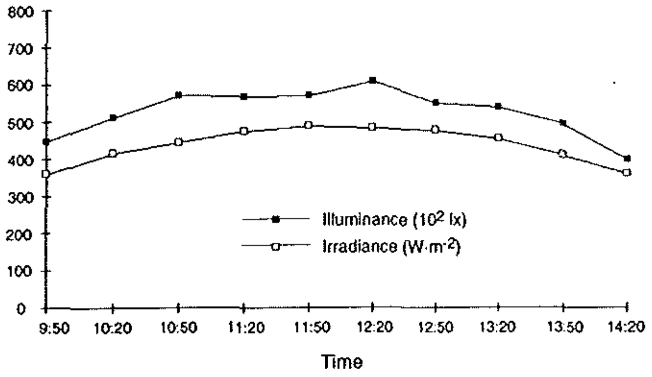

**Figure 2** *Comparative irradiance and illuminance measurements on a horizontal surface (Pittsburgh, Pa., Cathedral of Learning, November 10, 1993).*

## Daylight Model

**Computation of Indoor Illuminance Values** After the external illuminance levels are known, interior illuminance levels can be computed using a daylight simulation module (DSM) (Mahdavi and Berberidou-Kallivoka 1993). The direct sky contribution for arbitrary sky luminance distribution patterns is computed by discretization of the sky sphere and the application of numeric integration methods (Mahdavi et al. 1994a). Provided actual measured data are available, relative luminance values can be attributed to discrete patches of a spherical sky model (see Figure 3). Otherwise, standard or synthetic sky luminance distribution patterns can be adopted. The spherical sky model can be numerically organized in terms of a matrix with altitude ($\phi$) and azimuth ($\vartheta$) angles as dimensions (see Table 1). For example, given the sky matrix, the relative interior illuminance due to sky contribution at a reference point on a horizontal surface is given by:

***TABLE 1*** **Relative Luminance Distribution of the Sky Model Organized in Terms of Altitude ($\varphi$) and Azimuth ($\vartheta$) Angles**

| | $\phi_1$ | $\phi_2$ | ... | $\phi_n$ |
|---|---|---|---|---|
| $\theta_1$ | | | | |
| $\theta_2$ | | | | |
| ... | | | | |
| $\theta_m$ | | | | |

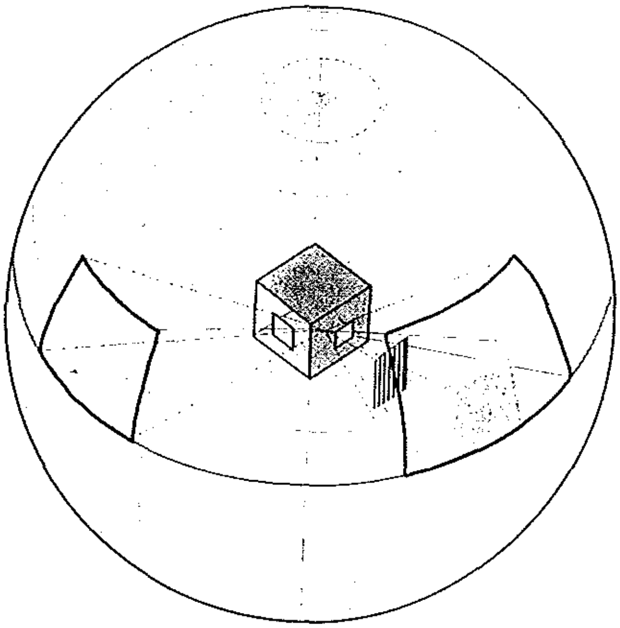

**Figure 3** *Spherical projection for treatment of the sky luminance distribution, determination of sky component and obstruction effect.*

$$E_{r,s} = \frac{\int_{\phi_1}^{\phi_2}\int_{\vartheta_1}^{\vartheta_2} \cos\vartheta \cdot \sin\vartheta \cdot z_{\phi,\vartheta} \cdot \tau_{\omega} \cdot d\phi \cdot d\vartheta}{\int_{\phi=0}^{2\pi}\int_{\vartheta=0}^{\pi/2} \cos\vartheta \cdot \sin\vartheta \cdot z_{\phi,\vartheta} \cdot d\phi \cdot d\vartheta} \cdot 100[\%] \quad (1)$$

where

$z_{\phi,\vartheta}$ = relative sky luminance,
$\tau_{\omega}$ = glazing transmittance,
$\phi$ = altitude, and
$\vartheta$ = azimuth.

The approach used for the calculation of the relative interior illuminance due to sky contribution on a horizontal surface also can be applied for the computation of daylight-based illuminance on other (arbitrarily oriented) surfaces that could "see" the terrain (e.g., walls, ceiling, furniture, etc.). To achieve this, the virtual sky dome (including its discrete patches) is mirrored about the horizontal plane (terrain). The discrete patches of this virtual "subterranean dome" can be adjusted using relative luminance factors to simulate actual terrain luminance distribution.

**Reflected Sky Contribution—Obstructions** Obstructions (overhangs, buildings, vegetation) are treated by projection of their outline from each reference point onto the virtual sphere (see Figure 3). A discretization of the external reflecting surface into small patches is applied and each patch is then projected onto the virtual sphere. The relative luminance values attributed to the obstruction replace those of the sphere patches occluded by the obstruction. Internal obstructions (e.g., partition walls) are modeled similarly except the relative luminance values attributed to the occluded sphere patches are zero.

**Interreflected Contribution** The interreflected contribution to the indoor illuminance levels is computed based on the radiosity method. Adapting a numerical approach, the room surfaces can be discretized, resulting in a series of small patches. For each patch the radiative balance equations can be formulated leading into a set of linear equations. In the thermal domain, this would yield the following generic equation:

$$J_i = \varepsilon_i \cdot W_{b,i} + (1 - \varepsilon_i) \cdot \sum_{j=1}^{n-1} F_{ij} \cdot J_j \quad (2)$$

where

$J_i$ = radiosity,
$\varepsilon_i$ = emittance,
$W_{b,i}$ = emissive power of the black body,
$F_{ij}$ = view factor from patch $i$ to patch $j$ (cp. Equation 3 and Figure 4:

$$F_{i,j} = \frac{\cos\vartheta_1 \cdot \cos\vartheta_2 \cdot dAj}{\pi \cdot r^2}. \quad (3)$$

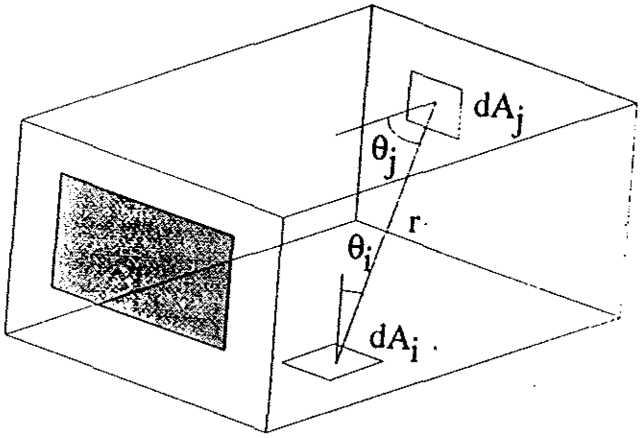

*Figure 4* *Determination of view factor from patch i to patch j.*

If the emissive power is replaced by the initial daylight-based illuminance ($E_{r,s,i}$), a set of simultaneous equations can be defined that yields for the (photometric) radiosity of patch $i$ ($J_{v,i}$) with reflectance ($\rho_{v,i}$):

$$J_{v,i} = \rho_{v,i} \cdot \left( E_{r,s,i} + \sum_{j=1}^{n-1} F_{ij} \cdot J_{v,j} \right). \quad (4)$$

After the radiosities of all patches are known, the interreflected contribution at any point in the room can be derived from the radiosity matrix.

## Electric Lighting Contribution

The selection of a computational algorithm for the simulation of electric lighting must be discussed in the specific context of the envisioned design support strategy. The essential motivation behind the development of an integrated lighting evaluation program is to provide "active" support for the design development phase and not merely evaluate finalized design solutions.

The "generate-and-test" and the implicit "bidirectional inference" approaches (Berberidou-Kallivoka 1995; Mahdavi and Berberidou-Kallivoka 1994) can use both simplified approaches, such as the zonal cavity methods (IES 1961, 1984), as well as more detailed algorithms (e.g., radiosity, ray-tracing). The explicit bidirectional inference method can only use simplified algorithms because a "direct" translation of performance requirements into design solutions cannot be supported by detailed simulation approaches.

To support the generate-and-test and the implicit bidirectional inference methods, a detailed computational module has been developed (Mahdavi et al. 1994a). This module calculates the direct illuminance based on the luminous intensity pattern of the source stored as a matrix or represented as a generative function. The interreflected component of the illuminance is determined based on the discretization of room surfaces, derivation of view factors, and computations of radiosities.

## A DEMONSTRATIVE CASE STUDY

### Model Assumptions

Earlier studies (Mahdavi and Berberidou-Kallivoka 1994; Mahdavi 1993) have demonstrated how bidirectional or "open" simulation environments can be used to guide the room and envelope design based on requirements of daylight availability. To demonstrate the functionality of the generate-and-test approach as the underlying mechanism behind an integrative lighting design environment, an illustrative design sequence is discussed here. This sequence starts with an initial office space design (see Figure 5).

Based on information on the statistical relationship between installed total flux and target average illuminance levels and a rule-based generation of basic luminaire layouts, and assuming two different luminaire types (see Figure 6), a demonstrative matrix of system configurations (luminaire layout) and their operational modi (on/off status) was derived (Figure 7). Two window configurations were considered for the envelope of the office (Figure 8). Other attributes (room surface reflectances, glazing transmittance) were kept constant throughout the simulations. Due to the demonstrative nature of this specific case study, the number of possible luminaire and layout configurations is rather small. However, there is no conceptual or computational reason against generation and management of a significantly larger set of options.

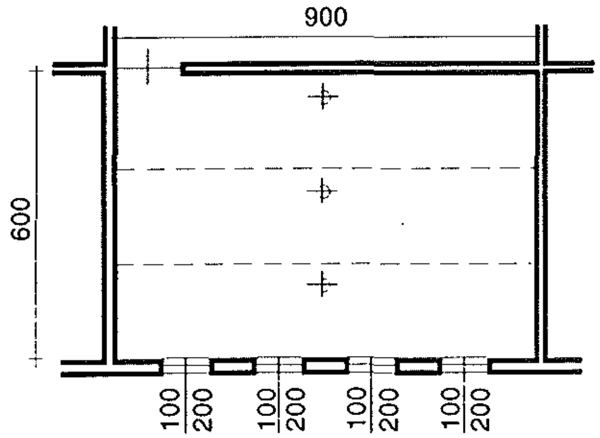

*Figure 5* Schematic illustration of the office space plan (all measures in cm) indicating the three lighting zones with the corresponding "virtual" illuminance sensors.

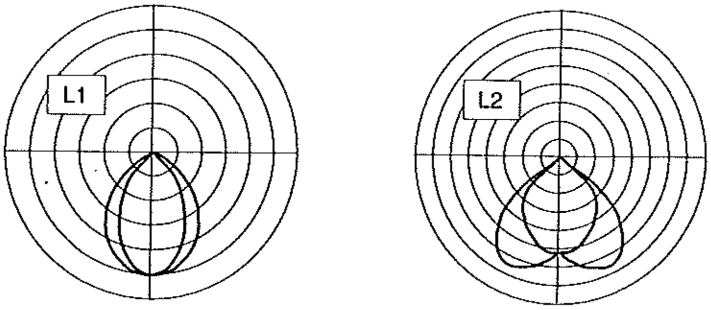

*Figure 6* Schematic illustration of the luminous intensity distribution patterns of the two luminaire types (L1 and L2).

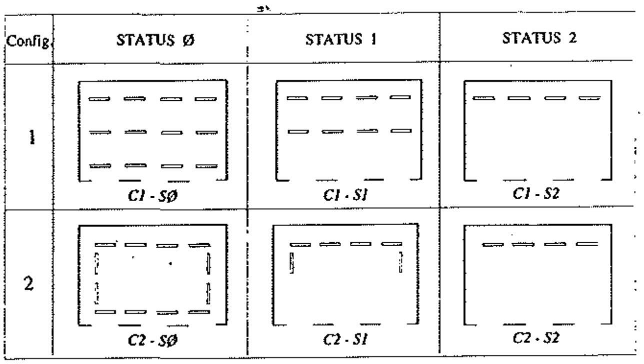

*Figure 7* Maxtrix of luminaire layouts (C1, C2) and their operational status (S0, S1, S2).

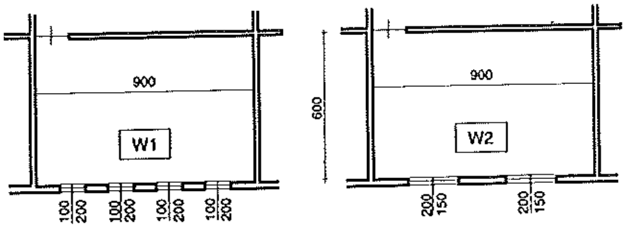

*Figure 8* Schematic illustration of the two window configurations W1 and W2.

### Performance Descriptors

Once a complete set of luminaire and room configurations is defined, system performance analysis can be performed computationally. The results can be organized in a matrix in terms of multicriteria performance indices, thus facilitating a comparative evaluation of different designs. These indices are typically (a) illuminance, (b) luminance, (c) uniformity factor, (d) glare index, and (e) system energy use.

As long as the design configurations are static, single values of these performance criteria may be sufficient for the comparative evaluation. This is, for example, the case when different electrical lighting configurations are studied without considering daylight use and occupancy fluctuations (and the associated dynamism of light control schedules). Various approaches can be adopted to cater to the dynamic nature of the environmental conditions and internal processes such as time-step (e.g., hourly) simulations or methods based on Fourier analysis. It is obvious that a detailed transient simulation of the lighting conditions can provide a realistic picture of the dynamic behavior of a proposed design. However, this also leads to the generation of a rather extensive set of numerical values for each performance indicator. Clearly these large sets of

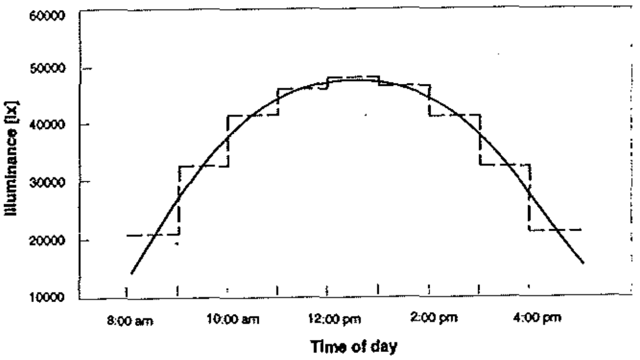

*Figure 9 Derivation of step-functions for time-dependent outdoor illuminance levels (demonstrative illustration).*

information must be "compressed" into manageable values if two designs are to be compared in their "totality."

For example, in the energy simulation domain, formats such as annual energy consumption (numeric accumulation of the hourly simulation results) are used as global performance descriptors. Also, statistical methods are applied to the extensive set of simulation results to achieve the data compression needed for comparative design evaluation. Furthermore, the requirements of standards and building codes often are formulated in terms of these global specifiers. Because there is no single valid method for this data compression, the approach adopted in this paper and detailed here should be seen as one of many possibilities. However, the general concepts and the computational methods proposed in this paper can accommodate many other compressed representations of large data sets.

In this study the time-dependent external illuminance level functions were translated into step-functions deriving discrete values for well-defined time periods (Figure 9). From these step-functions, matrices were derived to capture the dynamism of external illuminance levels in terms of computationally manageable discrete terms (see Table 2). Table 3 shows a highly compressed version of this matrix for a specific city where the illuminance levels are represented using only five discrete levels.

***TABLE 2*** **General Matrix for Time-Dependent External Illuminance Levels ($t_1, t_2, \ldots, t_m$ = Time Segment of the Day, and $D_1, D_2, \ldots, D_n$ = Day of the Year)**

| | $t_1$ | $t_2$ | ... | $t_m$ |
|---|---|---|---|---|
| $D_1$ | | | | |
| $D_2$ | | | | |
| ... | | | | |
| $D_n$ | | | | |

***TABLE 3*** **Compressed Version of Illuminance Matrix (cp. Table 2) for Pittsburgh, Pa. with Only Five Discrete Illuminance Levels (in lx) Representing the Year**

| | Illuminance (in lx) for Time Periods | | |
|---|---|---|---|
| | 8 am - 11 am | 11 am - 14 pm | 14 pm - 17 pm |
| June | 55000 | 80000 | 55000 |
| October | 30000 | 55000 | 30000 |
| December | 10000 | 20000 | 10000 |
| March | 30000 | 55000 | 30000 |

This simplification appears to be justified due to the lack of detailed illuminance measurements for most locations (illuminance data often must be derived from measured or computed irradiance levels) and the previously mentioned need for manageable data sets for comparative evaluation of design alternatives.

## Results

**Electrical Lighting** Table 4 summarizes the simulation results for comparative evaluation of various configurations using electric lighting only (the two envelope configurations, W1 and W2, are considered to be equivalent because the differences between the two options caused by the differences in the reflections from the inside glazing surface were found to be insignificant). It includes data on the average illuminance levels on various room surfaces, as well as the uniformity factor (expressed as the ratio of minimum illuminance to average illuminance), glare index (computed for two reference points/directions in the room), and estimated annual electric energy consumption. Figure 10 illustrates the relative performance of the solutions for multicriteria evaluations. It is important to note that Table 4 and Figure 10 do not intend to provide a single optimal solution. Rather, they should provide decision support through the criteria-based rating of various design options and the demonstration of the performance tradeoffs and their implications. Therefore, the identification of the most desirable design solution (or the decision to continue design exploration) is a function of pertinent performance criteria and their relative priority (importance, weight) as defined by relevant requirements and/or as perceived by the designer.

**Daylighting** Principally, various strategies can be applied to use daylight availability, thus reducing the dependency on electric lighting (selective operation of luminaires, occupancy-driven light controls, continuous dimming). To simulate the combined effect of electric lighting and daylighting, the following approach was selected. The office space (Figure 5) was subdivided into three lighting zones, each equipped with a (virtual) illuminance sensor. The luminaire set corresponding to each zone was turned off during those time segments when the "measured" illuminance level on the reference task level

***TABLE 4*** **Matrix for Multicriteria Comparison of Electrical Lighting Solutions (cp. Figures 5 to 8)**

| L | C | $E_{floor}$ (lx) | $E_{ceiling}$ (lx) | $E_{sidewall}$ (lx) | $E_{backwall}$ (lx) | $E_{frontwall}$ (lx) | Uniformity Factor (-) | Glare Index (-) | Elec. Energy Consumption ($kW \cdot h \cdot y^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|
| L1 | C1 | 490 | 69 | 211 | 239 | 285 | 0.75 | 15.96 | 2,592 |
| L1 | C2 | 485 | 70 | 227 | 237 | 284 | 0.74 | 19.34 | 2,592 |
| L2 | C1 | 757 | 103 | 352 | 313 | 382 | 0.71 | 14.71 | 2,592 |
| L2 | C2 | 723 | 98 | 326 | 325 | 392 | 0.71 | 18.38 | 2,592 |

***TABLE 5*** **Matrix for Multicriteria Comparison of Lighting and Envelope System Design Options Involving Daylight Utilization for Two Envelope Configurations (W1 and W2), Two Luminaire Types (L1 and L2) and Two Luminaire Layouts (C1 and C2)**

| W | L | C | $E_{floor}$ (lx) | $E_{ceiling}$ (lx) | $E_{sidewall}$ (lx) | $E_{backwall}$ (lx) | $E_{frontwall}$ (lx) | Uniformity Factor (-) | Glare Index (-) | Elec. Energy Consumption ($kW \cdot h \cdot y^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|---|
| W1 | L1 | C1 | 1,370 | 279 | 526 | 412 | 335 | 0.47 | 22.18 | 641 |
| W2 | L1 | C1 | 1,057 | 225 | 377 | 347 | 267 | 0.53 | 22.38 | 641 |
| W1 | L2 | C1 | 1,389 | 282 | 542 | 437 | 331 | 0.51 | 22.19 | 499 |
| W2 | L2 | C1 | 1,076 | 228 | 392 | 371 | 262 | 0.54 | 22.38 | 499 |
| W1 | L1 | C2 | 1,357 | 277 | 515 | 410 | 327 | 0.46 | 22.20 | 572 |
| W2 | L1 | C2 | 1,044 | 223 | 366 | 344 | 260 | 0.50 | 22.40 | 572 |
| W1 | L2 | C2 | 1,392 | 280 | 522 | 437 | 330 | 0.47 | 22.19 | 499 |
| W2 | L2 | C2 | 1,079 | 227 | 373 | 372 | 261 | 0.51 | 22.38 | 499 |

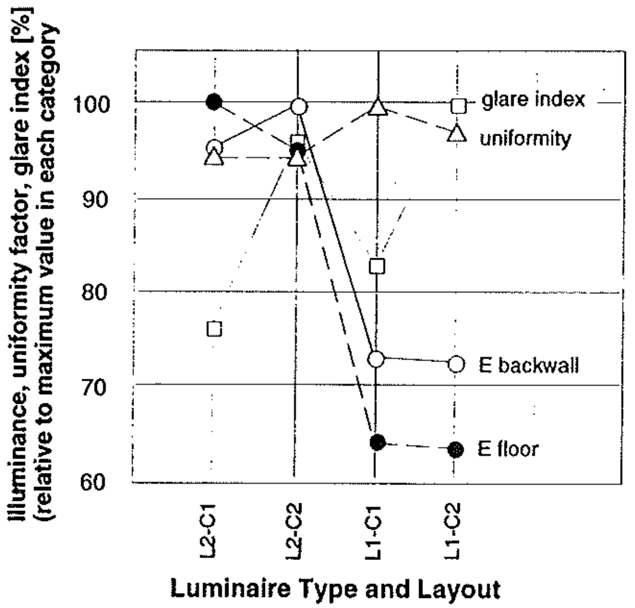

***Figure 10*** *Comparative illustration of illuminance, uniformity factor, and glare index (expressed as the percentage of the maximum value in each category) for various design configurations (electrical lighting only).*

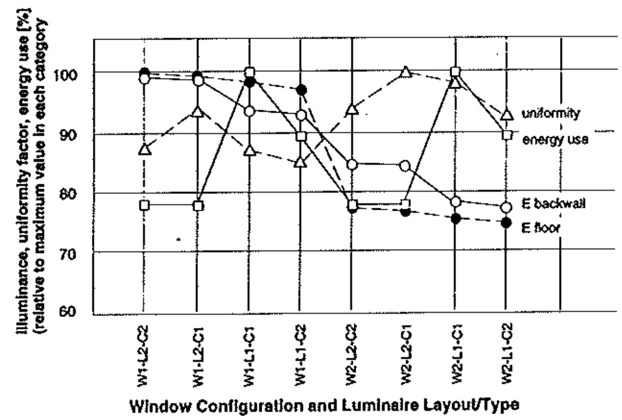

***Figure 11*** *Comparative illustration of average annual illuminance, uniformity factor, and annual energy use (expressed as the percentage of the maximum value in each category) for various design configurations (combined and electrical lighting).*

was more than 500 lx. Table 5 and Figure 11 show the simulation results (average annual values of illuminance, uniformity factor, glare index, and annual energy use) for comparative evaluation of various design options involving the combined effect of daylighting and electric lighting. This matrix, as such, does not (and is not intended to) provide an "optimal" solution. Of course, it is theoretically possible to apply numeric weights to individual performance criteria to derive a "definitive" ranking of the various designs. However, this numeric "homogenization" of inherently different parameters involves many conceptual shortcomings and practical difficulties. The authors believe it may be preferable to view the matrix of Table 5 as a structured informational framework explicating the criteria needed for a systematic trade-off analysis to be performed by the designer.

## CONCLUDING REMARKS

If it is true that mathematical reasoning involves an inherent noncomputable aspect, the same must undoubtedly apply to the design thinking process. The research presented in this paper should thus not be understood as an attempt toward the "automation" of building envelope and lighting system design. The objective, rather, is to support the design decision-making process through timely provision of well-structured and relevant technical information concerning the relative performance of various design alternatives. The active approach to design support is in order, as the conventional prescriptive rules and passive simulation techniques fail to sufficiently address the inherent dynamism of the contextual design parameter (such as climatic conditions) and the increasing complexity of building enclosure and lighting system options and controls.

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