"Open" Simulation Environments: A "Preference-Based" Approach

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This paper introduces in conceptual, algorithmic and implementation terms, the notion of an "open" simulation environment as a "multidirectional" approach to computer-aided performance modelling. A "preference-based" formalization of design intentions/criteria is proposed to cope with the "ambiguity" problem through dynamic control of degrees of freedom of relevant design-related parameters during the interactive design process. A prototypical realization of an open simulation environment called "GESTALT" for simultaneous treatment (parametric manipulation) of various design and performance variables is demonstrated. Some preliminary results of computer-assisted generation of performance-responsive designs are presented.

Keywords: open simulation environments, multidirectional building performance simulation, form-function mapping, preference-based convergence strategies, preference-index.

1 Motivation and Background

Existing performance simulation tools have not been integrated effectively in the architectural design process. Rather, the prevailing *modus operandi* characterizes them as verification tools and not as design support tools (Mahdavi and Lam, 1991). Particularly in the early stages of design, where crucial and often irreversible decisions are made, this evident lack of appropriate computational environments represents a serious drawback. The "mono-directionality" of many conventional simulation tools can be identified as one of the parameters responsible for this circumstance (Mahdavi and Berberidou, 1992).

Most available computer simulation tools do not "directly" provide information on design configurations that would meet the desired performance criteria, but instead require a computationally unsupported convergence toward the solution through extensive parametric studies. The conventional simulation procedure is based on the transformation of pertinent design data (geometry, materials, environment) into a set of performance indicators for a given context. This procedure produces theoretically "unique" results for a given algorithmic formulation.

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Earlier studies (Mahdavi, 1993; Mahdavi and Berberidou, 1992) identified the need for simulation environments that facilitate not only the evaluation of a given design solution in terms of its performance, but also the derivation of formal and "behavioral" implications of performance criteria, thus allowing parallel design generation and performance evaluation. It was implied that the representation of the dynamic link between performance indicators and their "design correlates" (formal configurations, materials, and system specifications) would increase the effectiveness of computer-aided simulation tools in supporting design decision making. This paper introduces the notion of an open simulation environment as a new paradigm for simulation-based computer-aided architectural design and education support systems and as a further development of the concept of a bi-directional inference approach, proposed in the earlier studies.

2 Open Simulation Environments: Concept and Problems

The notion of an open simulation environment denotes a design support tool that facilitates the interactive and simultaneous modification of properties and the observation of changes in various context, design, and performance variables. These variables represent potentially heterogeneous yet well-formalized concepts, views and representations that are related to designs in some constitutive, behavioral or contextual sense. An open simulation environment thus represents, in metaphoric terms, a "shaping/molding" framework, in which the designs evolve (approach a desired *gestalt*) as the designers freely access, modify and observe relevant variables at different levels of abstraction. From the human ecological point of view, this also responds to the desirability of an iterative-adaptive approach to complex design tasks (Mahdavi, 1992).

However, the comprehensive realization of an open simulation environment is not a trivial task. This is particularly evident in cases where numerous design parameters (with large degrees of freedom) and multiple complex performance indicators are involved. Moreover, the issue of "ambiguity," associated with the operational multi-directionality of open simulation environments introduces significant implementation problems. Since the same performance criterion may be met by different design configurations, the transformation of performance criteria into concrete design implications cannot be formalized in deterministic terms.

Earlier studies suggested that, due to the complex pattern of the factors involved in a design, the problem of ambiguity cannot be solved using a single method. It was concluded that it would be more feasible to utilize a set of flexible strategies (including the "lock" concept, the "priority" concept, heuristic rules, mathematical multi-criteria optimization techniques and regression-analytical methods). A terminology was proposed including formal (geometric) design information, "semantic" (attribute-related) design information (e.g., material and component properties), contextual information (e.g., outdoor climatic conditions) and performance indicators (e.g., daylight factor, reverberation time, etc.). It was implied that design definition includes formal and semantic information that for a given contextual framework can be transformed into performance indices utilizing conventional simulation tools. In this context, the computational strategies that would allow for a bidirectional transformation were labeled as "two-way" (Mahdavi, 1993; Mahdavi and Berberidou 1992).

Although these definitions are useful for many practical considerations and will also be utilized in this contribution, they do not satisfy the requirements of a rigorous terminological examination. The distinction between semantic information and performance indicators appears to be a matter of the strategic level of observation. Component properties might be interpreted as “low-level” performance indicators, whereas room performance descriptors might be interpreted as “high-level” behavioral properties. Some geometrical variables (e.g., areas and thicknesses) may be defined as attributes of discrete building components, whereas others (e.g., spatial relations and view factors) refer to multiple objects and their interrelationships.

Many “behavioral” component properties involve contextual parameters (boundary conditions). For example, the thermal component descriptor U-value (thermal transmittance) depends on surface resistances R_{si} and R_{se}:

$$U = [R_{si} + \sum_{i=1}^{n} (d_i \cdot \lambda_i^{-1}) + R_{se}]^{-1} \qquad [W \cdot m^{-2} \cdot K^{-1}] \qquad (1)$$

For example, external surface resistance R_{se} is a function of prevailing wind velocity as well as solar/thermal radiation:

$$R_{se} = (a_s + a_k)^{-1} \qquad [m^2 \cdot K \cdot W^{-1}] \qquad (2)$$

$$\alpha_s = -1.163\alpha_k - \left[5.78 \cdot 10^{-8} \cdot \varepsilon_0 \cdot 4\,(T_r)^3\right] \qquad [W \cdot m^{-2} \cdot K^{-1}] \qquad (3)$$

$$\alpha_k = 5.9 + 4.1 \cdot v \qquad [W \cdot m^{-2} \cdot K^{-1}] \qquad (4)$$

where a_s is the solar heat transmission coefficient, a_k the convective heat transmission coefficient, T_r the radiation air temperature, e_0 the emittance of building surface; and v the wind velocity (in $m \cdot s^{-1}$).

Even at the “lower” level of material property λ (thermal conductivity), a dependency on context (e.g., moisture content and temperature) exists. Material properties are often defined in view of the interactions of environmental factors (sound, light, or heat) with a building element and are thus often dependent on their prevailing pattern. For example, light and sound absorptance, reflectance, and transmittance are generally a function of the angle of incidence. Equation 5 expresses the light transmission τ_θ through a single pane of glass at a given angle of incidence θ as a function of θ and the transmission at normal incidence τ_0:

$$\tau_\theta = 1.018 \cdot \tau_0 \cdot (\cos\theta + \sin 3\theta \cdot \cos\theta) \qquad [-] \qquad (5)$$

Also, the sound reduction index R_f of a building component (with surface density m in $kg \cdot m^{-2}$) is a function of the frequency f (in Hz) of the incident sound wave:

$$R_f = 18 \cdot \log m + 12 \cdot \log f - 25 \qquad [dB] \qquad (6)$$

Similar terminological problems have to be encountered in dealing with the cybernetic concept of an “intelligent” building as a “system” involving dynamic and environmentally responsive components that could not be described in terms of static and context-independent specifiers. Examples of these components are glazing systems with spectrally selective transmittance films which “react” selectively to the various wavelengths of electromagnetic radiation. New types of “low-E glass” allow for the transmission of sunlight, but block long-wave infrared radiation. Electrochromic glass, also known as “switchable glazing," is activated by passing an electric current through the polymer. Depending on the intensity of electric current applied, the color of the glass will change within a range from blue-gray to clear. Furthermore, materials are being developed (e.g., Holographic Diffractive Structures) that will not only control the quantity of light emission but also manipulate light distribution.

Terminological "impressionism" can also be observed in the evolution of "high-level" performance descriptors such as daylight factor and reverberation time. The reverberation time, as defined by Sabine, was thought to be independent of the room geometry (other than room volume quantity), the location of the receiver in the room, the location of source, and the local distribution of sound absorption area. However, subsequent developments in the field have shown that these factors in fact affect the magnitude of the reverberation time. This implies a performance indicator that in reality cannot be abstracted from occurrences in the room and is thus an inherently dynamic property. A similar context-dependency can be pointed out concerning daylight factors since their definition is based on the notion of a specific sky condition/type. Moreover, both reverberation time and daylight factor are good examples of evolutionary changes in performance representation since, as examples of more recently introduced parameters such as "early decay time" or "coefficient of utilization" demonstrate, their role and position have been repeatedly questioned and/or modified. This redefining process reflects successive changes in our understanding of relevant design parameter as related to scientific development, technological innovation, and socioeconomic change.

It appears that representations of design and performance variables are in many instances not only derivatives of objects and behavioral patterns, but also indicative of human beings' goals, expectations, interests, intentions, and views. In this sense, performance indicators and design variables may be interpreted not necessarily as elements of a completed (closed) system of terms and rules but as flexible (open) and practical constructs. It is not essential if the notion of an open simulation environment is labeled as pragmatic (or utilitarian, evolutionist, ecological, ...) as long as it is understood that here, terms such as performance indicator, formal parameter, and component attributes are seen primarily as useful communicative references and not as elements of a rigid form-function discourse.

3 Some Convergence Strategies

3.1 Introductory Remarks

The "lock" concept involves the interactive selection of those formal/semantic design parameters which have a degree of freedom in responding to successive performance criteria changes, while other design features remain unchanged. If, as a result of a locking operation, only one formal/semantic variable is free to respond, then a deterministic transformation of the performance indicator into a formal or semantic property is in principle possible. However, this might be regarded as a naive and practically limited solution to the problem of ambiguity. The following examples from the domain of room and building acoustics demonstrate the application of a group of convergence strategies (toward achieving performance-based design configurations) involving more complex interrelations of various design parameters.

3.2 Rule-Based Generation of Geometrical Configurations

In certain cases, performance criteria can be formalized in terms of generative rules for formal configurations. As an example, Figure 1a illustrates schematically the principle of a rule-based generation of floor and ceiling geometries (in particular the size, location, and inclination of reflectors) for acoustically significant rooms (auditoria, concert halls, etc.) based on a set of well-defined performance criteria. Given the room function and the projected number of seats, specific indicators (appropriate volume/person or area/person) can be utilized to obtain general room area, room volume, room height and the approximate location of ceiling reflectors (cp. shaded area in Figure 1a). The inclination of the floor can be obtained according to the following procedure. A suitable performance criteria such as the desired view field angle γ is defined. The distance of the starting point of the floor inclination from the sound source d_0 is then computed based on the height of the sound source above the head level of the first seating row h_s:

$$d_0 = h_s \cdot \tan^{-1}(\gamma) \quad [\mathrm{m}] \qquad (7)$$

The required elevation h_d of seats at any distance d is given by:

$$h_d = h_s + d \cdot \tan\{\gamma \cdot [\ln (d \cdot d_0^{-1}) - 1] \quad [\mathrm{m}] \qquad (8)$$

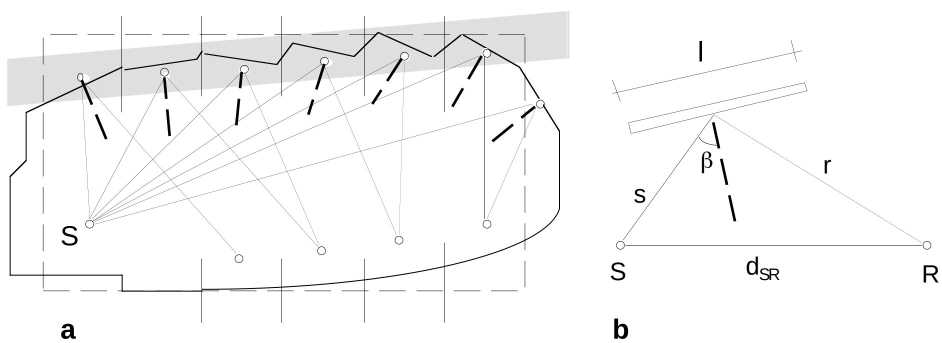

Figure 1. Illustration of a rule-based approach to acoustical design of concert halls (a) and schematic illustration of the determination of reflector sizes (b).

The desirable distribution of reflected sound energy is derived as a function of the available direct sound component. Based on this information, discretized ceiling regions are allocated to discretized audience areas (Figure 1a). The extension of the reflector areas are estimated based on boundary frequencies f_b for geometrical reflection (Figure 1b):

$$l = [2 \cdot c \cdot f_b^{-1} \cdot \cos^{-2}(\beta) \cdot r \cdot s \cdot (r + s)^{-1}]^{0.5} \quad [\mathrm{m}] \qquad (9)$$

For each set of a reflector region and an audience area, the sound rays are constructed. At this stage, the ellipse construction (Furrer, 1961) is utilized to determine if the time delay magnitude (time difference between direct and reflected sound wave arrival) is below a maximum acceptable value (Δt_{max}) or if adjustments are necessary. For first order reflections (Figure 1a) and given sound speed c, the respective condition is given by:

$$s + r - d_{SR} < \Delta t_{max} \cdot c \tag{10}$$

The inclination of reflector is determined in terms of the plane normal to the bisector of the angle β (cp. Figure 1b). The ceiling and reflector configuration is then finalized based on spatial conflict-solving strategies.

3.3 In Search of Adequate Material Configurations

In certain design situations it is necessary to specify the semantic of a formally defined design in way that predefined performance criteria are met. An example of this formal/semantic “pattern matching” deals with the classical design question of acoustically adequate selection of materials for room surface treatment based on the requirements of the reverberant field. A major problem of this task is the unmanageably large number of combinatorial possibilities. This problem is typical for those situations where the material configuration of a design (in this case, the configuration of materials for surface treatment in rooms) must be derived based on certain performance criteria (in this case, reverberation time). To demonstrate this point, Table 1 includes a matrix of α values (sound absorption coefficients) for *m* room components and *n* frequencies. Each matrix row represents a set of a variables designated to a room component. A large number of material specifiers applicable to that room component can be assigned to these variables (assuming each of the room's components can be treated by *q* different materials, the number of theoretically possible configurations *p* is given by $p = n \cdot q^m$).

Table 1. Matrix of room components and frequency-dependent absorption coefficients.

	f_1	f_2	...	f_n
C_1	$\alpha_{1,1}$	$\alpha_{1,2}$	...	$\alpha_{1,n}$
C_2	$\alpha_{2,1}$	$\alpha_{2,2}$	...	$\alpha_{2,n}$
...	...	...	...	
...	...	...	...	...
C_m	$\alpha_{m,1}$	$\alpha_{m,2}$	...	$\alpha_{m,n}$

One possible strategy to deal with this problem starts by the traditional procedure of deriving the required reverberation time (T_o) based on the room volume *V* and the room function, utilizing available guidelines (Fasold et al., 1987; Tennhardt, 1974). To limit the search space and to facilitate the initial search phase in the material data base, the notion of an average absorption coefficient α_m is adopted. Furthermore, as illustrated in Figure 2, a separate data base is allocated to each surface type (e.g., wall, floor, ceiling, window, or door). The required value for α_m of the room surface components can be obtained based on T_o, and the available total absorption of other sources (people, furniture, and air) A_z:

$$\alpha_m = S_{tot} \cdot T_o \cdot (0.163 \cdot V - T_o \cdot A_z)^{-1} \tag{11}$$

Assuming a tolerance range of $\pm \Delta\alpha$, a reduced number of materials are selected from the data base that are within the $\alpha_m \pm \Delta\alpha$ range. Interactive operations and additional rules (e.g., functional compatibility, economical priority) may further reduce the number of selected components in each data base. Given this limited set of *q'* elements for each surface component, reverberation times can now be calculated for all possible configurations of materials and surfaces in an exhaustive manner (the corresponding number of configurations p' is in this case is given by $p' = n \cdot q'^m$).

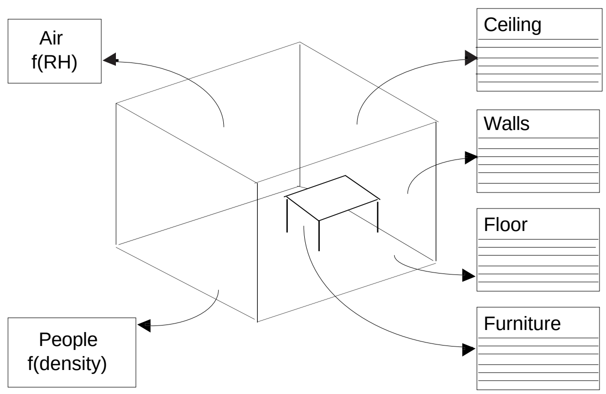

Figure 2. Schematic illustration of data base components pertinent to the design and evaluation of the reverberant field in a room.

A weighted performance indicator (ΔT_w in Equation 12) may be applied for the comparative evaluation of the solutions. The frequency dependent deviations of the calculated reverberation time from the target value are weighted according to considerations pertinent to the specific function of the room:

$$\Delta T_w = \sum_{i=1}^{n} k_i \cdot \Delta T_i, \qquad \left(\text{with} \sum_{i=1}^{n} k_i = 1\right) \tag{12}$$

where k_i is the weighting factor for frequency band i and ΔT_i the deviation of the calculated reverberation time from the target value for frequency band i.

In this specific case, an alternative search strategy would be to establish the spectral characteristics of the required absorption based on the frequency-dependent α_m values obtained from Equation 12. A search process in the material data base can then provide the closest approximation of these α values for each room surface component using similar weighting methods as formulated in Equation 13.

A different approach toward bidirectional design support strategies for acoustic treatment of room surfaces can be formulated utilizing linear and goal programming techniques. In this case, it is assumed that the designer has already selected a preliminary set of m materials/components and would like to obtain the optimal area of each of the corresponding surfaces ($S_1, S_2, ..., S_m$) which sum to the room's total surface area S_{tot}. Equation 13 includes a system of relationships between the functionally required frequency-dependent total absorption values ($A_1, A_2, ..., A_n$) and the product of surface areas and their respective absorption coefficients, implementing the deviation terms ($D_1, D_2, ..., D_n$) which have to be minimized. Since these deviation terms are defined for different frequencies, the minimization rule adopts the concept of spectral weighting factors $g_1, g_2, ..., g_n$, which sum to one.

$$
\begin{aligned}
&\min Z = g_1 \cdot D_1 + g_2 \cdot D_2 + \dots + g_n \cdot D_n \\
&\text{subject to:} \\
&\alpha_{1,1} \cdot S_1 + \alpha_{2,1} \cdot S_2 + \dots + \alpha_{m,1} \cdot S_m \pm D_1 = A_1 \\
&\alpha_{1,2} \cdot S_1 + \alpha_{2,2} \cdot S_2 + \dots + \alpha_{m,2} \cdot S_m \pm D_2 = A_2 \\
&\dots\dots\dots \\
&\alpha_{1,n} \cdot S_1 + \alpha_{2,n} \cdot S_2 + \dots + \alpha_{m,n} \cdot S_m \pm D_n = A_n \\
&S_1 + S_2 + \dots + S_m = S_{tot}
\end{aligned}
\tag{13}
$$

An important feature of this approach lies in its capability to adopt additional constraints. For example, the maximum possible surface area of a certain material S_i (e.g., carpet) can be restricted to the area of a certain room component S_i (e.g., floor) insuring that $S_i \leq Sj$. Furthermore, economical considerations can be taken into consideration. For example, given area unit price information $p_1, p_2, ..., p_n$, a maximum acceptable total material price P_{max} can be formulated in terms of a constraint to be added to Equation 14:

$$S_1 \cdot p_1 + S_2 \cdot p_2 + \dots + S_n \cdot p_n \leq p_{max} \tag{14}$$

3.4 *"Auto-Generative" Derivation of Construction Configurations*

In specific cases, the convergence toward the solution of a design problem can be based directly on the algorithmic relationship between the involved design variables. An example of this type of task is the problem of sound transmission between adjacent rooms which not only depends on the sound insulation characteristics of the partition element (wall or ceiling), but also on the construction and geometry of the flanking building elements. A number of models have been introduced to facilitate the calculation of the sound transmission between rooms on the basis of geometry and construction data (Mahdavi, 1991). According to the "modified" model (Mahdavi, 1990), the sound level difference *D* between two adjacent rooms (in massive buildings) with *n* flanking elements can be estimated according to the following equation:

$$D = C_V - 10 \cdot \log \left(10^{-0.1\, Dd} + \sum_{i=1}^{n} 10^{-0.1 D_{f,i}}\right) \quad \text{[dB]} \tag{15}$$

where C_V is the volume correction factor, D_d is the sound level difference due to the partition element, and $D_{f,i}$ is the sound level difference due to the flanking element *i* (all in *dB*).

This algorithm provides the possibility to translate changes in value of the performance indicator *D* into necessary modifications of design. In fact, the logarithmic nature of Equation 15 immediately reveals that improvements on the "weakest" transmission paths are most effective. This means that the algorithm itself implies the appropriate computational strategy to converge toward the solution (improvement of the overall sound level difference as the relevant performance criterion). Thus, instead of a "blind" search, a prioritized set of transmission paths can be identified and treated consequently.

3.5 Critical Comment

The above examples represent useful methods for the computational translation of performance-related design objectives into geometric and/or semantic design configurations. However, they do not represent a generalizable strategy for the development of open simulation environments. In some cases, they simply represent reversed versions of one-to-one mapping strategies of the conventional approach. In other cases, they rely on algorithmic formulations that are highly domain-specific. As far as the application of the conventional optimization approaches is considered, they seldom satisfy simultaneously the requirements of interactive flexibility, computational efficiency, and practical usability (particularly at the early stages of design).

4 The "Preference-Based" Convergence Approach

4.1 Ambiguity and Beyond

The ambiguity question refers to the circumstance that many different configurations of the elements in a set of design-related variables may satisfy predefined performance criteria. This implies that any organized and reproducible convergence strategy necessitates the definition of a set of constraints to control the interrelationships of design and context variables. This, of course, is also the central premise of the traditional optimization strategies. However, in the specific context of open simulation environments, additional requirements must be met, since these operate with a dynamic definition of design states and necessitate a flexible "on-the-fly" optimization technique. Furthermore, the optimization framework must accommodate a large number of variables subject to modifications of unknown magnitude, sequence, and direction. To be of practical relevance, the system must also be flexible enough to account for a large number of performance modelling applications and their specific domain requirements.

4.2 Preference as Paradigm

In the present 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 performance indicators. Operational preference scales can be defined for any design-related variable if and only 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. It is not implied that this correlation must be static. Depending on the relevant domain/ source, it can be subject to short-term interactive modification (e.g., as the result of the refinement process of individual preferences) or long-term external developments (e.g., in the case of socioeconomic changes and scientific/technological advancements).

4.3 Sources of Necessity

In a first narrow sense, preference denotes a set of priorities defined by the designer either *a priori* or as they evolve through the "dialogical" process of evaluating externalized design intentions. This definition covers both explicitly communicated preferences and the "depth-tendencies" that are implicit to the sequential pattern of design creation/evaluation and may be deduced from it (e.g., utilizing neural network learning methods). These idiosyncratic systems of preferences may address various design aspects insofar as these aspects can be formalized in terms of a continuum of values correlated with different levels of desirability. In a second broader sense, preference continua might be deduced from a variety of sources beyond designer-specific intentional and/or informational evidence and thus not directly under one's control. Examples of these sources are issues pertinent to economic 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.

4.4 The Notion of a Preference-Index

There is probably no unique solution for a computational implementation of a preference paradigm. The approach outlined below, should thus only be interpreted as a working hypothesis for testing purposes. 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/studied. A preference-index I_p for a design related parameter P_d can be defined if and only if I_p can be expressed as a continuous function of P_d:

$$I_p = f(P_d) \tag{16}$$

As the demonstrative samples of preference-index functions in Figure 3 illustrate, it is proposed that at the individual level (describing the preference function of a single parameter), the value range for P_d be from minimum to maximum permissible value and that the preference-index I_p vary from 0 (rejection) to 1 (maximum preference).

4.5 Is Weighting Necessary?

Preference-indices are defined at individual parameter level. However, a computational convergence strategy necessitates operations involving multiple variables. The conventional approach of multi-criteria evaluation utilizes weighting techniques to deal with this problem. Weighting factors can be interpreted as “global” or “spectral” numeric modification factors that aim to represent relative degrees of criticality/importance in a multiparameter evaluation field. Translated into the terminology of the preference-index, this would imply parameter with maximum I_p values of less than 1 (Figure 4).

This numerical “homogenization” of the complex interaction pattern of multiple design parameters has been criticized (Buckley, 1988). In fact, one should be extremely careful with the application of weighting methods and their implications, since weighting factors can be (and have often been) used in an essentially non-motivated manner. However, in cases where reliable data are available on the integrative experiential indices correlating to dynamic interaction patterns of multiple variables, the use of weighting strategies appears to be justifiable.

For example, if one assumes that the Fanger indices such as *PMV* and *PPD* (cp. Fanger, 1970) are, at least in statistical sense, of some informational and predictive value, then it would be easy to deduce from comfort equations weighting factors applicable to the elements of the complex set of parameters pertinent to the inhabitants' rating of thermal environment. It thus appears that the discourse on the applicability, motivation, and justification of weighting strategies in multi-criteria evaluation methods should not be carried out on a ideological level, but rather be based on the reliability of the domain-specific data and the theoretical soundness of the operational steps that lead to the deduction of weighting factors.

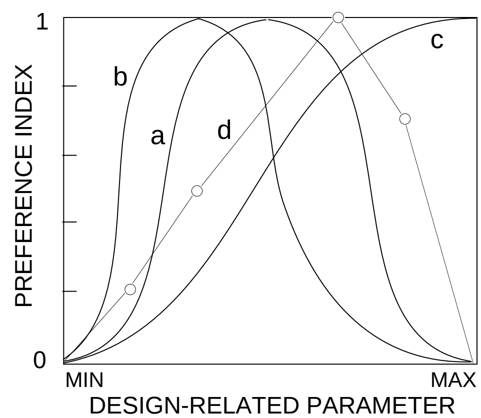

Figure 3. Demonstrative samples of preference-index functions: “Gaussian” (a); “asymmetrical” (b); monotonically increasing (c); and “discrete” distribution (d).

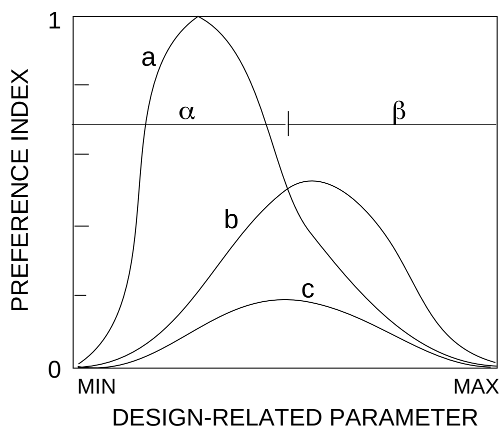

Figure 4. Demonstrative illustration of dominance relations of weighted preference functions. (In range α parameter *a* dominates parameter *b*, i.e., incremental changes of parameter *b* have priority. In range β parameter *b* dominates parameter *a*, i.e., incremental changes of parameter *a* have priority.)

The evaluation of the necessity and importance of the application of weighting factors depends on the intended character of the design support environment. In those cases where the notion of an interactively controlled process of parameter modification and an evolutionary emergence of designs is emphasized, weighting factors are probably not essential. They must be considered, however, if the design support environment is expected to provide at least partially automated convergence sequences.

4.6 Flexibility: Temptation and Cost

The minimum requirement to label a computational environment as open, is that changes in a specific parameter (usually referred to as a performance indicator) can be translated into an orderly modification of a set of design-related variables (the reverse operation can already be performed by conventional simulation environments). It is important to mention that, utilizing concepts and methods introduced in this paper (particularly the preference-based convergence strategy), most existing performance simulation programs can already be integrated in this “weak” version of an open simulation environment. However, it is desirable (and the notion of an open simulation environment implies an inherent tendency) to increase further the operational flexibility. Ideally, one would like to activate each and every design-related parameter individually, triggering a readjustment wave propagating throughout the system. However, the implementation of this “strong” version of an open environment represents some major theoretical, algorithmic and (computationally relevant) economic problems.

Table 2. Matrix of design-related parameters and computational formulations for maximum operational flexibility.

Modified Parameter	Responding Parameter					Computational Formulation
a_1	-	a_2	a_3	...	a_n	$a_1 = f(a_2, a_3, ..., a_n)$
a_2	a_1	-	a_3	...	a_n	$a_2 = f(a_1, a_3, ..., a_n)$
a_3	a_1	a_2	-	...	a_n	$a_3 = f(a_1, a_2, ..., a_n)$
...	...	...	...	...	...	...
a_n	a_1	a_2	a_3	...	-	$a_n = f(a_1, a_2, a_3, ... a_{n-1})$

As Table 2 illustrates, to achieve the theoretical maximum degree of freedom in modification of *n* design parameters (defined in terms of an algebraic equation system), *n* concurrent algorithmic formulations of the interactions-scheme of the involved parameter are necessary. This is an extremely difficult task, other than in the case of simple design situations (limited number of parameters) and/or simple (e.g., linear) algorithmic formulations. The situation is particularly problematic in those performance simulation areas where the relevant knowledge-base involves often “heterogeneous” algorithmic approaches (analytical formulations, numeric methods, etc.) or where the performance indicator is the cumulative result of recursive application of computational procedures, such as in time-step oriented (e.g., hourly) formulations. Thus, higher flexibility involves considerably higher “expenses” particularly in terms of system-design investments associated with the anticipation of the permutative configurations of relevant design-related parameters and the logistic accommodation of necessary computational formulations (subject to mathematical feasibility).

5 GESTALT

5.1 Motivation

In the context of the development of application-oriented simulation environments, pure conceptual considerations are not particularly useful. Thus, already the first systematic reflections about bidirectional systems for building performance simulation were introduced in the practical context of architectural daylighting design (Mahdavi and

Berberidou, 1992). Although this earlier study provided a demonstrative “fast-response” module for the computation of 2-point daylight factors and although convergence strategies were outlined in general terms, no working system was demonstrated. The ongoing development of “GESTALT” (A Generative Simulation Tool for Architectural Lighting) is intended to respond to the need for a working system prototype for open simulation environments as a proof of concept and as a test-bed for further improvements.

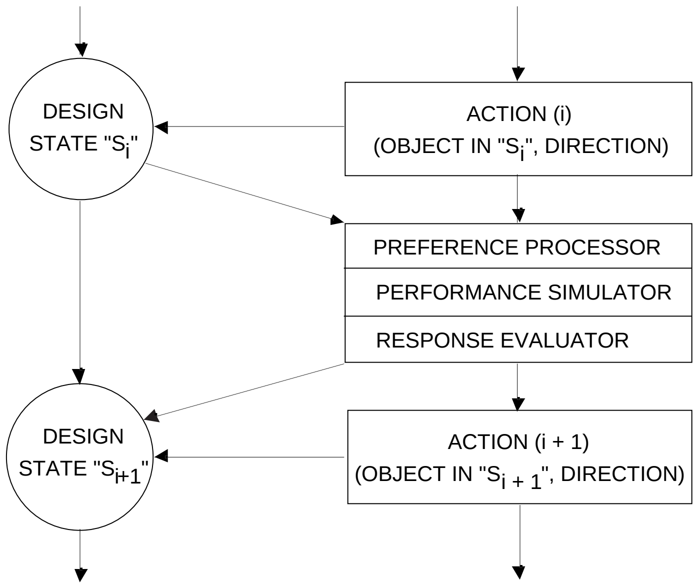

Figure 5. Schematic representation of the structural and procedural elements of GESTALT.

5.2 General Structure

A simplified representation of the general design transformation strategy in GESTALT is given in Figure 5. It involves modular and flexible components facilitating communicative actions and computational operations. .

Table 3. Matrix of Action and Direction as Structure of User Interaction in GESTALT

	“M”		***“D”***	
	+	-	*u*	*d*
v_1				
v_2				
...				
v_m				

It is assumed that desired actions *“M”* (modification of a specific design-related parameter) can be communicated to the system via an interactive user-interface. Assuming $S_i = \{v_1, v_2, ..., v_m\}$ represents the set of design-related variables pertinent to performance simulation at state i, a variable v_j is identified as the object of *"M"* with *"D"* as directional attribute *"u"* or *"d"* (cp. Table 3). Not represented in Figure 5 and Table 3 are other elements of the user operation repertory such as preference modification and selective variable activation/deactivation.

Table 4. Interpretation key to the *DLQ* values

DLQ =	-2	-1	0	1	2
"Subjective" evaluation	very poor	poor	neutral	good	very good

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 control the order of parameter in $S'_i = S_i \setminus \{v_i\}$ onto which modifications of v_i are mapped. This involves the initial identification of a parameter in S'_i with $I_{p,max}$. Performance simulation involves the computation of the v_i based on the current state of S'_i. The related knowledge base currently implemented for this purpose, is described in section 5.3. The response evaluation routine compares the intended and the resulting direction of changes in v_j and examines if alternative responding variables in S'_i 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 S_{i+1}.

5.3 The Knowledge-Base

Extensive statistical analysis of occupancy evaluation of the daylight quality in residential buildings (DIN 5034) (Seidl, 1986) implies a significant correlation between the average value (DF_{2p}) of the daylight factors at two reference points in a room (Figure 6) and the subjective occupational evaluation (DLQ) of the daylight quality (Table 4):

$$DLQ = 3.2 \log DF_{2p} + 6.6 \qquad [-] \qquad (17)$$

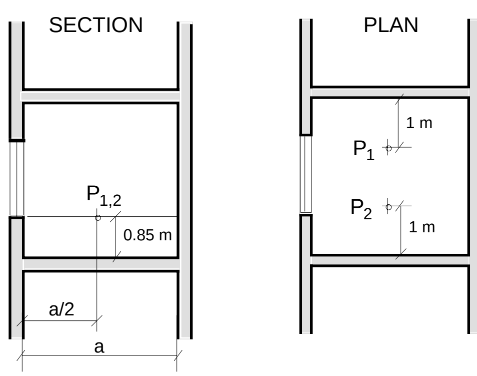

Figure 6. Reference points for the evaluation of daylighting (after DIN 5034).

Using a daylighting simulation program (Mahdavi and Berberidou, 1991), daylight distribution patterns were generated for a significant number of rooms with different proportions. Based on the simulation results, a regression analysis was performed (Mahdavi and Berberidou, 1992) which revealed a significant correlation between the average values for the two-point daylight factors and a set of design variables:

$$DF_{2p} = F_d \cdot \tau \cdot [R_g \cdot (9.33+32.7 \cdot \rho_m) - (0.037+4.57 \cdot R_g) \cdot d \cdot w^{-1}] \qquad [\%] \qquad (18)$$

where F_d is dirt depreciation factor, τ glazing transmittance, R_g ratio of the glazing area to room floor area, ρ_m room average reflectance, d room depth, and w room width.

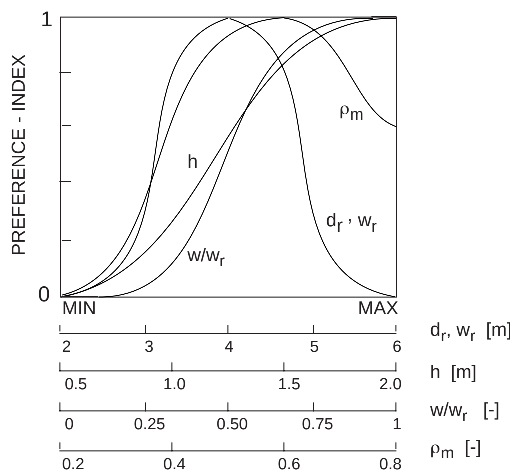

Figure 7. Preference-indices for five daylighting design-related variables implemented in GESTALT. (d_r, w_r: room depth and width, h: window height, w/w_r: window width to room width ratio, ρ_m: room average reflectance).

Theoretically, this algorithm can be substituted with any other (more complex) simulation module that could perform a similar data transformation. However, the formulation in Equation 18 provides, due to its simplicity, the maximum flexibility (cp. Table 2), required for the “strong” version of the open simulation environments.

Table 4 has been utilized in the current GESTALT version to define a preference-index $P_{I,DF}$ for the performance indicator DF_{2p} (for DF_{2p} values up to 7.5%):

$$P_{I,DF} = (DLQ + 2) \cdot 5^{-1} \qquad [-] \qquad (19)$$

The initial definition of the preference-indices for the design-related parameter in the current GESTALT version is illustrated in Figure 7. This definition is partially based on the result of occupational studies in 582 residential units (cp. Figure 8) that address the inhabitants' preferences concerning the size/dimensions of windows (Klingenberg and Seidl, 1978; Seidl, 1986).

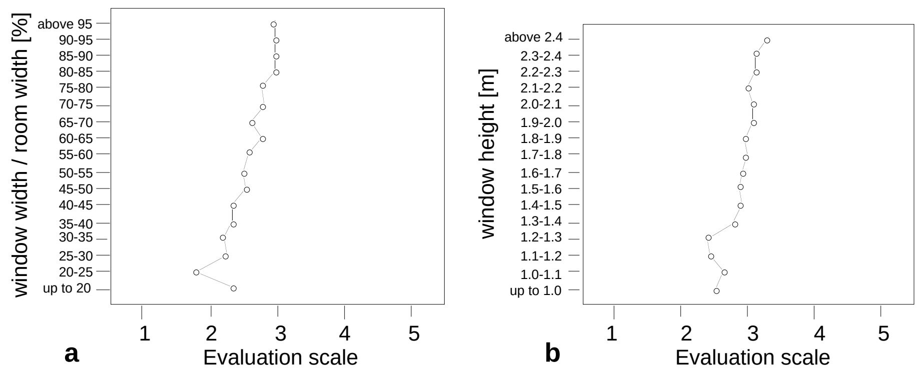

Figure 8. (a) Occupancy evaluation of the window width (as related to room width) in residential buildings; (b) Occupancy evaluation of the window height in residential buildings (after Klingenberg and Seidl; 1978).

5.4 A Demonstrative Sequence

Figure 9 illustrates “snapshots” selected out of a demonstrative sequence of design states created during a session with GESTALT. The sequence starts with the initial design definition and illustrates its consequent evolution triggered by the increasing DF_{2p}-values and guided by the dynamic interplay of preference-indices. Although not demonstrated in this sequence, GESTALT allows at any time for the reversal of operations, redistribution of degrees of freedom (lock operations) and redefinition of preference-functions. To demonstrate the outline of a potential user-interface for open simulation environments, each frame in Figure 9 includes a simple geometric design representation, the current state of attributes of the design- and performance-related variables (represented in terms of proportional scales), as well as the current state of corresponding preference-indices (including the mean preference-index for all variables involved).

The particular evolution trajectory of Figure 9 was motivated by the preference-index distributions illustrated in Figure 7. Values of F_d, τ, as well as the room area were locked throughout the session. Minimum and maximum values were assigned to the relevant design-related variables (room depth and width, window width and height, room average reflectance) as well as to the window area. The sequence illustrated in this figure demonstrates various distinctive evolutionary phases. A complex distribution of actions on various parameter transformed the initial design state *S-1* whereby initially the preference-indices of the design-related variables increased with higher DF_{2p}-values. The design state *S-4* represents a turning point, in that further increase in DF_{2p}-value resulted in lower preference-indices of the design-related parameter. It represents, thus practically the “most preferable” configuration of design-related parameter. Given the underlying definition of preference-indices, this configuration (and the corresponding DF_{2p}-value) represents a unique design state as its emergence is independent of the initial state of design.

Design state *S-6* represents the maximum achievable DF_{2p}-value for the given range of design variables. It can also be seen as the unique final stage of the convergence, as its attributes are also independent of the initial design state. However, the “intermediate” values of DF_{2p} are not uniquely related to specific configurations of design-related

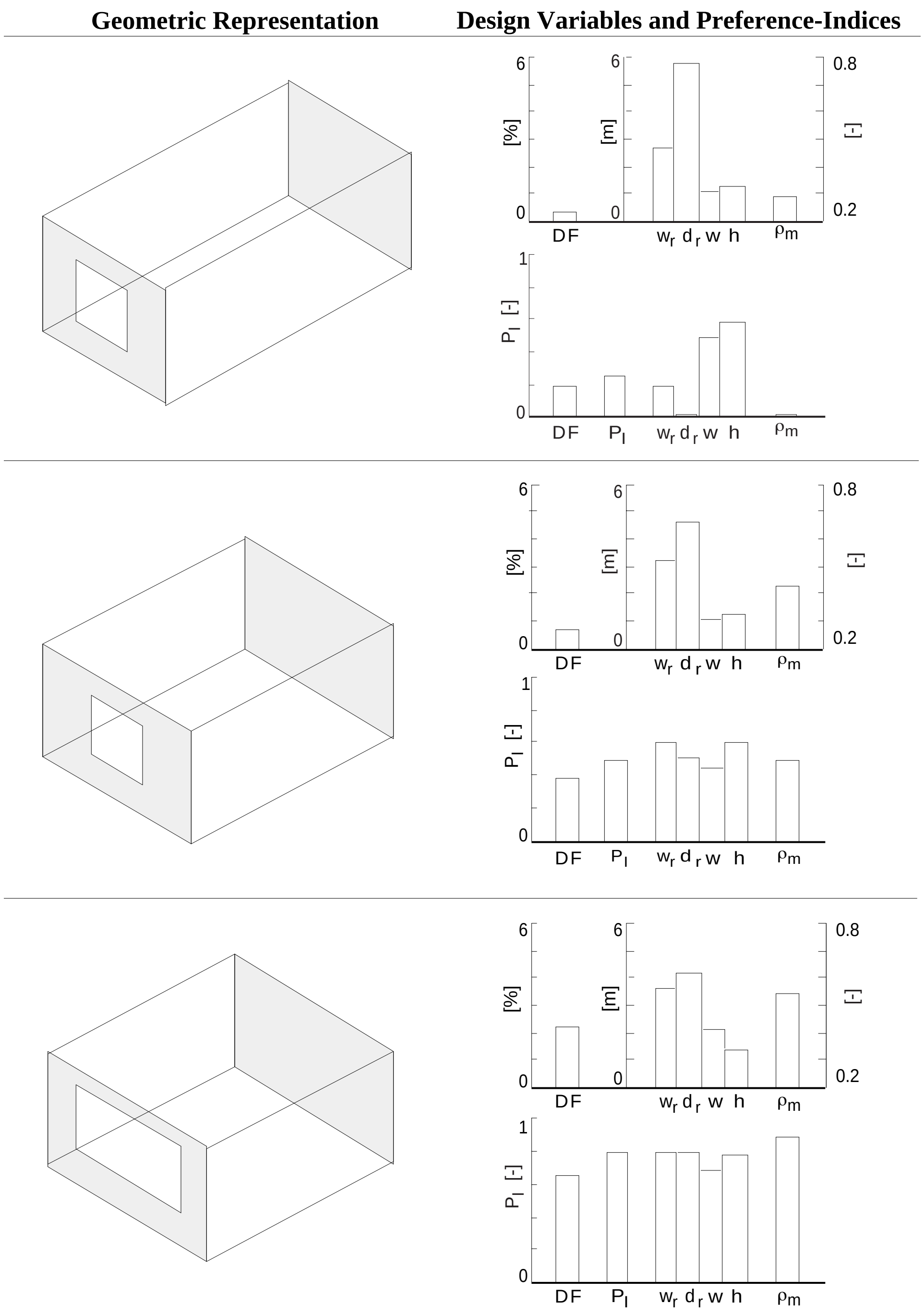

Figure 9a. Selective Illustration of a Design Sequence using GESTALT.

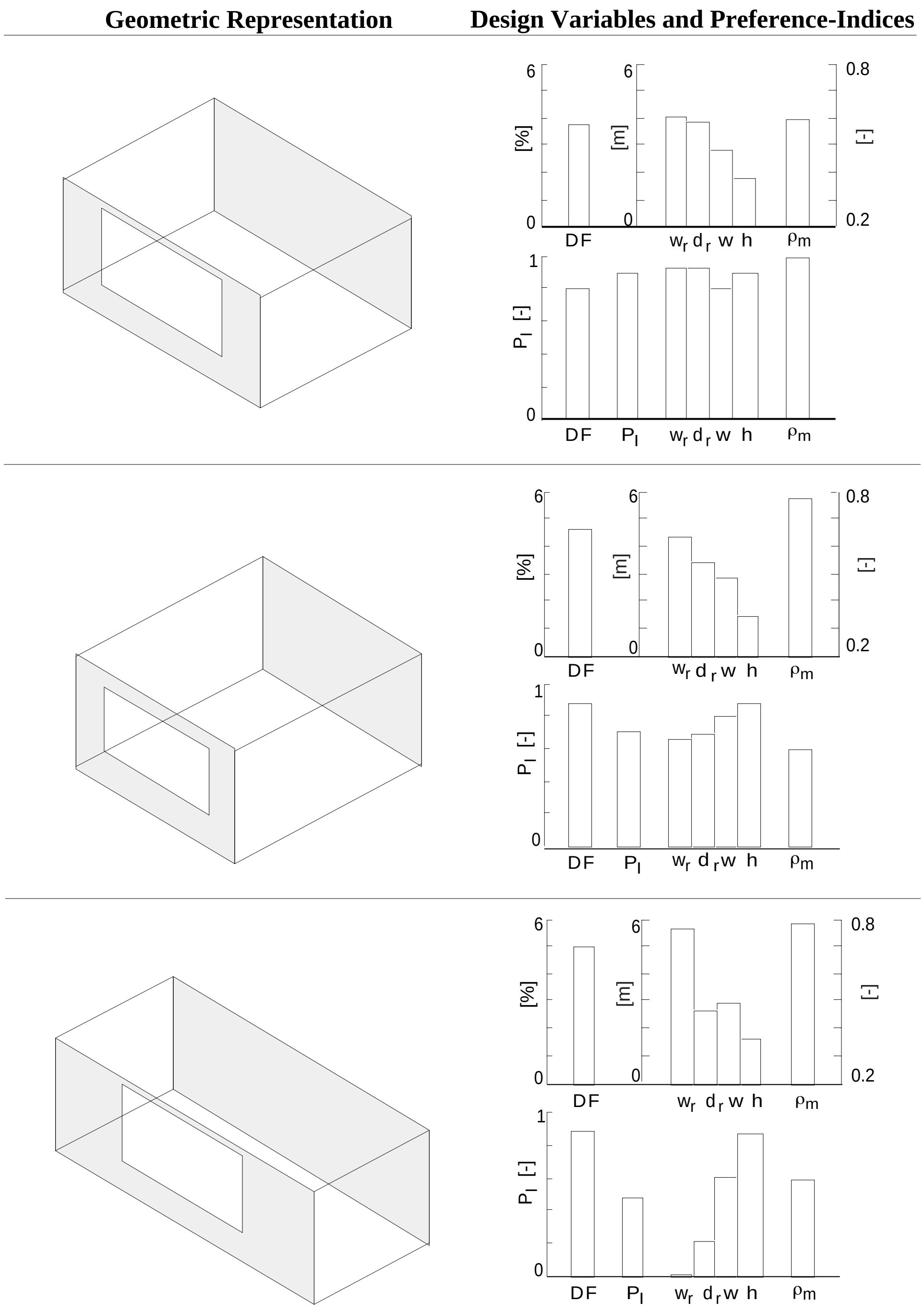

Figure 9b. Selective Illustration of a Design Sequence using GESTALT.

parameters. These intermediate relations between design configurations and performance states depend on the starting point of the sequence. However, since the currently implemented computational kernel of GESTALT allows for the "strong" operational mode of the open simulation environment, it is possible to derive for any discrete DF_{2p}-value, the most "preferable" attribute of the design-related variables. Also these configurations may be regarded as unique, subject to the invariance of the initially defined preference functions.

6 Conclusion and Future Directions

The concept of open simulation environments was introduced as a new multidirectional approach to computer-aided performance modelling. To cope with the related problem of ambiguity, a preference-based formalization of evaluation criteria for design elements and performance indicators was introduced facilitating the dynamic control of the different degrees of freedom of relevant design variables during the interactive design process. A general structure for open simulation environments was proposed. A prototypical realization of an open simulation environment (GESTALT) for simultaneous treatment of daylighting-related design and performance variables was demonstrated. To document the potential for an interactive design and evaluation process and the related preference-based convergence strategies in the GESTALT environment, preliminary results of a demonstrative session were presented and discussed.

Future studies will involve the integration of existing/new complex performance applications in an initially weak version of an open simulation environment. The feasibility and the potential of dynamic multidirectional formalizations in the relevant knowledge-domain (building performance, architectural physics) will be explored toward the development of strong versions of an open simulation environment. Studies will be carried out to define effective strategies/frameworks for the communication and formalization of preference functions. Also, efforts will be directed toward the development of user-interfaces appropriate for the interactive control of convergence processes and for the real-time geometric, symbolic and numeric representation of the design states and their modifications.

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