Simulation-based Performance Evaluation as a Design Decision Support Strategy: Experiences with the "Intelligent Workplace"

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This paper presents the application of geometric modeling and various performance simulation tools in architectural design, highlighting their respective impact on the design decisions made in the process. Based on the experiences gained in this process, a critical review of the potentials and problems of current simulation tools and simulation-based design decision-making strategies is offered. Particular attention is given to the crucial dialectic of process and tool in supporting knowledge transfer and decision-making in building design. Suggestions for improvements to current performance simulation tools and future alternative building simulation environments are discussed.

1. INTRODUCTION

Increasingly sophisticated tools are being developed to support the design decision-making process both in terms of expressing and communicating aesthetic and formal intentions as well as simulating the environmental performance aspects in architectural design. However, there are still perceivable barriers in the consistent and effective use of performance simulation tools in practice, particularly in the early conceptual design stage. Two major attributive factors can be identified. First, many of the existing computer simulation tools are conceived and developed for design verification purposes during the "back-end" of the design process. Hence, they require fairly detailed input information which is often unavailable at the early stages of the design. Second, the functionality of these tools reflects the traditional notion of the design process whereby formal and aesthetic decision-making and the fulfillment of building performance requirements (e.g. thermal, lighting, acoustics) are regarded as discrete and sequential rather than concurrent activities. Such approaches have repeatedly shown to result in unsuccessful and costly design solutions. Especially in view of the increasing complexity of buildings, it is necessary to review the effectiveness of the traditional design process and explore alternatives. In short, the traditional design process needs to be critically reviewed in view of the potential of simulation-based decision-making while the simulation tools have to be re-examined to address new requirements in the process.

2. CBPD "Intelligent Workplace"

2.1 Project Background

To demonstrate the exploratory efforts in implementing simulation-based performance evaluation in design, the process of conceptualizing and developing the design of the Center for Building Performance and Diagnostics "Intelligent Workplace" (CBPD-IW) project at Carnegie Mellon University, Pittsburgh, Pennsylvania, is presented. The building is to be constructed on the rooftop of an existing building on campus at Carnegie Mellon University (Figure 1). This project is sponsored by the Advanced Building Systems Integration Consortium (ABSIC), a university-industry partnership whose primary focus is to anticipate and meet the requirements of future "intelligent" workplaces. Its goal is to achieve higher quality environments, occupant comfort and satisfaction, as well as rationalized integration of advanced building systems to sustain a human ecologically adequate work environment while improving economic and energy effectiveness (Hartkopf, et al. 1986a, 1986b).

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From the outset, a fairly exhaustive search for the most innovative building systems and their performance capabilities in North America, Europe and Japan (Hartkopf, et al. 1993) was conducted. Periodic design brainstorming sessions were held to explore various potential avenues of design, involving leading researchers and practitioners from building related disciplines, utility company representatives as well as product manufacturers who are members of ABSIC.

Such exercises have been beneficial in assembling a knowledge base of concepts, critical research findings on building and occupant related issues, and innovative building systems available or under development. The process also raised many pertinent questions, especially with regard to new ideas of system integration for better performance, energy and ecological conservation, and the need to evaluate these potential options at the conceptual stage.

The conceptual foundation of the simulation exercises is based on the adoption of an integrative approach to performance evaluation in building design (Mahdavi and Lam 1991). The following sections describe the various modeling and simulation tasks that were undertaken primarily during the early conceptual design stages of the project, focusing particularly on studies that have yielded a definite impact on the design decision-making process. Tools that are fairly well-established and commonly used in practice are employed where available, and occasionally augmented with prototypical simulation programs that have been developed within CBPD.

2.2 Geometric Modeling

Spatial organization and management is one of the prerequisites for effective systems integration. The CBPD-IW has been modeled using a 3-D CAD program which facilitates the visualization of spatial disposition of the different building systems (e.g., structural configuration, curtain wall system with integrated external shading devices, etc.) and their relationships to each other as well as with the interior layout (Figure 2). This has proven to be a tool of critical importance for the discovery and resolution of spatial conflicts particularly with regard to achieving a rationalized integration of many innovative building systems introduced in this project, such as the integrated structural/raised floor system and the underfloor HVAC and telecommunication network infrastructure. Figure 3 illustrates one case where spatial conflict between the structural floor system and the HVAC ductwork was identified and subsequently resolved through the CAD modeling process.

2.3 Energy Simulation

Preliminary simulative investigations showed the significant importance of some fundamental questions of determining building envelope configurations in terms of geometry and elemental composition. Such decisions cannot be made without critically reviewing and ensuring a reasonably reliable micro-climatic database.

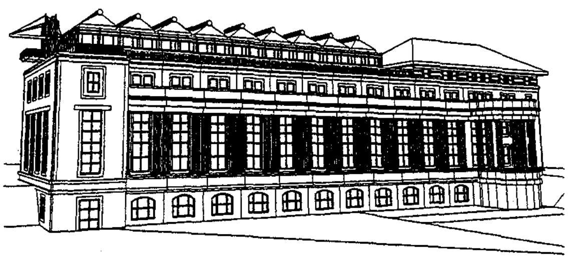


Figure 1 The Center for Building Performance and Diagnostics "Intelligent Workplace" (CBPD-IW) to be constructed on the rooftop of the Margaret Morrison Building at Carnegie Mellon University

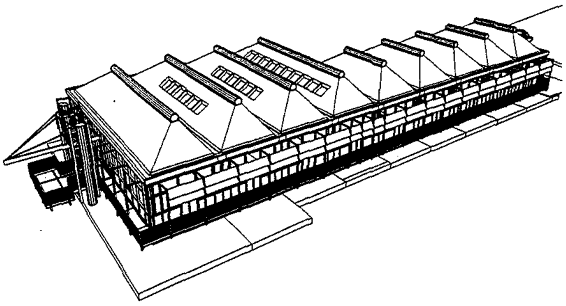


Figure 2 CBPD-IW: Detail view of enclosure showing roof configurations and innovation external shading/light redirecting devices

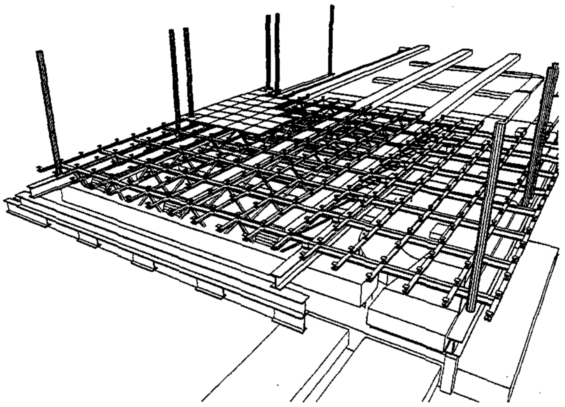


Figure 3 CBPD-IW: Identification of spatial conflict between the structural floor system and the HVAC ductwork through CAD modeling

Figure 4 illustrates the significant variance in diffused and direct solar irradiance on a south slope roof surface between using a simplified clear sky model and a more sophisticated energy simulation program with actual local Pittsburgh weather data (DOE-2 1989).

Using the more detailed micro-climatic database, an assessment of appropriate roof geometrical configuration for effective load management and solar energy utilization was conducted. The study showed that on an annual basis, the total irradiance of either roof configuration did not vary significantly. In this context, the preferred solution depended largely on the solar energy utilization strategies envisaged for the CBPD as indicated in Figure 5.

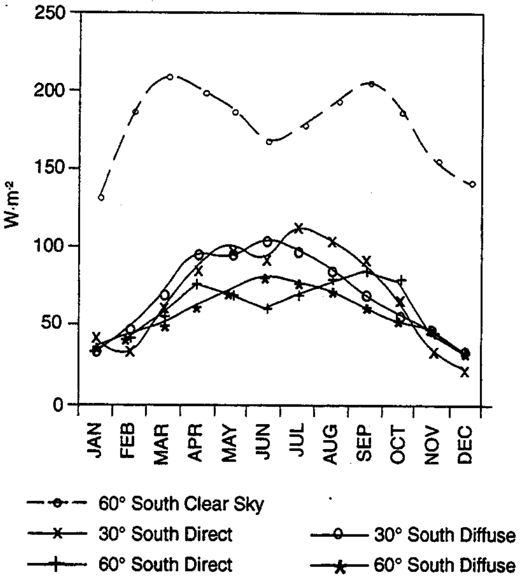


Figure 4 Diffuse and direct components of the solar irradiance incident on south sloped surfaces (30° and 60°) based on extensive hourly simulation, compared with the result obtained by applying a simple clear sky model for direct component on a 60° pitch south facing surface

Investigations were also conducted to test the performance of different glazing specifications on the overall loads of the building. In one study, two glazing products (Table 1) were compared in terms of their impact on the overall energy consumption. As shown in Figure 6, the change in overall energy consumption is greater for the north office area than the south office area. This phenomenon cannot be understood unless the interaction pattern of the building systems are comprehensively considered. In this specific case, load balancing is facilitated by the proposed closed-loop water to air heat pump system in the north office area as opposed to the all air HVAC system in the south office area. The application of the sungate-azurlite glazing, with its lower shading coefficient, in the south office area reduces the cooling load but this is substantially offset by the increase of the heating load as a result of the reduction of solar gain during the heating season. However, with the load balancing mechanism in the north office area, the reduction of cooling load has not been offset by the increase of the heating load to a similar extent. These results demonstrate clearly that the change of one design parameter (in this case, the glazing system properties) does not necessary yield the "intuitive" outcome because of the complex interactive pattern with other building systems and components involved.

Glass Type	Daylight			Total Solar		U-Value ($W \cdot m^{-2} \cdot K^{-1}$)		S.C. (%)
	Trans (%)	Reflect (%)		Trans (%)	Reflect (%)	Winter Night	Summer Day	
		out	in					
Sungate100 (2)	75	13	13	50	19	1.76	1.82	0.68
Sungate 100(2) Azurlite	60	10	11	26	7	1.76	1.93	0.41

Table 1 Performance data of selected glazing systems

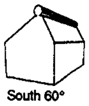
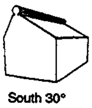
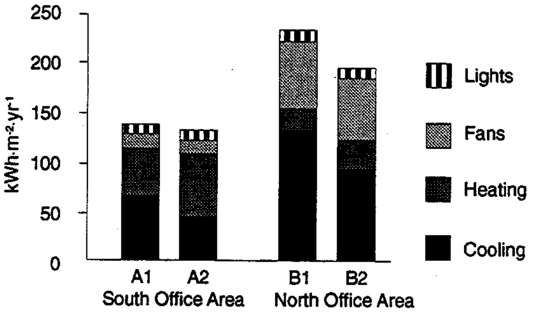
	Passive Solar	Active Solar (Photovoltaics)	Active Solar (Collection)⁺	Active Solar (Cooling)
 South 60°	+	-	+	-
 South 30°	-	+	-	+

Figure 5 Example of a local technical decision making platform based on energy simulation data (relative evaluation of two roof configurations for the proposed CBPD building with regard to their effectiveness for different solar energy utilization strategies. (⁺ for heating purposes)



A1, B1: Sungate glazing; A2, B2: Sungate-Azurlite glazing

Figure 6 CBPD-IW: Synergistic impact of mechanical systems (with and without load balancing capabilities) and glazing specifications on energy use

So far, none of the energy simulation programs provide the facility to determine another important design criterion in terms of internal surface temperatures and the associated mean radiant temperature which is critical to the evaluation of thermal comfort.

For this purpose, a supplemental computational procedure to the DOE-2 program was formulated to evaluate the impact of glazing systems integrated with an innovative water-mullion system proposed for the CBPD-IW and to be manufactured by the a curtain-wall manufacturing company in Germany. One of the main purposes of implementing this system is to provide a mechanism for load shifting/load balancing within the building in response to the changing outdoor climatic conditions. Furthermore, in winter, the circulating warm water helps to maintain higher surface temperatures on the glass thus avoiding potential surface condensation, radiant asymmetry and provide a more uniform air temperature distribution vertically in the space. In summer, the circulating water also serves as a source of heat removal, particularly from solar radiation falling directly on the water-filled mullions. Figure 7 shows the simulation results of the mean radiant temperature distribution for a typical space in the CBPD-IW.

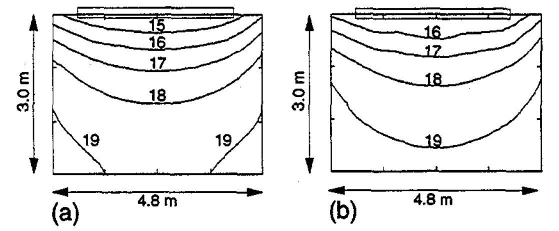


Figure 7 Schematic plans with comparison of mean radiant temperature isolines in °C for (a) Azurlite glazing, and (b) Azurlite glazing with a water-filled mullion system (assuming water temperature = 30°C, outdoor air temperature = -15°C, indoor air temperature = 20°C)

The simulated overall energy budget for the CBPD-IW was compared with two other office buildings in downtown Pittsburgh (B1 and B2 in Table 2). It is important to note that any energy consumption comparison has to be made with care as there could be critical differences between buildings in terms of the massing and shape of the building, the area and visible transmittance of the glazing as well as HVAC system configurations.

Building	Enclosure area / floor area	Glazed area / floor area	Glazing visible transm.	kWh·m⁻² per year	Average HVAC zone size
B1	0.36	0.23	12%	189	91 m²
B2	0.37	0.2	14%	252	91 m²
CBPD-IW	1.9	0.55	61%	204	62 m²

Table 2 Comparison of annual energy consumption with respect to multiple performance parameters

Although the energy budget for the CBPD-IW is slightly higher than B1 but lower than B2, the design criteria is substantially different from the latter "conventional" office buildings with respect to a smaller HVAC zone size for providing more flexible indoor environmental control, as well as increased glazing/floor area ratio and higher visible transmittance for improved daylighting and visual contact with the outdoor environment.

2.4 Lighting Design

The motivation for lighting design for the CBPD is to maximize utilization of available daylight and investigate its integration with electrical lighting. Besides considering the impact of the roof geometry on thermal loads as discussed earlier, studies were also conducted to determine the feasibility of providing skylights in both the north and south office blocks (Figure 8). Early daylight simulation studies were conducted concurrently with energy simulation within the DOE-2 environment. This offered preliminary insight into the synergistic impact on energy efficiency and daylighting illuminance levels, which was limited to just two data points per zone.

Subsequently, a dedicated lighting simulation program was used to further explore the effects of various fenestration configurations and innovative shading devices (e.g. lightshelves) on distribution of available daylight. An example of a study was to determine the correlation between geometrical attributes of lightshelves with different clerestory heights and the uniformity of illuminance distribution expressed in terms of a uniformity index (DIN 5034).

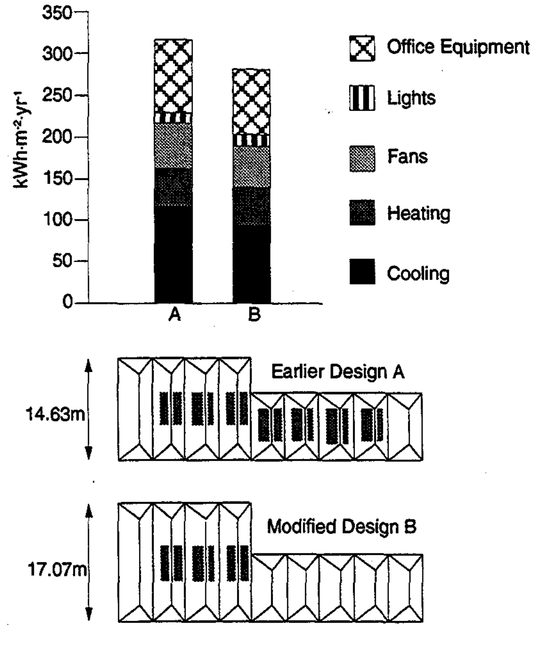
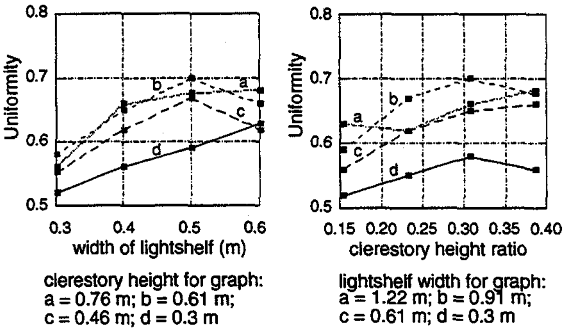


Figure 8 Evaluation of alternative schematic design proposals based on simulation of annual energy consumption

As shown in Figure 9, the study reveals that there is no linear correlation between the uniformity index and the width of lightshelf or with the clerestory ratio (defined as clerestory height/total height of the opening). For the CBPD-IW design, the daylight illuminance of the simulated configurations exceeded the target value. Given the controlling structural grids, appropriate ranges for clerestory heights and width of lightshelf as well as internal and external shading strategies were derived to respond to requirements of uniformity and to provide user-based control.



clerestory height for graph:
a = 0.76 m; b = 0.61 m;
c = 0.46 m; d = 0.3 m

lightshelf width for graph:
a = 1.22 m; b = 0.91 m;
c = 0.61 m; d = 0.3 m

Figure 9 Uniformity index plotted against the width of the lightshelf and height ratio of clerestory

2.5 Acoustical Design

Acoustical simulation studies were also conducted to investigate the choice of materials and surface treatment for appropriate reverberant fields in the CBPD-IW. Literature provides corresponding orders of magnitude for reverberation times which relate to the criteria of speech intelligibility as well as noise reduction.

As a preliminary indicator, reverberation times were simulated for both the open office configuration and individual offices for non-treated/non-occupied as well as non-treated/occupied conditions. The results demonstrated a necessity for additional absorption to achieve the desired reverberant field (Figure 10).

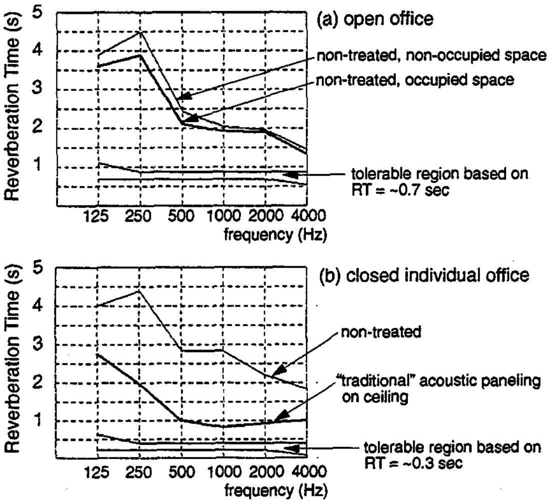


Figure 10 Simulated reverberation times for both the open office and closed individual office for non-treated/non-occupied as well as non-treated/occupied conditions

A "morphological" study of the available and desired absorptions provided by "common" interior surface treatments indicated that they do not adequately meet the varying frequency-dependent absorption characteristics requirement (Figure 10b and Figure 11). Clearly, an integrative treatment of the interior components is necessary to modify the reverberant field. Figure 11 also shows the results of a second "morphological" study whereby two products were selectively combined to achieve a better approximation of the desirable absorption characteristics as well as an increased absorption potential in the critical frequency range of 500 to 2000 Hz.

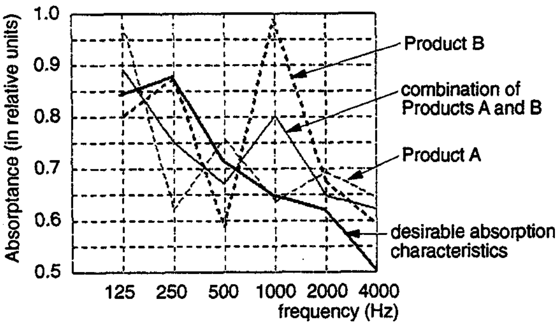


Figure 11 The morphological study of the frequency characteristics of the desirable absorption in the open office area using Products A and B

The above study demonstrates clearly the lack of adequate simulation tools particularly for extended parametric search processes for identification of appropriate component configurations and material properties. Efforts are being directed toward the development of tools appropriate for those purposes (Mahdavi 1993a).

3. Limitations of Current Tools

Despite having established an elaborate geometric database in the CAD model, it has not been possible to transfer or share this information across the various performance simulation domains to evaluate the CBPD-IW design. A separate geometric model, with the associated construction specifications, has to be created for the energy simulation. Likewise, the enclosure components have to be redefined for the dynamic hygro-thermal analysis to evaluate potential interstitial condensation and moisture accumulation over a typical meteorological year. There are also a host of other complex and dynamic enclosure components such as electrochromic, photochromic, prismatic and holographic diffractive glazing that were considered for application in the building but their performance could not be determined by existing simulation tools.

Besides exploring the impact of enclosure component specification on energy utilization, a dynamic shading device was proposed as an integral part of the enclosure system, intelligently controlled according to daylight availability and illuminance requirements in the workspaces for the purpose of studying daylight-artificial lighting interface concepts. None of the lighting design simulation tools was able to model this design feature adequately. Another design intention, also partially motivated by energy conservation, was to determine the feasibility of natural ventilation under favorable climatic conditions (rather than simply adopting the traditional approach of fully relying on mechanical systems for space conditioning). The DOE-2 program which is perhaps one of the most comprehensive energy analysis tools available today, does not cater for this design option. Interestingly, the genesis of the program itself reflects partially the bias towards the HVAC-based thermal conditioning practice in non-residential buildings in the United States.

Currently, support tools are utilized around the accepted design process and standards, whereby CAD programs tend to emphasize the notion of design as the production of drawings and documents while simulation programs focus on design verification. Computers are not thought of as a tool to enhance the design process as a whole. The current design process has seldom been creatively exposed to the innovative potential of computer-aided design support tools.

4. Evolving CAAD Environments

4.1 Integration and Autonomy

In addressing the inadequacies of existing design supporting tools, there seems to be certain general consensus with regard to the conceptual requirements of future computer-aided architectural design supporting systems. It is well acknowledged that building design is an integrative process involving participants from different disciplines. Therefore, design tools must respond to the necessity for integration across the various performance domains.

Associated desirable features should include mechanisms for reducing or eliminating data input replication (as encountered in the CBPD-IW design) to meet various idiosyncratic data structure requirements inherent to each performance simulation tool as well as providing intuitive user interfaces that are responsive to the manner in which designers operate in practice.

To realize integrative simulation environments, many of the current major research efforts revolve around the development of so-called intelligent CAD systems which normally comprise a geometric modeler (with an attached hierarchical database for the semantic representations), which is then coupled with numerous extensive knowledge bases created for separate design domains for building performance evaluation. The central problem of these approaches is the issue of complexity. Conventional geometric representations utilized in common CAD systems and the corresponding data structures do not allow for intensive data transfer processes and cannot maintain the consistency of design representations in a multi-instance decision-making environment. The hierarchical path of data exchange between performance "agents" have created informational "bottleneck" conditions where central control or "conflict-solving agents" of inherently limited capacity and repertoire are incapable of assuring convergence and representation coherency.

Recent CAD research tendencies appear to respond to this circumstance by exploring the potential of object-oriented building data models in conjunction with distributed (non-hierarchical) information exchange routes. In the domain of performance simulation, these tendencies imply the need for integrated representations of multiple-expert views with autonomous decision-making agents as opposed to the conventional sequential array of different representations with the need for data conversion and translation routines. A recent research effort in CBPD addresses this point by exploring the potential of the synthesis of a "high-level" geometric modeler with a structurally homologous nodal analysis environment suitable for the representation of energy transfer processes in buildings.

4.2 "Two-way Approach and Open Simulation Environments

The existing simulation tools for the evaluation of the CBPD-IW design did not effectively support the convergence process towards design solutions which had to be approached through extensive (mostly "blind") search. This is due to the "mono-directionality" of the conventional tools which require contextual, formal and semantic information and transform them into values for performance indices (Table 3). In this sense, these procedures can be considered as "one-way" (or mono-directional).

From the designer's point of view, it would be advantages to provide a tool that can 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. The representation of the dynamic link between performance indicators and their "design correlates" (i.e. geometric configurations, materials and system specifications) would increase the effectiveness of computer-aided simulation tools in supporting design decision-making. This approach can potentially reduce the number of parametric iterations during the design development stage and perhaps more importantly, this would enhance the designer's knowledge and experience with regard to the interdependencies and complex patterns of the different parameters involved in design.

Contextual	weather data (temp., RH, solar radiation, etc.)
Formal	geometric configuration, orientation
Semantic (or Attributive)	dynamic material properties (e.g. moisture related thermal conductivity, moisture distribution mechanism), sound absorption coefficient, etc.
Performance Indices	condensation risks, energy conservation, component integrity, daylight distribution, noise level, etc.

Table 3 Categorization of parameters for building performance simulation

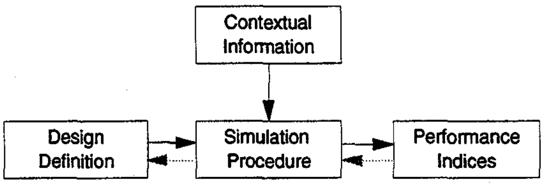


Figure 12 Schematic illustration of the conventional simulation process versus a "two-way" approach

To this end, a two-way inference approach as a new paradigm for computer-aided design has been proposed (Figure 12). This approach was initially tested within prototypical daylighting and acoustical simulation domain (Mahdavi and Berberidou 1993, Mahdavi 1993a). Further development of this concept was conducted to expand the notion to a multi-directional approach within an "open" simulation environment (Mahdavi 1993b). While these newly developed prototypical design tools have not been directly applied to the design of the CBPD, it is nonetheless important to expound further the underlying concepts and problems.

The notion of an "open simulation environment denotes a design support tool that facilitates the interactive and simultaneous modifications of properties and the observation of changes in various context, design and performance variables. 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/representation. From the human ecological point of view, this also responds to the desirability of an iterative-adaptive approach to complex design tasks.

As it has been alluded to and demonstrated earlier, good integrated design solution may not necessarily be achieved through simply aggregating a series of "unique" deterministic criteria in each performance domain. There are often certain trade-offs that have to be negotiated. To meet this requirement, a preference-based approach is proposed for the 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 performance indicators. Operational preference scales can be defined for any design-related variable if and only if an "orderly" (functionally expressive) 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 beyond the scope of this paper to further elaborate on this concept but interested readers may refer to Mahdavi 1993b for a detail description of the model.

5. Dialectic of Process and Tool

The experiences gained from the application of simulation tools for the evaluation of design of the CBPD confirm many of the observations and comments that have been articulated in the building industry for a long time. The building industry is a fragmented industry and the building delivery process has invariably remains as a discrete and sequential set of activities. This state of affairs is the result of a historical evolution driven by many factors, one of which might be the necessity to organize the activities for the purpose of establishing a professional fee structure that is commensurate with the scope of work and level of accountability or responsibility. However, within the context of rapid changing technologies, production processes as well as knowledge explosion, the existing framework no longer seems effective or capable of meeting the increasingly complex demands associated with the creation of the built environment. Superficial attempts to patch the current decision-making approaches may lead to miscommunication of intentions resulting in unsatisfactory solutions which are costly to remedy in terms of time and resources.

The capabilities of tools are expanding but they still fall short of anticipating or challenging the very logic of the rather static processes they are supposed to support. It is understandable that processes tend to be more resilient to structural changes because of their inherent communicative nature, evolved over time through general acceptance and consensus. Notwithstanding the importance and value of tradition, it is eminently necessary that a co-evolutionary development of process and tool be encouraged, in that the critical evaluation of the shortcomings of the existing process implies the need for enhanced tools and the introduction of new technologies triggers reevaluation of and improvements in the existing structure and process (hierarchy, labor division, decision making process, economical and environmental orientation, etc.). Significant qualitative progress toward advanced knowledge-transfer mechanisms in the building delivery process are not likely unless efforts are made to provide the necessary conditions for a positive co-evolutionary cycle of process and tool dialectic.

While many tools exhibit deficiencies due to their rigid adherence to existing process structures, there are occasions where tools have the *a priori* intention or the *a posteriori* effect of introducing new procedural alternatives. In these instances and given "favorable" conditions (strong qualitative advantages of new tools, the dynamic logic of competition, insight in structural problems of existing processes, etc.), a true co-evolutionary development can occur (Mahdavi and Lam 1993).

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