A HOMOLOGY-BASED MAPPING APPROACH TO CONCURRENT MULTI-DOMAIN PERFORMANCE EVALUATION

ARDESHIR MAHDAVI, PAUL MATHEW
Department of Architecture,
Carnegie Mellon University, Pittsburgh, PA, USA

AND

NYUK-HIEN WONG

Abstract. Over the past several years there have been a number of research efforts to develop integrated computational tools which seek to effectively support concurrent design and performance evaluation. In prior research, we have argued that elegant and effective solutions for concurrent, integrated design and simulation support systems can be found if the potentially existing structural homologies in general (configurational) and domain-specific (technical) building representations are creatively exploited. We present the use of such structural homologies to facilitate seamless and dynamic communication between a general building representation and multiple performance simulation modules - specifically, a thermal analysis and an air-flow simulation module. As a proof of concept, we demonstrate a computational design environment (SEMPER) that dynamically (and autonomously) links an object-oriented space-based design model, with structurally homologous object models of various simulation routines.

1. Introduction

Over the past two decades numerous computational simulation tools have been developed to facilitate performance evaluation of buildings in multiple domains (e.g. energy use, acoustics, lighting). This has enhanced performance prediction capability in at least three critical ways: buildings could be modeled with a greater level of detail, sophisticated performance modeling algorithms could be incorporated within simulation programs, and detailed performance data could be obtained from the programs. However, computational performance simulation tools are still mostly used only by domain-specific experts, and are not widely applied in building design practice. Many of the reasons for this predicament pertain to the limitations of simulation tools, such as problematic
user-interfaces, poor integration with CAD systems, the absence of "active" design support, among others. In particular, there have been significant research efforts directed at the so-called "integration problem", i.e. the quest for effective containment of performance simulation in the general computer-aided design environment. This paper focuses on this problem specifically from the perspective of a building designer seeking to obtain concurrent, detailed performance evaluations during conceptual design and design development. We begin with a discussion of the nature and parameters of the integration problem vis-à-vis concurrent building performance simulation, and briefly review some approaches that have been taken to address it. We then present an alternative approach that utilizes homology-based mapping to couple simulation models and the general building representation, using as a demonstrative example the coupling of a nodal energy simulation model and air flow model within a prototypical multi-aspect design and simulation environment.

2. Concurrent Performance Evaluation and "The Integration Problem"

The integration of building design and simulation tools has been the subject of many research efforts, which vary widely in their scope, approach, and the types of the tools that they integrate (Augenbroe 1992, Fenves et al. 1994, Fruchter 1996, Khedro 1996, Mellotte et al. 1995, Pohl and Myers 1994, Softdesk 1996). Despite these efforts, the effective integration of detailed simulation tools and design environments remains an open research question, particularly because of the semantic limitations of existing CAD tools and the idiosyncratic informational requirements and formats of existing simulation tools. Simulation tools typically use representations that correspond to their particular "view" of the building - one which reflects the underlying mathematical methods of the simulation technique. For instance, a room acoustic simulation tool that relies on a sound-particle distribution technique requires a representation that includes spatial volumes with bounding and internal surfaces that can be discretized. Such a representation does not map directly to the building representation in common computer-aided architectural drafting tools which is typically devoid of spatial enclosure information and/or surface attribute information. As a result, a designer will typically need to input the building data separately for each domain application - a process that is time-consuming, cumbersome, and error-prone (cp. figure 1).

We suggest that many difficulties in overcoming certain obstacles in solving the integration problem may be largely attributed to the "non-integrated" informational context and problem solving methodologies of the professional communities involved. The architectural CAD 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 CAD systems as service utilities (i.e. glorified user interfaces) for their simulation modules that in many instances have not gone beyond mere algorithmic routines (Mahdavi and Mathew 1995). We argue that better solutions for the integration problem are more likely to be found if the potentially existing structural homologies in general (configurational) and domain-specific (technical) building representations are exploited.

![Diagram](image)

*Figure 1: Conceptual illustration of the "Integration Problem" in multi-aspect building performance simulation*

### 3. Homology-based Mapping

As noted earlier, the desired integration of detailed simulation methods and CAD systems is complicated by the fact that the building representation needed for detailed simulation methods do not adequately match the representation used in
commercially available CAD systems. For example, in the case of energy simulation, 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. Yet almost all currently available commercial CAD systems rely on building representations that do not include spaces. Consequently, in order to integrate a detailed simulation tool with such a CAD system, mechanisms like geometry interpretation (which are inherently brittle and unscalable) would have to be used. On the other hand, a semantically enriched space-based CAD system would provide a representation that is practically homologous to the thermal representation needed for a detailed heat-balance-based energy simulation tool, and thereby could facilitate integration much more effectively and reliably. Here, the term "homologous" is used to mean that the two representations have information structured in a manner such that they can be derived from each other without having to interpret semantics (e.g. geometry interpretation). Thus, with homology-based mapping, it is possible to have multiple application-specific representations generated automatically from a shared, space-based building object model (figure 2).

![Diagram](image_url)

*Figure 2: Automated generation of multiple application-specific representations using homology-based mapping (compare to figure 1)*

The use of homology-based mapping has been demonstrated within SEMPER - a multi-aspect design and simulation environment which has various performance simulation modules linked with a prototypical object-oriented, space-based design environment (Mahdavi 1996, Mahdavi et al. 1996). Figure 3 indicates the architecture of SEMPER, the components of which include a) a shared object model which encapsulates a space-based representation of the building; b) various simulation modules (domain applications), each of which have application-specific object-model representations of the building; c) a
database; and $d$) a user interface. With this software architecture, direct links between individual domain 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.

![Diagram of the architecture of SEMPER](image)

*Figure 3: The architecture of SEMPER*

The homology-based mapping from the shared building representation to that of multiple performance simulation domains can be illustrated for the thermal analysis and air-flow simulation modules. SEMPER incorporates a heat balance-based nodal energy simulation module called NODEM (Mahdavi and Mathew 1995), which utilizes a spatial representation consisting of spatial units (cells). Each cell is thermally represented by a node that defines a finite control volume for heat-balance calculations. To increase the operational efficiency of the system, a 3-dimensional grid for discretizing the spaces into cells is adopted, which also serves as a building geometry input framework. Spaces are agglomerations of cells, as are HVAC zones (figure 4). This cell-based discretization allows for efficient derivation and solution of the system of equations. As the design progresses, the resolution of this grid may increase, resulting in a more detailed analysis.

Analogous to NODEM, the air-flow simulation module operates by discretizing the simulation domain into a network consisting of nodes that represent regions of differing pressures interconnected by virtual paths (figure 5). Here again, the network is numerically described by a system of equations formed by applying an appropriate flow equation to each path. These equations
formed by applying an appropriate flow equation to each path. These equations are solved by determining the pressure distribution such that a mass flow balance is preserved for each node.

*Figure 4: Cell-based discretization of spaces in NODEM*

The shared space-based building representation embodies topological
information and it therefore has "knowledge" of architectural spaces and their relationships (adjacencies, etc.). The underlying spatial representations in both the NODEM and air flow simulation modules are configurationally homologous to the space-based representation of the building in the shared object model, and can therefore be directly (and unambiguously) derived from it. Figure 6 illustrates the derivation of the nodal network and corresponding equation system in NODEM. 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 shared building representation. This homologous mapping between representational and analytical building object models thus provides "on-line" simulation feedback to the user while eliminating the need for explicit definition and updating of the underlying simulation modules. Furthermore, this is done without having to use complex application-specific translators or communication frameworks.

![Figure 6: Derivation of nodal network and corresponding equation system in NODEM](image)

The strength of homology-based is especially evident when used for concurrent multi-aspect design generation and evaluation. Consider for example the sequence shown in figure 7, in which the geometric manipulation of an initial design scheme (e.g., addition, deletion, or resizing of spaces) is automatically mapped into an updated nodal configuration in the simulation modules. As spaces are added to the initial scheme, the modules create the cell nodes for the new space, and automatically update the boundary conditions for the wall nodes. For the thermal analysis module, the wall nodes are updated to reflect the internal walls between the two spaces. For the air-flow simulation module, the virtual path linking the adjacent nodes is disconnected to reflect the presence of an internal wall/partition. In the presence of a door/window, the virtual path reconnects the two adjacent nodes. Through all the steps of the sequence, both the thermal node configuration and the nodal network for air-flow simulation are automatically updated based on design modification in the shared object model. The user is thereby able to manipulate a design using a representation familiar to him/her, and concurrently perform detailed
performance simulations without any additional intervention or manipulation of
the application-specific representations.

Figure 7: Automated updating of nodal model in NODEM and air flow simulation
modules, based on changes in CAD model
It should be noted that within SEMPER, the two simulation modules are dynamically linked to each other through the object communication framework. This allows NODEM to use the air-flow rates in each zone to compute temperature profiles, and the air-flow module to use the temperature data computed by NODEM for the computation of air-flow due to stack effect. Here again, the simulation-related communication between the modules is done without any intervention by the user.

4. Concluding Remarks

We have suggested that the integration of design and simulation tools can be more effectively facilitated if the potentially existing structural homologies in their respective building representations are exploited. We do not, however, imply the universal applicability of the homology-based mapping technique in all building application domains, as the existence of homologous representations and the potential for their effective computational use must be explored on a case by case basis. In this paper we demonstrated the use of homology-based mapping to integrate a thermal analysis module (NODEM) and an air-flow simulation module within a space-based design environment (SEMPER). However, homology-based mapping is also being successfully applied within SEMPER to integrate a component-based HVAC model, a sound-particle-based acoustic simulation module, and an Eco-balance-based life-cycle-analysis module.

References


