SYNCHRONOUS GENERATION OF HOMOLOGOUS REPRESENTATIONS IN AN ACTIVE, MULTI-ASPECT DESIGN ENVIRONMENT

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ABSTRACT
We introduce SEMPER, a computational tool for active and multi-domain design and evaluation support. We demonstrate SEMPER's unique synthesis of three fundamental system requirements: 1) a methodologically consistent performance modeling approach through the entire design process; 2) a structurally homologous building representation across multiple domains; and 3) a "preference-based" performanceto-design mapping technology.

1. INTRODUCTION

Insights into the importance of energy modeling in the building design phase have not yet resulted in sufficient and systematic use of modeling tools in practice (Augenbroe and Winkelmann 1991, AIA 1987). Many explanations have been offered (Mahdavi and Berberidou-Kallivoka 1993, Augenbroe 1992, Brown 1990, Mathews and Richards 1989), indicating a noteworthy consensus as to the nature of the contributing factors (material and time implications, problematic user-interfaces, inefficient data communication structures, poor integration within general CAD systems, absence of "active" design support).

In this context, this paper entails a twofold contribution:

- At a *paradigmatic* level, requirements will be discussed that, if met by design support environments, could contribute to the removal of a number of (system-immanent or "endogenous") obstacles to the widespread use of computational design generation and evaluation methods in practice. The discussion explicitly involves the critical review of the traditional responses to the following questions: a) what are the appropriate levels of design representation for evaluation and feed-back purposes at different design stages? b) What are the possible strategies for a structurally "seamless" containment of performance simulation in the general design development environment? c) What are the promising methods for "active" design support?
- At an *operational* level, the development and functionalities of a specific computational (building) design and (energy) simulation tool (SEMPER) is the central point of discussion (Mahdavi 1995a). Conditioned by the above mentioned paradigmatic orientation, this prototypical development provides a proof of concept and test-bed for synchronous generation of (topologically, configurationally, and algebraically) homologous representations in an active, multi-aspect design environment.

2. CONCEPTUAL BACKGROUND

2.1 Introductory Remark

In the following, we discuss some observations, concepts, and arguments to help better understand the motivational background of the implementation efforts which will be presented later (cp. section 3). However, we do not imply that the implementation was "causally" resulted from the conceptual discussion quasi in the manner that a software product would result - at least in the ideal software engineering scenario - from a system specification. Rather, the process of conceptual refinement and system development has been an iterative one. Thus, as we focus on certain ideas that, *de facto*, triggered explorations in system development, we maintain that the significance of some other concepts became clear only *ex post facto*.

2.2 Design Process and Representational Resolution

In the past, various computational design evaluation concepts have been suggested (and partially implemented) to cater for the dynamic (temporal) transitions in the design process and the associated changes in the quantity of available information. A traditional approach appears to rely (at least implicitly) on the equations

early design =
simple relationships/configurations =
low informational density

and

final design =
complex relationships/configurations =
high informational density.

This has often lead to a problematic dichotomy implying the appropriateness of using "simplified" models for (the less "complex") early design and detailed simulation for the (more "complex") later stages of design. The problem lies, in part, in the semantic impressionism of the term "complexity" in this context. As to the nature of the relevant physical phenomena involved in the energy performance, the early design schemes do not imply lesser levels of complexity that the more detailed ones. The relevant difference for the simulation process lies rather in the resolution of the specifications of constitutive building components both in terms of geometric and "behavioral" properties.

From these observations we conclude that a thermally relevant building representation at the initial stage of design, although ill-defined (in terms of component specification), still can (and probably should) be subjected to a simulation methodology that relies on the consistent ("first principles") modeling of the fundamental physical processes involved.

2.3 "Seamless" Containment of Evaluation Routines

The quest for effective containment of performance simulation in the general computer-aided design environment belongs to the class of issues in computational tool development commonly labeled as the "integration problem". We suggest that many difficulties in overcoming certain obstacles in solving this integration problem may be largely attributed to the "non-integrated" informational context and problem solving methodologies of the professional communities involved.

The CAAD system designer with a software engineering or general architectural background has usually treated evaluation routines as isolated (black-box type) application modules without questioning or investigating their inherent computational logic and underlying data structures. As a result, in many instances, the integration problem has been reduced to the technicalities of module interfaces, translational overlays, and data transfer mechanisms. On the other side, the researchers dealing with the development of computational performance simulation routines may well have reinforced this reductionist approach by viewing CAAD systems as service utilities (i.e. glorified user interfaces) for their simulation modules that in many instances have not gone beyond mere algorithmic routines.

This argument implies that more elegant and effective solutions for the integration problem are likely to be found if the potentially existing structural homologies in general (configurational) and domain-specific (technical) building representations are creatively exploited.

2.4 Active Design Support

We suggested that structural homologies of high-level object models and the domain-specific building representations may be intelligently utilized to facilitate the integration of multiple evaluation modules within a general computational design support environment (cp. section 2.3). However, this may not suffice to realize a different type of integration, namely the integration of evaluation tools within the design process. The difficulties in achieving this second type of integration are, to a significant degree, due to circumstances outside the immediate realm of tool-making (Mahdavi and Lam 1993). Nonetheless the structure and functionalities of computational design support tools may in fact hinder or encourage their routine use in the design process.

The motivation for including active design support in design environments lies in a fundamental limitation of current simulation tools in that they are not flexible enough to handle the primary ways in which design questions are often posed. Concerning building performance, these questions are typically inverse to the way simulation tools operate (Augenbroe and Winkelmann 1991). The questions are usually of the type "What design changes can bring about the desired performance?" or "How much can a design parameter be changed while still maintaining performance in a given range?" or even "What are the various combinations of design parameters that yield the same performance in a given context?".

This suggests that simulation tools used by designers should facilitate the exploration of relationships between design decisions and performance results; they should support the generation of design options and identification of ranges within which designers can make decisions; and the information they provide should help explicate trade-offs in design. Clearly, current simulation tools are not configured to address these issues. They are "one-way" in that they simulate performance, given a well defined set of parameters (Mahdavi and Berberidou-Kallivoka 1993).

There have been numerous efforts to augment the capabilities of the "first-generation" simulation programs using knowledge-based routines, optimization techniques, and more recently, through "active" approaches such as the "generate-and-test" method and the "open" simulation environment (Mahdavi and Berberidou-Kallivoka 1994, Mahdavi 1993, Hitchcock 1991, Bouchlagem and Letherman 1990, Shaviv and Peleg 1990, Tham et al. 1990, Radford and Gero 1988, Mattar et. al 1978). However, viewing these possibilities merely as appendices to the conventional simulation routines may not be the most effective system development strategy. It is unlikely that active procedures would operate efficiently if the specific computational mechanisms and data-structures that they require are not considered while developing the overall architecture of the design support environment.

3. SEMPER

3.1 Overview

SEMPER, a prototype of an active multi-aspect prototype design environment (Mahdavi 1995a) is being developed in response to some of the functional system requirements identified in the above discussion. These include:

- Consistent and coherent modeling of the fundamental physical processes (relevant to the building's performance) throughout the conceptual design and design development phases.
- "Seamless" and dynamic communication between the simulation model and an object-based design model.
- Design refinement using active (mainly preference-based) design support i.e. derivation of the design implications of the desired changes in performance attributes.

3.2 The Thermal Model in SEMPER

In the past, many arguments have been suggested for the use of simplified energy calculation techniques in the early stages of the design process. These arguments typically state that

a) detailed simulation tools require long computation times;

b) due to the "simplicity" (schematic character) of initial design ideas, "complex" methods are not needed;

c) detailed methods require detailed geometry and material/component specification often unavailable in the initial design phase;

d) detailed methods are difficult to learn and cumbersome to use.

We will not deal with the argument *a*, as the as the computational time argument is fast disappearing. Argument *b* is the only one dealing with the nature of thermal phenomena involved, implying that lower levels of "complexity" in the early design stage would justify the application of simplified approaches. However, it is not the nature of the relevant thermal processes (and their inherent complexity) that changes during the course of design development, but rather, the number and variety of the components and the resolution of their specifications. Even the most schematic design ideas, such as the basic building massing and orientation concepts, involve a host of thermal processes (incident solar radiation, shading and self-shading, functional and zonal differentiation, ground contact, etc.) most of which cannot be modeled with simplified single-zone steady-state calculation methods.

One might argue that within specific domains, simplified techniques such as steady-state energy calculations may well provide reasonable results. For instance, there are energy analysis tools based on steady-state degree-day calculations that are fairly reliable for detached, single-family, low-mass, single-thermal-zone houses typical in North America (EEDO 1990). However, these methods would not be as reliable for simulating passive solar houses or for that matter, urban in-fill housing. The use of the simplified techniques for commercial buildings is particularly problematic, especially when the building is question has "non-conventional" features (Mahdavi et al. 1995a, Mahdavi 1995b, Brotherton et. al 1987). Prediction based on regression analysis of a large number of parametric simulations have also been developed for office buildings. Here again, the predictions may be reliable only for "typical" office buildings, where "typical" is based on the limited geometries, material types and control options that have been considered in the parametric runs.

Our discussion of the arguments *a* and *b* implies the necessity for a physically consistent thermal modeling approach throughout the design process. In fact, in SEMPER, a heat-balance based modeling tool NODEM is adopted. In NODEM, spaces are discretized into cell nodes, and walls are discretized into wall nodes based on the number of layers in the wall. Although NODEM uses the same heat-balance techniques as the detailed heat-balance simulation programs (Clarke 1985), it is designed in a manner that allows for operation with a "course" resolution of the spatial building representation. The data structures and system architecture in NODEM have been developed with the perspective of it being integrated with an object oriented design environment, details of which will be discussed in the next section.

With this brief description of NODEM in mind, we must now return to the problems mentioned in arguments *c* and *d* above. In fact, these arguments seem to be still largely valid today, since most available detailed simulation tools do indeed require considerable input, and are thus cumbersome to use, particularly in the early stages of design. Furthermore, they are difficult to operate, maintain and update as the design and its multiple versions evolve. However, we suggest that most of the problems addressed in arguments *c* and *d* can be largely alleviated through appropriate integration of the simulation tool with the design environment.

3.3 "Seamless" Dynamic Communication

The desired integration of detailed simulation methods and CAD systems is complicated by the fact that, commonly, the building representation needed for detailed simulation methods does not adequately match the representation used in commercially available CAD systems. Specifically, detailed simulation methods require the definition of spaces and zones, and not just bounding surfaces, as would be the case with single-zone steady state simulation programs. Almost all currently available commercial CAD systems rely on building representations that do not include spaces. A space-based CAD system, however, would provide a representation that is practically homologous to the thermal representation needed for a detailed heat-balance-based simulation tool, and thereby could facilitate integration. Here, the term "homologous" implies that the two representations have information structured in a manner such that they can be mapped into each other without having to interpret semantics (e.g. geometry interpretation). SEMPER demonstrates this by dynamically linking an object-oriented space-based design environment called Semantic Modeling System (SMS) (Snyder 1993), with NODEM.

SMS is generated using a high level agent collaboration language which allows for fully object-oriented representations of the different application models in an object model (cp. figure 1). Note that in such a scheme, direct links between individual applications are avoided. Instead, the links occur at the object model level through mechanisms such as derived values, allowing for individual applications to be developed fairly independently, while still communicating in an effective manner. The automatic bindings between the application data structures and their corresponding objects ensures consistency between them.

In SMS, the traditional "CAD system" merely becomes part of the graphical interface to the object model, and the geometric constructs in the CAD system have corresponding "geometry objects" which may be related to other objects such as spaces, walls, etc. The space objects which are bound to the corresponding data structures in the simulation application can thereby access the geometry of a space without creating direct links between the simulation application and the "CAD System".

Since NODEM's underlying spatial representation is homologous to that of SMS, it can directly derive the thermal node configuration and the corresponding equation system from the object model of the building in SMS (cp. figure 2). Furthermore, the thermal node configuration is automatically updated based on design modification in the SMS without any additional user intervention. To increase the operational efficiency of the system, a 3-dimensional grid for discretizing the spaces into cells (cp. figure 3) is adopted, which also serves as a building geometry input framework. Spaces are agglomerations of cells, as are HVAC zones. This cell-based discretization allows for efficient derivation and solution of the system of equations, which in turn facilitates operations necessary for active design support. As the design progresses, the resolution of this grid may increase, resulting in a more detailed result.

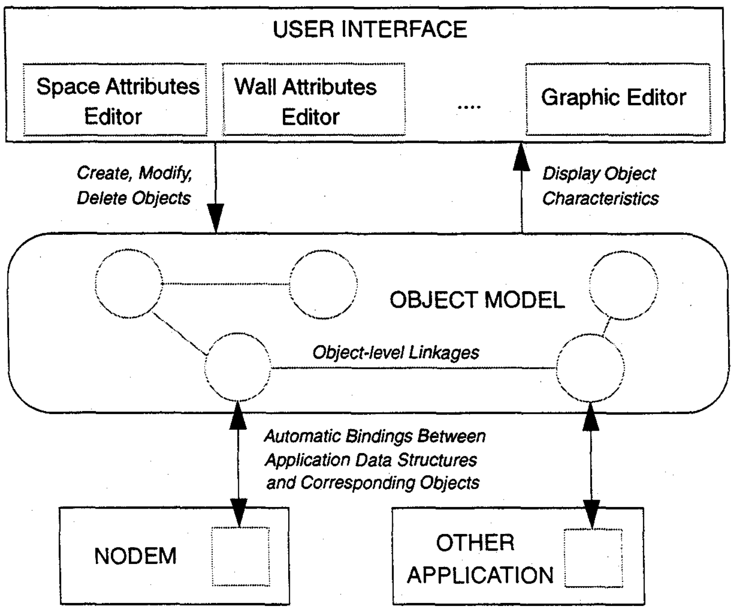


Figure 1. Schematic representation of the Semantic Modeling System and its linkage to NODEM and other applications

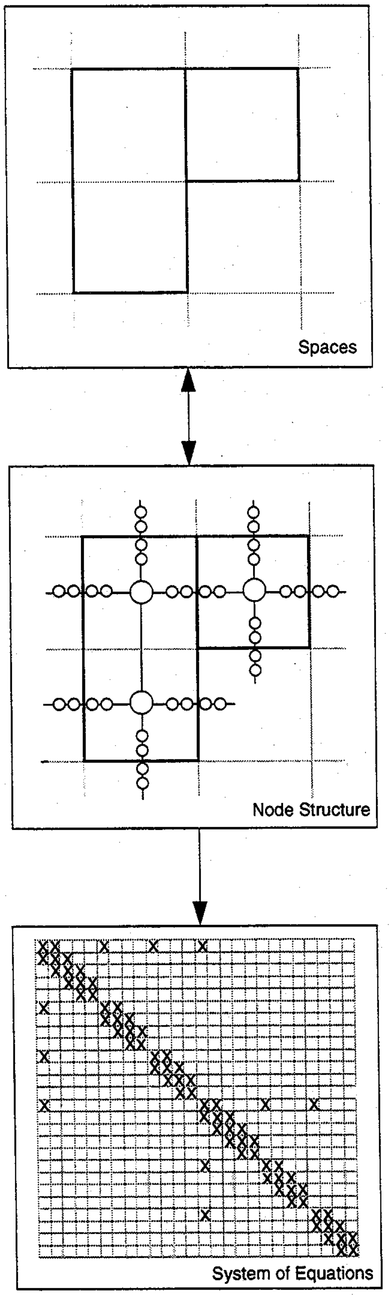
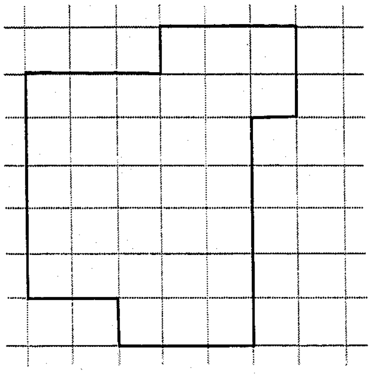
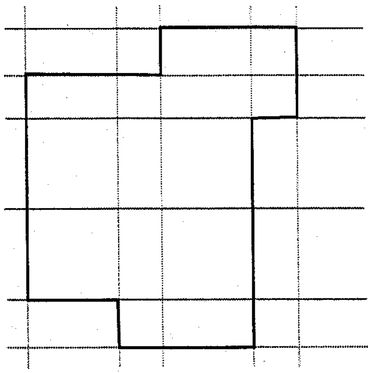


Figure 2. Derivation of the node structure and matrix representations of the building from the homologous space-based design representation

The discretization of the spaces into cells, the creation of the homologous node structure and the system of equations for hourly simulation is completely automated from the object model representation of the building in SMS. This provides "on-line" simulation feed-back to the user while eliminating the need for explicit definition and updating of the underlying thermal model.



Discretization based on uniform grid



Discretization based on "minimum" grid

Figure 3. Demonstrative illustration of basic alternative schemes for discretizing the spaces into cells

3.4 Active Design Support

The active design support that we envision in SEMPER may be characterized as design refinement rather than design generation. It is anticipated that this feature can increase the effectiveness of design support environments in at least two ways: reducing the number of parametric variations a designer may need to explore; and enhancing the designer's understanding of the interactions between various design and performance variables for a given partial design solution. With that perspective, the active design support in SEMPER would provide two functionalities or use-cases, beyond the traditional design-to-performance mapping scenario:

- The designer makes a change in a design attribute and observes resulting changes in other design variables when one or more relevant performance variables are constrained. This is a way of examining tradeoffs among design attributes for a given set of performance indices.

- The designer makes a change in a performance variable in order to see the corresponding changes in design variables.

Since there are multiple ways to make changes in design attributes, an inference mechanism is required to determine appropriate design attribute changes. This is done using a preference structure which determines which variables should be changed, the order in which each should be changed, and to what extent they should each be changed (Mahdavi 1993). The preference structure may be directly specified by the designer (e.g. preferences in glazing type), obtained based on empirical studies (e.g. desirable room proportions), or derived from relevant codes, standards and other technical literature. There is already a prototypical implementation of an active design support for daylighting that employs user preferences to suggest design changes in response to desired values of performance variables (Mahdavi and Berberidou-Kallivoka 1994). SEMPER extends these techniques to thermal performance variables. It differs from traditional approaches to performance driven optimal design generation in that the aim here is design refinement using optimization techniques "locally" to move from one design state to another based on objectives and constraints that are desired and/or relevant to the current design state.

4. CONCLUSION

While there is no *via regia* to the comprehensive integration of various applications in building modeling, we have demonstrated that integration in the performance domain may be effectively facilitated by the use of existing structural homologies between appropriate spatial representations in certain CAD systems and the corresponding building representations for building performance simulation. With SEMPER, we have specifically shown the integration of a space-based design environment (SMS) with a heat-balance-based energy simulation tool (NODEM). However, a number of other performance evaluation modules are also being integrated into SEMPER, addressing thermal comfort, daylighting, natural ventilation, and life-cycle analysis (Mahdavi et. al 1995b). Some of these modules use data not just from the design environment, but also from each other (e.g. the thermal comfort module uses internal surface temperatures generated by NODEM). Here again, the linkages between these modules are realized at the object level through the high-level agent collaboration language, which provides a common framework for integration. We believe that continued efforts in exploring and utilizing the structural homologies between various (general and domain-specific) building representations will inform and aid the research on common product models for buildings.

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