A GENERATIVE SIMULATION TOOL FOR ARCHITECTURAL LIGHTING

Ardeshir Mahdavi and Liana Berberidou-Kallivoka
Center for Building Performance and Diagnostics
Department of Architecture
Carnegie Mellon University
Pittsburgh, PA 15213

ABSTRACT

This paper presents the concept of an "open" simulation environment for performance-driven design exploration as a multi-directional approach to computer-aided daylighting modeling. A prototypical realization of a Generative Simulation Tool for Architectural Lighting (GESTALT) for simultaneous treatment of daylighting-related design and performance variables is introduced.

Earlier studies demonstrated that GESTALT can operate in an "explicit" mode, using a fast-response computational module. This paper introduces a further refined "implicit" mode of operation that uses a comprehensive simulator and investigative projection techniques. filustrative sequences of design explorations with this new GESTALT version are presented and discussed.

1. INTRODUCTION

The "mono-directionality" of the conventional simulation tools has been identified as one of the factors responsible for insufficient integration of computational lighting modeling tools in the design process (Mahdavi and Berberidou-Kallivoka 1993). A "multi-directional" or "open" simulation environment represents, in metaphoric terms, a "shaping/molding" framework, in which the designs evolve as the designers freely access, modify and observe relevant variables at different levels of abstraction (Mahdavi 1993).

In the context of daylighting simulation, this implies a system in which the evolution of a design can be triggered, observed and evaluated as the designer manipulates various elements of designs and their performance correlates. In other words, the basic requirement to label a computational environment as open, is that changes in a performance indicator (e.g. daylight factor, average illuminance level, uniformity factor, etc.), can be translated into an orderly modification of a set of design-related variables (e.g. geometrical configuration and material properties). The reverse operation can already be performed by conventional simulation environments.

2. THE GESTALT ENVIRONMENT

2.1 Implicit and Explicit Realizations

An open simulation environment is referred to here as "explicit", if numeric attributes for a design variable can be directly derived as a function of the numeric attributes of the pertinent performance indicator and other design variables. However, this direct derivation of design attributes is possible only if the functional relationship between performance indicator and design variables can be expressed in terms of simple (e.g. linear) algorithmic formulations that could be easily inverted for each and every design variable (an example of such an algorithmic formulation is provided in section 2.4.2).

The advantage of the explicit approach is its extreme computational speed which allows for the "real-time" visualization of design changes resulting from manipulation of performance indicators. However, only highly simplified representations of domain knowledge (in this case daylight availability in rooms) can be formulated in terms of such easily invertible functions. More detailed and flexible simulation routines involve complex and heterogeneous algorithmic approaches, where the performance indicator may be the cumulative result of numerous (sometimes conditional) applications of computational procedures involving variable (quasi-stochastic) input data (e.g. dynamic exterior illuminance values).

Since a comprehensive daylighting simulation module (such as the one introduced in section 2.4.1) cannot be explicitly inverted (i.e. it cannot be explicitly solved for design variables) the desirable values of design variables can be derived implicitly based on a trial-and-error approach (investigative projection technique). This new approach, in which changes in the design parameters are tested and adopted only if the subsequent effect on the performance indicator is desirable, allows for the realization of an implicit version of GESTALT as an open simulation environment.

2.2 The "Preference-Based" Convergence Approach

The issue of "ambiguity", associated with the operational multi-directionality of open simulation environments, introduces significant implementation problems. The term ambiguity denotes here the circumstance where a desired value for a performance indicator may be achieved by a variety of design configurations (e.g. increased average illuminance levels on the task surface can be realized by appropriate changes in the design of the building envelope, or the room proportions, or the material properties). As one possibility to cope with this "one-to-many" mapping problem, the concept of a preference-based convergence approach is suggested (Mahdavi 1993).

In this context, preference is used to label a specific strategy for formalization and organization of a set of constraints that control the complex and dynamic pattern of the interrelationships between design-relevant parameters as they "respond" to changes in the numeric value of performance indicators. Preference scales can be defined for any design-related variable if an "orderly" (functionally expressible) correlation is explicated between successive degrees of necessity/ desirability (preference rating) and a well-defined set of continuous or discrete values associated with a design-related parameter.

There is probably no unique solution for a computational implementation of a preference-based convergence strategy. The approach outlined below, should thus only be interpreted as one possibility. Furthermore, the starting preference conditions are meant to serve rather as the initializer of a process in which the relationship between the design evolution trajectory and the underlying preference pattern may be observed. Based on the proposed approach a preference index I_p for a design related parameter P_d can be defined if I_p can be expressed as a continuous function of P_d:

$$I_p = f(P_d) \qquad (1)$$

It is further proposed that the preference index I_p vary from 0 (minimum preference) to 1 (maximum preference).

Theoretically, preference functions may denote a set of priorities either defined by the designer, or deduced from a variety of sources beyond designer-specific intentional and/or informational evidence. Examples of these sources are issues pertinent to economical optimization, constraints dictated by performance requirements under concurrent evaluation, requirements formulated in codes and standards, implications of social/psychological studies, post occupancy evaluation results, as well as insights provided by physiological studies on health and comfort.

As an example, the demonstrative preference functions in figure 1 are partially based on the results of occupational studies in 582 residential units (cp. figure 2) that address the inhabitants' preferences concerning the dimensions of windows (Klingenberg and Seidl 1978, Seidl 1986).

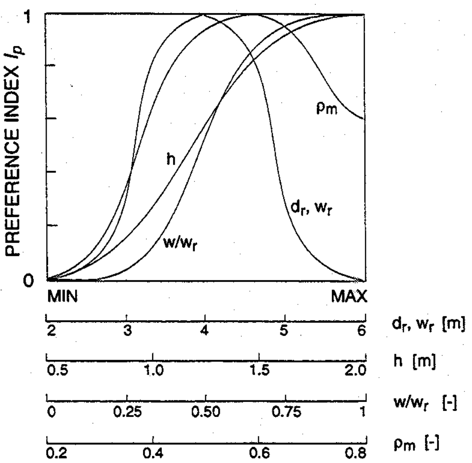

Figure 1. Examples of demonstrative preference indices for five daylighting design-related variables implemented in GESTALT. (d_r, w_r: room depth and width, h: window height, w/w_r: window width to room width ratio, ρ_m: room average reflectance)

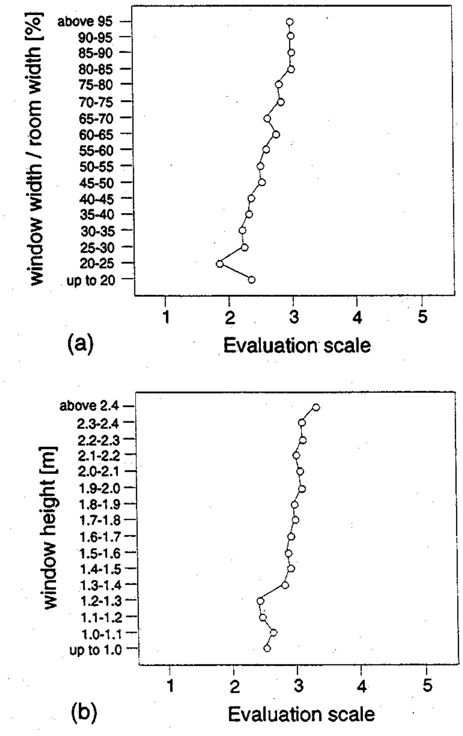

Figure 2. a: Occupancy evaluation of the window width (as related to room width) in residential buildings; b: Occupancy evaluation of the window height in residential buildings (Klingenberg and Seidl 1978)

2.3 The General Structure

A simplified representation of the general structure and design transformation strategy in GESTALT is given in figure 3. The desired actions (i.e. modifications of design-related parameters) are communicated to the system via an interactive user-interface. The computational part of the system involves a ternary sequence of preference processing, performance simulation, and response evaluation. Preference processing involves assessment and updating of preference indices and the associated weighting factors as well as the dynamic analysis of preference relations (e.g. maximum, minimum and mean preference index, "dominance" pattern of the preference index distribution). In the "default mode", this module uses a preference maximization strategy to determine the order of design parameters based on the desirability of their modifications. Performance simulation involves the computation of relevant performance indicators based on changes of the design parameter identified by the preference processor. The response evaluation routine compares the intended and the resulting direction of changes in the simulated performance and examines if alternative responding design variables must be considered. The result of this evaluation controls/terminates the recursive procedure of computation and leads to the definition of the new design state.

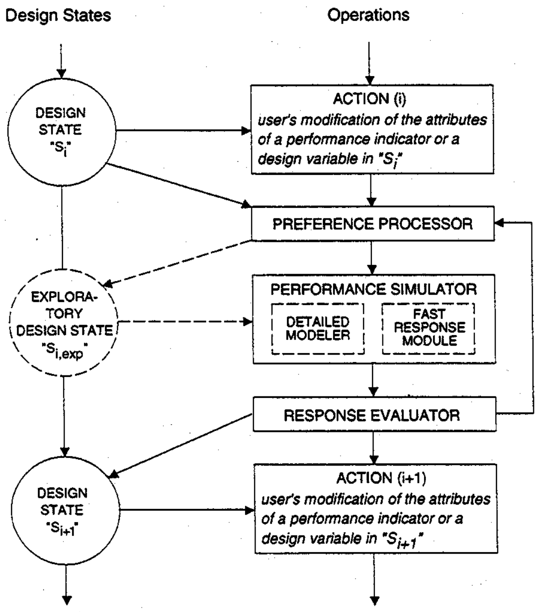

Figure 3. Schematic representation of the structural and procedural elements of GESTALT

2.4 Computational Methods

2.4.1 Comprehensive Daylight Simulation Module

As mentioned before, the implicit version of GESTALT allows for the utilization of a detailed daylighting simulator. This routine accounts for isotropic and non-isotropic sky models as well as a number of relevant design parameters such as complex geometrical configurations, overhangs, obstructions, partitions, etc. (Mahdavi et al. 1995, 1994). 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. The spherical sky model can be numerically organized in terms of a matrix with altitude (φ) and azimuth angles (ϑ) as dimensions. For example, given the sky matrix, the relative interior illuminance due to sky contribution $E_{r,s}$ at a reference point on a horizontal surface is given by:

$$E_{r,s} = \frac{\int_{\varphi_1}^{\varphi_2}\int_{\vartheta_1}^{\vartheta_2} \cos\vartheta \cdot \sin\vartheta \cdot z_{\varphi,\vartheta} \cdot \tau_\omega \cdot d\varphi \cdot d\vartheta}{\int_{\varphi=0}^{2\pi}\int_{\vartheta=0}^{\pi/2} \cos\vartheta \cdot \sin\vartheta \cdot z_{\varphi,\vartheta} \cdot d\varphi \cdot d\vartheta} \qquad (2)$$

where $z_{\varphi,\vartheta}$ is the relative sky luminance and τ_ω is the glazing transmittance.

The approach used for the calculation of the relative interior illuminance due to sky contribution on a horizontal surface, can also 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.

Obstructions (overhangs, buildings, vegetation) are treated by projection of their outline from each reference point onto the virtual sphere. 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.

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. Given 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 ($\rho_{v,i}$):

$$J_{v,i} = \rho_{v,i} \cdot \left(E_{r,s,i} + \sum_{j=1}^{n-1} F_{ij} \cdot J_{v,j} \right) \qquad (3)$$

where F_{ij} is the view factor from patch i to patch j.

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

2.4.2 A "Fast-response" Module

As mentioned earlier, the explicit realization of GESTALT calls for an easily invertible functional relationship between a performance indicator and a number of relevant design-related variables. To arrive at such a simple linear function ("fast-response" module) that links a daylight performance indicator to a limited number of design parameters, regression-analytical methods were applied (Mahdavi and Berberidou-Kallivoka 1993). Using the comprehensive daylight simulator described in section 2.4.1, daylight distribution patterns were generated for a large number of rooms with different proportions. The CIE standard overcast sky model was utilized along with a predefined set of variables (room area, fenestration area and transmittance, reflectance values of room surfaces). Based on the simulation results a regression analysis was performed which revealed a highly significant correlation between the daylighting performance indicator DF_{2p} (two-point daylight factor, Seidl 1986) and design parameters such as room and component geometry and photometric properties:

$$DF_{2p} = F_d \cdot \tau \cdot \left[R_g (9.33 + 32.7 \cdot \rho_m) - (0.037 + 4.57 \cdot R_g) \cdot \frac{d}{w} \right] \cdot \left[1 - 0.60 \cdot \frac{d_o}{h_r} \right] \cdot [1 - 0.011 \cdot \vartheta] \quad [\%] \tag{4}$$

where F_d is the dirt depreciation factor, τ is the glazing transmittance, R_g is the glazing to floor area ratio in percentage, ρ_m is the room average reflectance, d is the room depth, w is the room width, d_o is the overhang depth, h_r is the room height, and ϑ is the angle of obstruction from the center of the window.

Obviously, this function can be easily solved for all the variables involved and serve, thus, as the computational background for the explicit GESTALT version.

2.5 The "Depth" of the Investigative Projections

Figure 3 (GESTALT's basic structure) illustrates schematically the mechanism for the transition from a design state i to a design state i+1. In the earlier (implicit) versions of GESTALT (Mahdavi and Berberidou-Kallivoka 1994) this transition was realized by a procedure resembling the "greedy" algorithm in the area of optimization. This approach reduces the "depth" of the investigative projections as, at each step, the effects of changes in the design variables on the performance indicator are obtained only for one discrete increment in each direction. Thus, as one follows a rather narrow path through the design space, in-depth "lateral" possibilities for design transformation may be ignored and local minima and maxima cannot be transcended. To illustrate this point, figure 4 shows, for a specific design, that while average illuminance acts as a monotonically decreasing function of the overhang depth, the uniformity factor (the ratio of the minimum illuminance to the average illuminance) behaves as a non-monotonic function of the same design variable. Although it is not feasible (may be not even desirable) to conceptualize exhaustive search strategies, one could still improve the search's lateral coverage to a certain degree. Possible approaches are:

a) increase the number of the increments (i.e. investigative projections) for each design variable (in both directions) for which sequential performance assessment is performed at each step;

b) at each step perform a local optimization on all relevant design variables (assuming for each variable a limited set of incrementally related attributes) to maximize the (weighted) average preference;

c) apply probabilistic and Artificial Intelligence methods (particularly considering learning systems) to improve the efficiency of the approaches described in points *a* and *b* above.

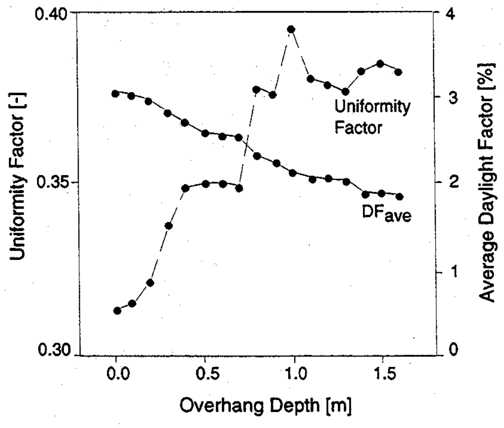

Figure 4. Demonstrative monotonic and non-monotonic functional relationships between performance indicators and design variables

In the current version of GESTALT the above described option *a* is implemented. The depth of the investigative projections (number of the discrete incremental changes of the design variables that are subjected to trial simulations) can be initially defined and dynamically changed. A simplified version of the option *c* has been also realized (although not applied in the course of the following case studies) as the depth of investigative projections can be reduced if, after a certain number of design state transformations, no local minima or maxima has been identified. This approach reduces the penalty in computational efficiency associated with wider lateral depth in design exploration.

3. DEMONSTRATIVE CASE STUDIES

3.1 An Illustrative Sequence

To illustrate some of the capabilities of the GESTALT environment, a series of demonstrative case studies are described below. These case studies are documented through illustrative "snapshots" selected out of sequences of design states created during multiple sessions with GESTALT. The sequences (figures 7 through 9) start with an initial design configuration and follow the evolution of the design as the result of the (emulated) user's intention to increase a performance indicator (such as average illuminance, uniformity factor) and the dynamic interplay of various preference functions. Although not shown in these sequences, GESTALT allows also at any time for the reversal of operations, change of "critical" performance indicator, redistribution of degrees of freedom, and redefinition of preference functions.

For the purpose of these sequences a set of demonstrative preference functions were derived using input from a small group of student designers (Suter 1994). Rather than defining absolute values for design parameters such as room width and depth, window width and height, or overhang depth, the students were asked to select preferred relationships between these design parameters based on illustrative visual material (e.g. scale drawings of rooms and facades). After applying standard statistical procedures, preference functions were defined as illustrated in figure 5 for the following design-related parameters: room width to room depth (r_w/r_d), window width to window height (w_w/w_h), overhang depth to room height (o_d/r_h), window width to wall width (w_w/r_w), window area to room area (w_a/r_a), window height to room height (w_h/r_h), and wall average reflectance (ρ_m). The preference index for the window location is defined as a function of the window location factor k:

$$k = |0.5 \cdot (R_w - W_w) - d_c| \qquad (5)$$

where R_w is the room width, W_w is the window width, and d_c is the horizontal distance of the corner of the window from the corner of the room.

A second set of preference functions was also generated utilizing the declared preferences of one, randomly selected, student, to serve as a comparison for the intended demonstrative case studies. These preference functions are illustrated in figure 6.

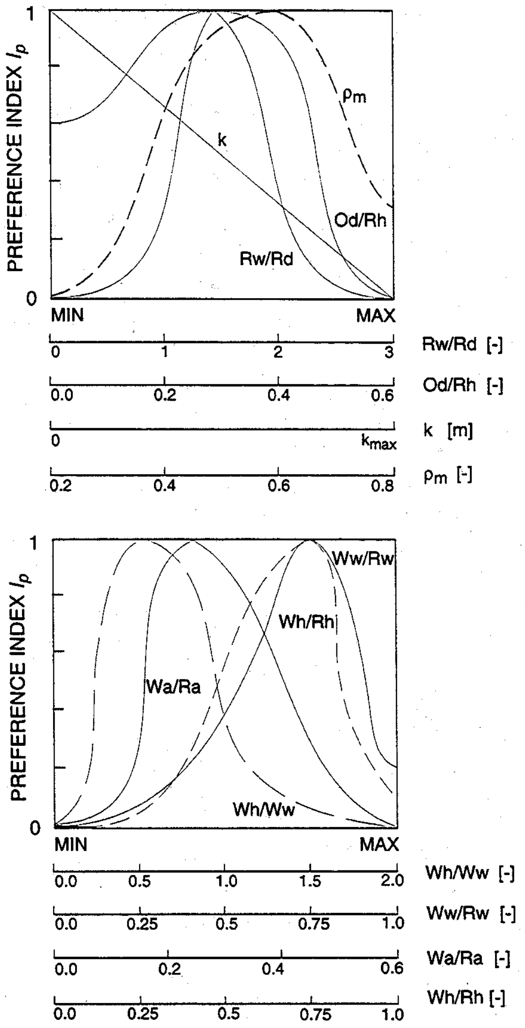

Figure 5. Demonstrative preference indices for design-related functions used in GESTALT. (Rw/Rd: room width to room depth, Od/Rh: overhang depth to room height, k: window location factor, ρ_m: wall average reflectance, Wh/Ww: window height to window width, Ww/Rw: window width to room width, Wa/Ra: window area to room area, Wh/Rh: window height to room height)

Values of dirt depreciation factor, glazing transmittance and reflectance, room area, room height, ceiling, floor and overhang reflectance as well as window sill height were locked throughout the sessions.

Each frame (snapshot) in figures 7 through 9 includes the geometrical representation of a design state together with a scale representing the corresponding value of the driving performance indicator (average illuminance E_m, uniformity factor U), and the corresponding average preference index of the design variables (P_m). The evolution trajectories of figures 7 and 8 were guided by the preference index distributions illustrated in figure 5. The sequence shown in figure 9 was evolved on the basis of the preference functions given in figure 6. The average room illuminance (on a horizontal plane 85 cm above the floor) was the designated performance indicator in the case of figures 7 and 9. Figure 8 illustrates a design sequence based on actions on the uniformity factor.

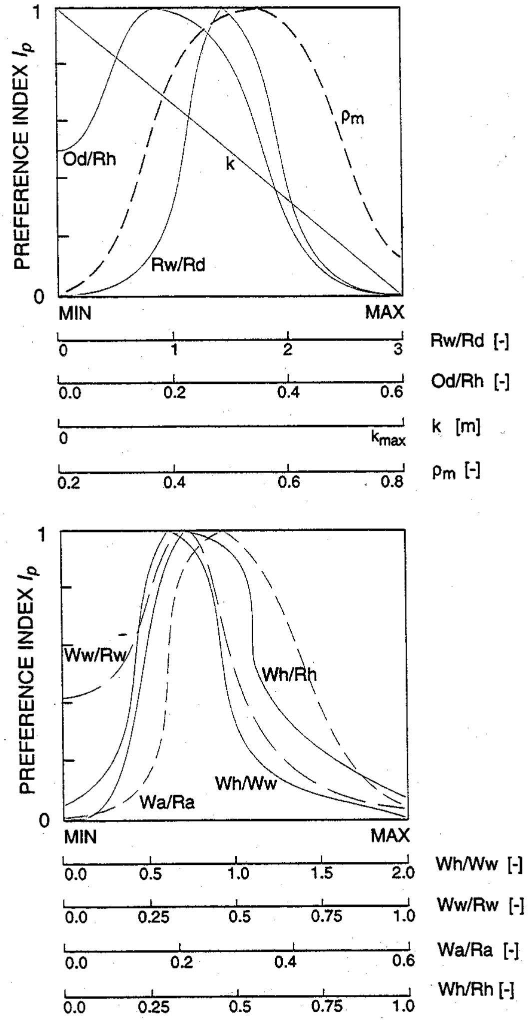

Figure 6. Demonstrative preference indices for design-related functions used in GESTALT. (Rw/Rd: room width to room depth, Od/Rh: overhang depth to room height, k: window location factor, ρ_m: wall average reflectance, Wh/Ww: window height to window width, Ww/Rw: window width to room width, Wa/Ra: window area to room area, Wh/Rh: window height to room height)

3.2 Discussion

The sequence illustrated in figure 7 demonstrates various distinctive evolutionary phases. The initial design state *S-1* shows a very low value for the average illuminance as well as relatively low average preference index. A complex distribution of actions on various parameters transformed the starting design state whereby initially the average preference index of the design-related variables increased with higher average illuminance values. The design state *S-4* represents a turning point, in that further increase in the average illuminance results in a lower average preference index. Given the underlying definition of preference indices, this quasi "optimal" configuration represents a unique design state as its emergence is independent of the initial state of design. Design state *S-6* represents the maximum achievable average illuminance for the given range of the design variables. It also represents the unique final stage of the convergence, since its attributes are independent of the initial design state as well as the underlying set of preference functions. However, the "intermediate" design states may vary depending on the initial design and the specific sequence of operations performed.

The choice of the performance indicator can significantly influence the design evolution. For example, figure 8 illustrates a sequence based on the same preference functions as in figure 7. However, in this case the uniformity factor is selected as the driving performance indicator. This leads to a final design state distinguishable from that of figure 7 with respect to the overhang element. The "optimal" design state though, is the same in both sequences as it depends on identical preference functions.

Figure 9 demonstrates the impact of a different set of preference functions on the design evolution. This particular sequence starts with the same initial design configuration as in figure 7 and is also driven by operations on average illuminance. However, the preference functions (cp. figure 6) deviate significantly from those guiding the sequence shown in Figure 7. The differences between the "optimal" design configurations of figure 7 (different window sizes and proportions, different overhang dimensions) can be traced back to the differences in the respective definitions of the preference functions. However, both sequences lead to the same final design state as both approach the maximum possible average illuminance.

4. CONCLUDING REMARKS

The above described case studies illustrate only a small set of possible scenarios for using GESTALT in the context of design exploration. Nonetheless, they demonstrate clearly the possibility and feasibility of flexible and multi-directional design to performance mapping operations. Based on a set of preference functions derived from various sources of information, GESTALT actively supports the designer in dealing with the question: "What should I do to get the desired answer?" (Augenbroe and Winkelmann 1991). However, it must be emphasized, that preferences should not be viewed as a rigid and unchangeable set of constraints. In fact, a remarkable attribute of GESTALT lies in the fact that it provides an environment in which preferences themselves can be subject to parametric design exploration.

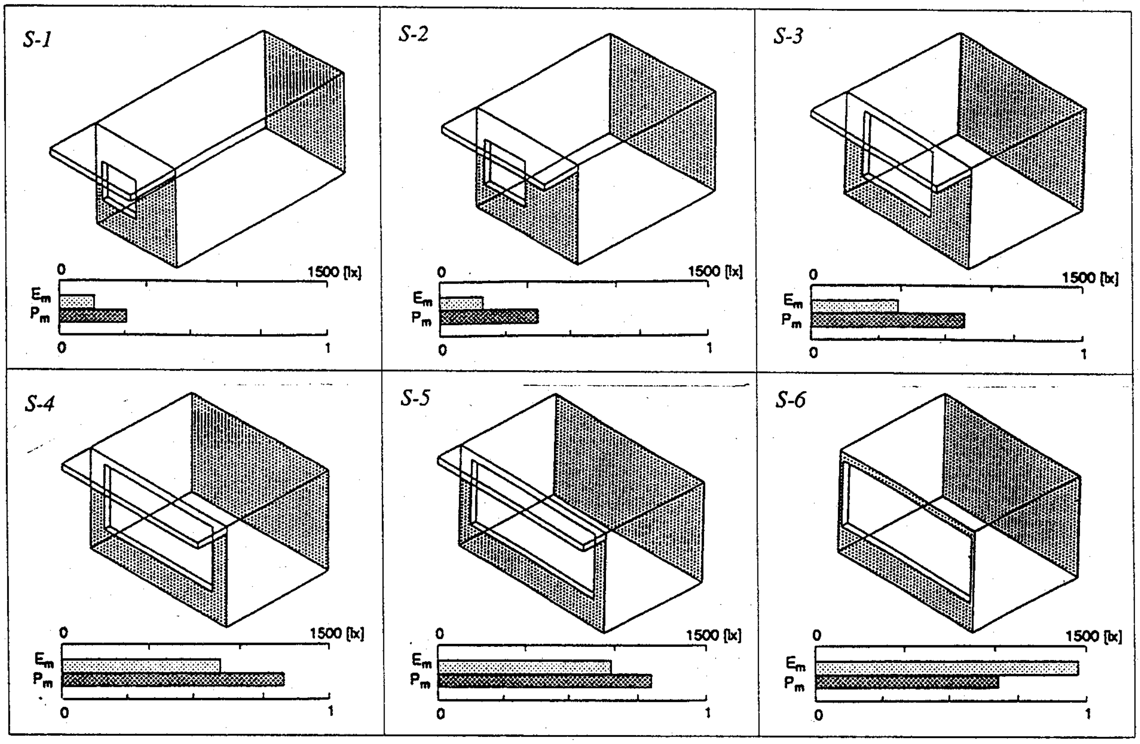

Figure 7. Selective illustration of a demonstrative design sequence with GESTALT. Convergence based on the preference functions shown in figure 5 (average illuminance E_m is the driving performance indicator)

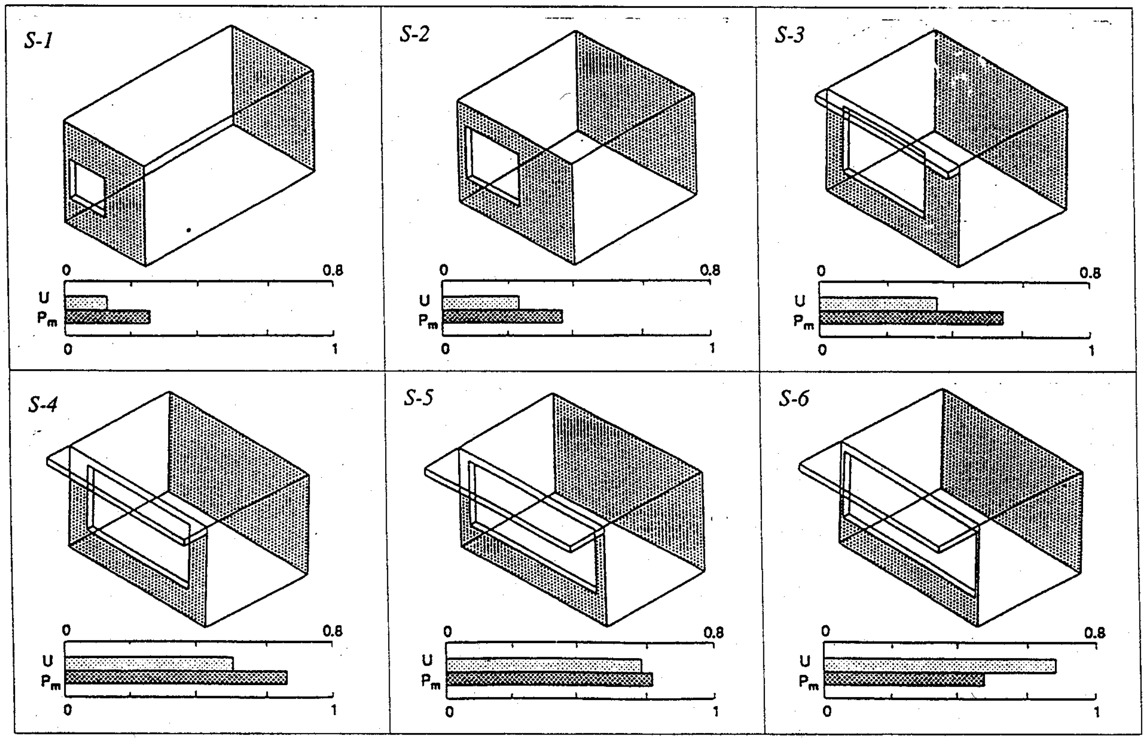

Figure 8. Selective illustration of a demonstrative design sequence with GESTALT. Convergence based on the preference functions shown in figure 5 (uniformity factor U is the driving performance indicator)

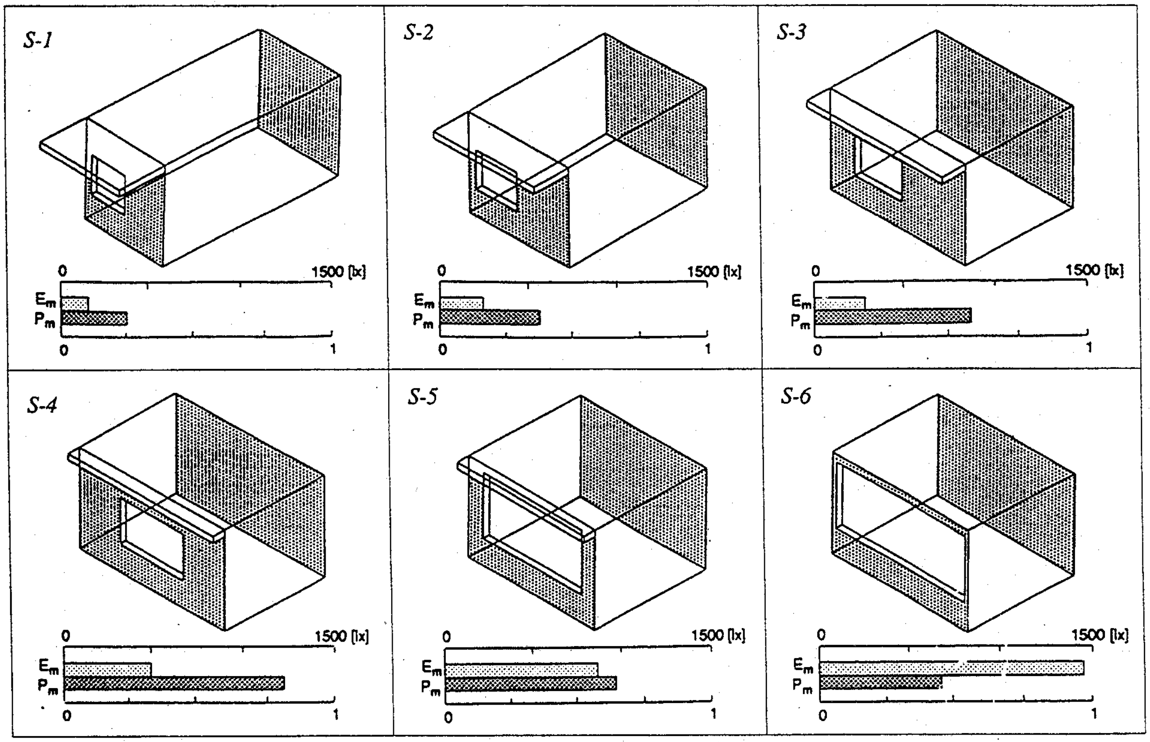

Figure 9. Selective illustration of a demonstrative design sequence with GESTALT. Convergence based on the preference functions shown in figure 6 (average illuminance E_m is the driving performance indicator)

REFERENCES

Augenbroe, G., and F. Winkelmann. (1991). "Integration of Simulation into the Building Design Process." *Proceedings of the 2nd World Congress on Technology Improving the Energy Use, Comfort and Economics of Buildings,* 1991 IBPSA Conference. Ed. J. A. Clarke, J. W. Mitchell, and R. C. Van de Perre, pp. 367 - 374.

Klingenberg, H., and M. Seidl. (1978). "Forderungen an Abstandflächen und Fenster im Hinblick auf Kommunikation und Privatheit." *Bundesministerium für Raumordnung, Bauwesen und Städtebau.*

Mahdavi, A. (1993). "Open Simulation Environments and the Problem of Ambiguity: A 'Preference-based' Approach." *Proceedings of the CAAD Futures '93 Conference,* Pittsburgh, PA: pp. 195 - 214.

Mahdavi, A., and L. Berberidou-Kallivoka. (1994). "GESTALT: A Prototypical Realization of an 'Open' Daylighting Simulation Environment." *Journal of the Illuminating Engineering Society,* Vol. 23, No 2, Summer 1994, pp. 62 - 71.

Mahdavi, A., and L. Berberidou-Kallivoka. (1993). "A 'Two-Way' Inference Approach to Daylighting Simulation." *Journal of the Illuminating Engineering Society,* Vol. 22, No 1, Winter 1993, pp. 66 - 74.

Mahdavi, A., L. Berberidou-Kallivoka, and Z. Li. (1995). "Active Computational Support for Concurrent Building Envelope and Lighting System Design." Submitted to the 1995 *ASHRAE/DOE Thermal Performance of the Exterior Envelopes of Buildings VI Conference,* Florida, December 4-8.

Mahdavi, A., L. Berberidou-Kallivoka, K. P. Lam, and Z. Li. (1994). "Computational Support for the Concurrent Design of Natural and Electrical Lighting Systems in Buildings." Proceedings of the 1994 *IESNA Annual Conference,* Miami, August 7-11, pp. 721 - 730.

Seidl, M. (1986). "Tageslicht in Innenräumen" (Daylight in Indoor Rooms), from Beckert, Mechel and Lamprecht, *Gesundes Wohnen; Wechselbeziehungen zwischen Mensch und gebauter Umwelt,* Düsseldorf, Beton-Verlag: pp. 206 - 216.

Suter, G. (1994). *Empirical Assessment of Designer Preferences for Selected Design Variables.* Independent Study Project, Center for Building Performance and Diagnostics, Dept. of Architecture, Carnegie Mellon University.

ACKNOWLEDGEMENT

This study was partially funded by the Advanced Building Systems Integration Consortium (ABSIC) and the Center for Building Performance and Diagnostics (CBPD), Department of Architecture, Carnegie Mellon University.