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ASPECTS OF A REPRESENTATION FRAMEWORK FOR PERFORMANCE-BASED DESIGN

Georg Suter and Ardeshir Mahdavi
Building Physics and Human Ecology
Vienna University of Technology
Vienna, Austria

ABSTRACT

We introduce a representation framework that is aimed at supporting performance analysis during schematic and detailed design. The framework is based on two distinct representations as well as automated, bi-directional mappings to maintain consistency. Schematic building configurations are defined in a *sheet representation*, and may be expanded into a *solid representation*, where outlines of building and space enclosures may be further decomposed into construction layers or components. Model manipulation in both representations as well as mappings is supported by spatial partitioning and offsetting techniques. A case study illustrates how the framework could be used in performance-based design practice.

INTRODUCTION

In the past decade, there have been a number of efforts in the building performance simulation community to achieve integration of analysis tools (see, for example, Augenbroe et al. 1995, Mahdavi 1996, Papamichael et al. 1997, Pelletret and Keilholz 1999). Most work focuses on schematic design because many decisions are made in this phase that have significant impact on performance aspects such as energy use, lighting, acoustic, or thermal comfort. System prototypes have demonstrated that, for schematic design, it is feasible to integrate a disparate set of tools typically used by different disciplines and professionals. However, the reuse of schematic models for analysis tasks typically performed during detailed design, such as thermal bridge or moisture transfer analysis, has received little attention so far.

We describe selected aspects of a representation framework which includes sufficient information to enable a wide range of performance-based design analysis tasks throughout schematic and detailed design. We illustrate the potential benefits of the proposed representation framework with an illustrative example involving the thermal design of a small studio.

Throughout the paper, the terms representation and model will be used frequently. We use the term representation when referring to a generic, geometry-centered building description (as opposed to a building product data model, where semantics are commonly emphasized over geometry). Thus the work presented in this paper should be understood as complementary to the development of building product data models. We use the term model when referring to a particular building instance.

USE SCENARIO

We begin with a use scenario that has guided the development of the representation framework:

A designer creates a three-dimensional digital building model. As the model evolves and is sufficiently detailed, the information contained in the model can be used for energy use as well as thermal bridge analysis. Input to both simulation tools is provided automatically and consistently without additional designer effort. The enclosure design is modified to improve energy use and address thermal bridge problems. Without further designer intervention regarding simulation input, another simulation session is run, and the results are compared with the first session.

REQUIREMENTS

The requirements for a computational environment to support the scenario can be categorized into information completeness, integrity and consistency, design development, and spatial queries (Suter and Mahdavi 1998).

Detailed performance computing for thermal, lighting, or acoustics design is typically based on site, building, zone, and space information that includes shape, location, material, and other properties. The information content of individual representations, however, may vary greatly depending on the supported domain or task. For example, in most energy analysis tools, walls are represented as surfaces with attributes that refer to multi-layered construction types. In thermal bridge applications, on the other hand, walls are modeled more explicitly as individual solid volumes with references to construction materials. Such volumes may form joints which are usually not included explicitly in energy analysis tools. Clearly, both levels of detail need to be provided for performance analysis in the above scenario.

Integrity and consistency of a representation is an issue that is often ignored in computer-aided design systems. Lack of integrity in data structures may cause system failure or, worse, misleading feedback to users. At present, most tools require massive and often repetitive manual input, which opens many possibilities for errors. Simulation tools rarely check, for instance, whether openings overlap, or whether each space is properly enclosed. As a result, integrity maintenance is almost entirely left to the user. Robust representations should thus perform automated integrity maintenance.

Design development support refers to the ease of generating and modifying building models from a designer perspective. This issue is of particular importance in integrated simulation environments, where potentially large and detailed models are created by users. Operations should be scalable (Suter and Mahdavi 1998). For example, a designer should be able to modify the overall length, height, or depth of the building regardless of how many floors or spaces it contains.

FRAMEWORK OVERVIEW

Introduction

In order to support the above scenario, the approach is to simultaneously maintain two distinct representations, a sheet and solid representation (SHR and SOR, respectively). Each can serve as a shared representation for several performance analysis applications. The representations are tightly coupled through bi-directional mapping mechanisms. That is, a change in one representation is initially propagated and validated within itself and then communicated to the other representation, where a similar internal procedure is repeated.

Building models are generated by spatial partitioning in a top-down fashion. In both SHR and SOR, a set of generic decomposition operations may be applied uniformly to geometric entities regardless of their dimensionality. Most operations are scalable, that is, they are propagated automatically without further user intervention and regardless of model size. Specific operations are required for more complex model manipulation such as the insertion of buildings or openings.

We will focus on selected aspects of the representation framework, which include certain primitive and macro operations as well as mapping mechanisms between SHR and SOR. Mappings between a shared representation and individual applications are not covered. Furthermore, most integrity issues may be raised rather than resolved.

Sheet representation (SHR)

Representations for schematic design analysis tools are often based on collections of volumes enclosed by faces. Volumes define buildings, zones, spaces or sub-spaces and are made up exclusively of air material. Conceptually, one can think of the boundaries shared by such volumes as double-sided faces or sheets because they do not bound solid material. The first representation in the framework has similar properties, and we thus call it sheet representation, or SHR. One important difference between SHR and related schematic design representations concerns material information. Whereas faces in the latter refer to construction type information such as wall layers, those in the former include only face finish information explicitly. Construction type information is automatically derived from SOR and stored in dedicated nodes in a decomposition hierarchy.

Solid representation (SOR)

The solid representation, or SOR, is the second representation in the framework. It consists of a collection of solid volumes and is used to define component layers and materials that make up a building and space enclosures. Some of these solid volumes may be made of air material, for example those representing spaces. Joints are neglected in SHR, but may be modeled more explicitly in SOR. Consequently, SOR is geared towards supporting analysis during detailed design.

Faces that bound a volume can be considered as one-sided because they separate a material from void. Gaps between volumes are not allowed. Faces might have individual finish properties. Portions of the solid representation are derived from SHR through mappings. An important high-level entity in SOR is the *building enclosure volume* which consists of an outer and one or more inner boundaries. This volume reflects exterior building and interior space boundaries. It is continuous and provides the context for the definition of construction layers and joints.

PRIMITIVE OPERATIONS

Introduction

Users can manipulate both SHR and SOR building models with a set of primitive operations that are applicable to volumes, faces, and edges. Operations are described in the following as rules that permit recursive decomposition of an entity into constituent entities. A comprehensive description of all operations is beyond the scope of this paper. Rather, the operations are presented with illustrative examples from a user perspective.

Perpendicular partitioning

Edge-based perpendicular partitioning. Perpendicular partitioning is explained with a face partitioning example. A user would pick a face that is part of a volume boundary, and an edge within that face. According to the *insert-new* operation, the edge is divided into two or more sub-edges. The selected face is then sliced or partitioned into two or more sub-faces based on the edge partitioning. Since partitioning occurs by default perpendicular with respect to the sub-edges, the term edge-based perpendicular partitioning is used for this kind of operation. Volume partitioning is an extension of face partitioning. Together with the face normal, a face partition defines a plane that can be used to partition volumes. Figure 1 illustrates the *insert-new* operation for volumes. The pink arrows represent partitioning directions and may be reversed. A solid arrow indicates the selected edge. Similar partitioning mechanisms support the modification of sub-edge dimensions or the insertion of sibling entities.

Face-based perpendicular partitioning. A variation of the above edge-based perpendicular partitioning is face-based, perpendicular partitioning. This partitioning technique is introduced to facilitate the decomposition of volumes with holes. Holes may either be created explicitly by users, or emerge as a side effect of the mapping between SHR and SOR. The *insert-new* operation for volumes is based on a face that is part of a an inner boundary of a target volume. The face boundary is extruded perpendicular and in opposite direction to the face normal, that is, towards the interior of the target volume. The extruded volume is intersected with and subtracted from a copy of the target volume. These new volumes are inserted as new child nodes in the decomposition hierarchy (Figure 2). Again, the information concerning the target volume is preserved as a parent node in the decomposition hierarchy.

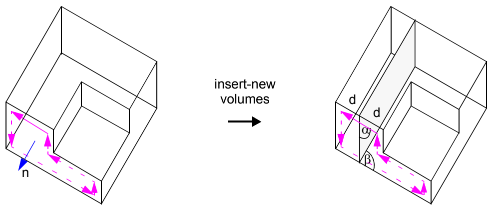

Figure 1. Illustration of edge-based perpendicular partitioning operation for volumes.

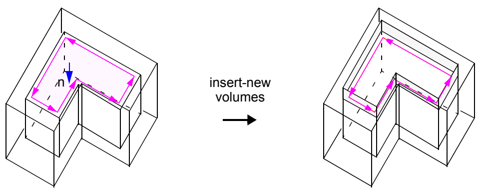

Figure 2. Illustration of face-based perpendicular partitioning operation for volumes.

Parallel partitioning

Parallel partitioning rules allow the modeling of configurations with holes. This is not only relevant for modeling openings, but for building and space enclosures as well as construction layers. Figure 3 illustrates parallel partitioning for volumes. Each face in a target volume has a parameter that indicates the distance by which a copy of a face should be moved away or offset from its original - hence the term parallel partitioning. The new child entities are obtained based on two copies of the target volume. A first copy of the target volume is made and its faces are offset according to user-defined parameters. This is a non-trivial operation as faces might not only change their location but also their shape when related faces are adjusted simultaneously. Subsequent to the transformation by offset, the volume is subtracted from the second copy of the target volume. The resulting volumes are inserted as new nodes in the decomposition hierarchy below the target volume (Figure 3, right hand side).

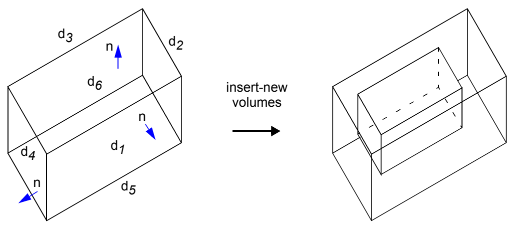

Figure 3. Illustration of parallel partitioning operation for volumes.

Offsets

Offset operations are related to parallel partitioning and are introduced for the refinement of existing faces and edges. Offsets enhance the geometric variety of configurations.

Similar to parallel partitioning, a distance parameter associated with an edge or faces indicates its desired repositioning or offset. There are two types of offsets: *face* and *volume boundary offset* (Figure 4). As in parallel partitioning, *filler* faces or edges might be created automatically to avoid gaps in a modified configuration. These emerging entities are inserted at the same level as the target face or edge. These entities are inserted automatically in a decomposition hierarchy. Whereas parallel partitioning results in decomposition, a target face or edge itself is transformed in an offset operation. Offsets may be used, for example, to adjust the boundary of a volume generated by face-based perpendicular partitioning.

An offset operation does not only affect the boundary of the target volume or face, but related boundaries as well. Adjustment occurs by updates and evaluation of corresponding parameters and entities.

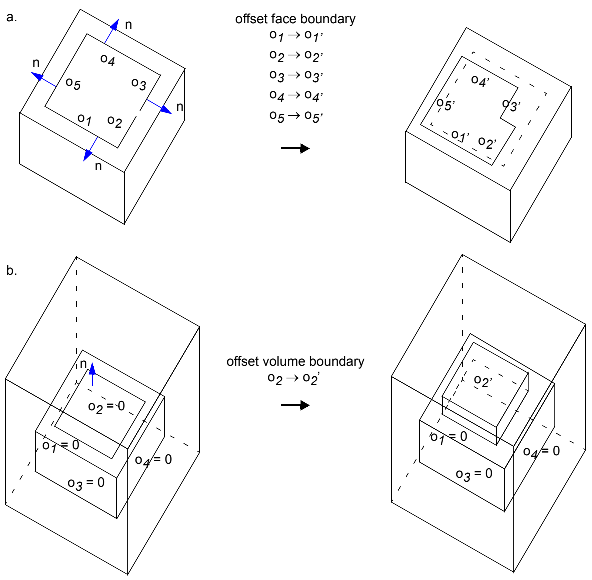

Figure 4. Illustration of offset operation. a. face boundary offset, b. volume boundary offset.

SHR/SOR MAPPINGS

Introduction

In addition to update mechanisms within each representation, mappings between SHR and SOR maintain consistency and integrity for discrete and continuous modifications. Certain operations such as the insertion of a building or an opening may require more specific mappings. These are described later. Paoluzzi and Sansoni have proposed a similar mapping procedure to add thickness information to enclosure elements via offsets (Paoluzzi and Sansoni 1992).

Relationship between SHR and SOR

As mentioned earlier, SHR and SOR are tightly coupled, which has implications on the model generation process. It is assumed that a designer would start building a model in SHR, which can be expanded to SOR, where joints and other construction details may be added. Most entities in SHR have a counterpart in SOR. In contrast, SOR incorporates construction information that is either ignored or present only in abstracted form in SHR. The modification of an entity that exists in both representations is initially propagated in SHR. It is subsequently mapped to SOR, where a similar propagation procedure is repeated. The propagation sequence reflects the different roles of each representation. For example, walls or windows may be inserted only in SHR, from where they are mapped to SOR. As certain operations could result in spatial conflicts during propagation in either representation, a reversal or rollback to the state prior to the operation is necessary. Only modifications that are successful in both representations are committed.

Mapping from SHR to SOR

The mapping between SHR and SOR is illustrated with an example. The left hand side of Figure 5 shows a portion of a SHR floor plan. The floor plan is simplified for clarity. In addition to space boundary nodes (red and blue), there are *space enclosure leaf nodes* (green), each of which separates exactly two spaces. This requirement is important for applications such as energy analysis. Space enclosure leaf nodes are derived automatically from relevant space boundaries to the left and to the right of an imaginary wall or partition that spans several spaces from top to bottom of the floor plan. New wall nodes are obtained by intersecting a pair of left and right leaf parent space boundaries. If the intersection is different from either input shape, it is inserted in the decomposition hierarchy as a shared child node.

Each SHR space boundary is offset in two steps during the mapping process. First, the boundaries of all leaf volumes below the inner building volume that are labeled as spaces are offset according to distance parameters associated with individual faces (the rule for defining a building enclosure is described in the next section). In the second step, these volumes are subtracted from the volume defined by the outer building volume, which itself might be offset. In SOR, the mapping creates a continuous volume with holes. The holes are filled with space air volumes, that is, merged copies of the subtracted offset volumes. These are not shown in Figure 5 for simplicity. The continuous volume contains all physical building components (Figure 5, right hand side). The inner boundaries of such a *building enclosure volume* are space boundaries. Individual face decompositions are mapped as well.

Wall thickness information is stored in the space enclosure leaf nodes and obtained by adding relevant offset parameters. The continuity of the building enclosure volume appears suitable for the definition of construction details as it does not determine the composition of walls or joints.

Mapping from SOR to SHR

Since SOR includes detailed spatial information regarding construction layers and materials, a mechanism is required to map this information back to SHR in aggregated form. A simplified procedure is introduced for this purpose. A center point is computed for each space enclosure leaf node. The center point and the face normal define a ray that starts in one space and pierces the space boundary. A filter is required for the selection of those face normals that ensure consistent sequencing of construction layers (Figure 6, left hand side). First, the intersection points with relevant intermediate volume nodes containing construction layer information are computed. The procedure is terminated when the corresponding face of the adjoining space is reached (Figure 6, right hand side). Finding intermediate volumes requires searching the decomposition hierarchy below the building enclosure volume node in SOR. As there is no limit to the depth of that decomposition hierarchy, some heuristics might be necessary to determine an appropriate abstraction level that includes the desired construction layer information. Furthermore, a plausibility check is required to eliminate those rays that may not pierce the target space boundaries due to offset side effects.

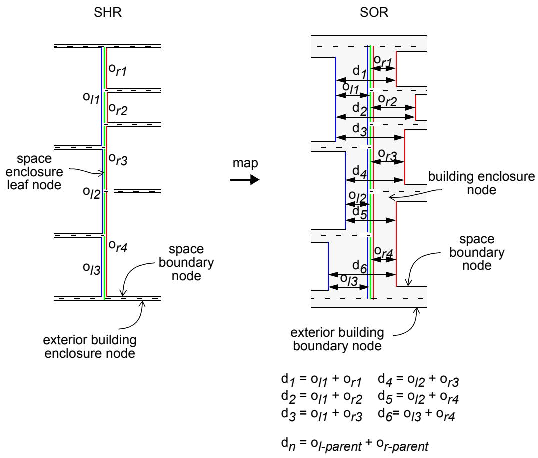

Figure 5. Mapping between sheet and solid representation

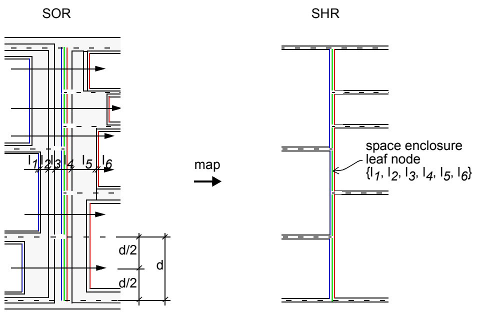

Figure 6. Mapping between solid and sheet representation.

MACRO OPERATIONS

Introduction

Specific operations are required for certain building entities such as building enclosures, spaces, and openings. These consist of several primitive operations, including attribute assignment and navigation. Outlines are given below for *insert-building* and *insert-opening* operations.

Insert-building

In both SHR and SOR, the highest level building nodes may be inserted immediately below a root volume. This provides maximum flexibility for defining the relationship between a building and its environment.

In SHR, the *insert-building* operation uses generic parallel partitioning to create a site, building and space boundaries (Figure 7). The site has a soil and outdoor space sub-entity. The site volume itself is a composite entity bound by an outer and inner entity, which is the outer building boundary. The inner highest-level building or zone volume is a separate entity that fills the void enclosed by the outer building boundary. That is, outer and inner building boundaries touch each other. Moreover, they may have - except for openings and volume boundary offsets - decoupled face decompositions. This reflects common practice where exterior and interior building boundaries are often treated independently. The inner building boundary encloses an air volume and may be further differentiated into zones (floors), and spaces with generic partitioning and attribute operations.

SOR derives the building enclosure volume from SHR as outlined earlier. The volume is further automatically decomposed into openings based on SHR information (Figure 7). Unless a homogeneous construction material is used, a building enclosure volume is initially undifferentiated and therefore not sufficient for the analyses both representations are intended to support. It can be used as a starting point for the definition of individual construction layers or materials.

Figure 7 includes an example pair of relations between SHR and SOR. These links are introduced and maintained by the mapping mechanisms described earlier. Through links with SHR, it is possible to identify directly, for example, the two faces in SOR that bound a wall and access their offset parameters. Furthermore, it is possible to perform partial updates with such links. Adjusting the width of a window in SHR, for instance, triggers propagation in SHR as well as in SOR.

Insert-opening

An opening may be inserted in an outer/inner building, zone or space boundary face. The operation is again first applied to SHR and then mapped to SOR. It is more involved because openings are shared by two faces, that is, they are a important exception of independent face decomposition. Given a target opening that is initially inserted into a face by parallel partitioning, its connection by projection to the adjacent face occurs in two steps. First, the face decomposition hierarchy is traversed upwards until a relevant local root node face is reached. A local root node is a face that represents one side of a virtual partition generated by a partitioning operation. Such a face has a direct relation to its adjacent face, which is also a local root. Once that face is identified, the opening geometry is subtracted from it, and the result as well as a reference to the original opening geometry are inserted immediately below the face as new child nodes (Figure 8). Consequently, all existing child levels would be pushed down one level and reevaluated to reflect the new opening. The procedure in case of existing opening projections is similar. However, the opening to be projected would be subtracted from the non-opening entities below the local root node. Sub-entities would be reevaluated, but no push-down would be required.

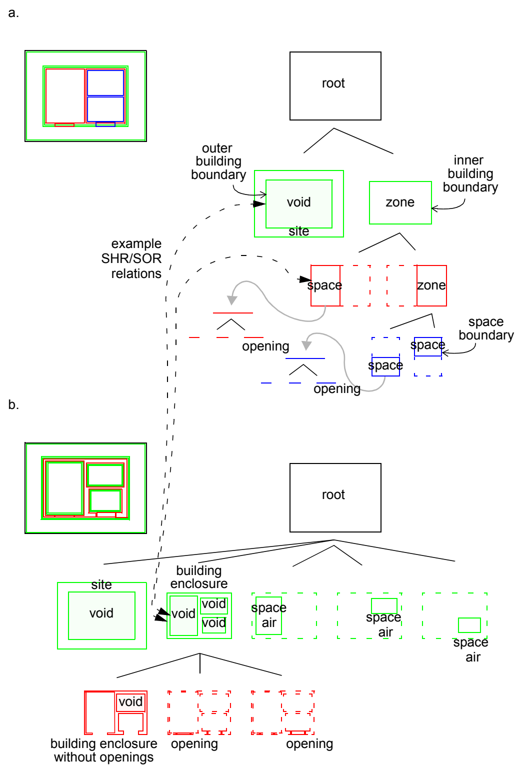

Figure 7. Decomposition hierarchy for a simple house on a site. a. SHR, b. SOR.

The opening geometry originally created by the user 'owns' its counterpart. The owned opening geometry merely mirrors every modification of the owner opening shape. A face and its sub-faces may include either owner or owned openings. Mixing owner and owned openings in the same face decomposition are not be permitted. This is to ensure transparency regarding the positioning of openings, which may only be modified within an owner face decomposition.

As shown in Figure 8, openings in SHR do not necessarily need to exist at the same level in the two face decompositions. In SOR, however, holes for openings as well as openings are always at the same level. The holes are created by subtracting the opening geometry from the building enclosure volume. The opening geometry itself is generated by extruding the sheet opening by the enclosure thickness. Individual openings may span multiple spaces or floors only when the wall thickness is constant.

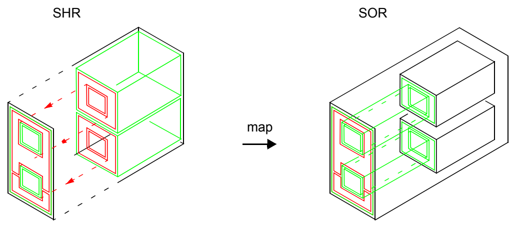

Figure 8. Mapping of openings between sheet and solid representation.

CASE STUDY

Introduction

The case study follows the use scenario presented at the beginning of the paper. The design of a small studio in Vienna, Austria, illustrates the benefits of the representation framework. In this example, a designer investigates the implications of design decisions on overall energy use and potential thermal bridges in the building enclosure. For the purpose of this case study, NODEM (Mahdavi and Mathew 1995), an energy analysis tool, and PHYSIBEL-VOLTRA (Physibel 2002), a thermal bridge analysis tool, are used. Both simulation tools provide detailed transient heat transfer analysis but focus on different performance aspects. They are based on representations that include design information similar to SHR or SOR.

Initial configuration

The studio has a gross area of 45 m^2 and a volume of 157 m^3 (Figure 9). In SHR, openings are defined with respect to space boundaries and shared with the outer building boundary. This initial configuration is generated with parallel and perpendicular partitioning as well as offset operations (Table 1).

Table 1. Operations used to generate model features.

FEATURE	OPERATION
Massing	Parallel partitioning and offset
Openings	Offset
Site	Parallel and perpendicular partitioning
Roof (SOR)	Offset
Foundation (SOR)	Offset and parallel partitioning

Unless a homogeneous construction material is used for the whole building (except for openings), the model does not include sufficient information for simulation at this stage. Figure 10 shows how the building enclosure volume, which includes two space holes, is decomposed further using both parallel and perpendicular partitioning. For each volume, material information is either inherited from the parent volume or overridden by the designer. Figure 10c demonstrates how level 5 entities are generated with face-based perpendicular partitioning followed by offsets. It should be noted that building components exist at different decomposition levels. For example, while the interior plaster volume is realized at level 4, most other materials are realized at level 6. The ray technique outlined earlier is used to map construction information automatically back from SOR to SHR.

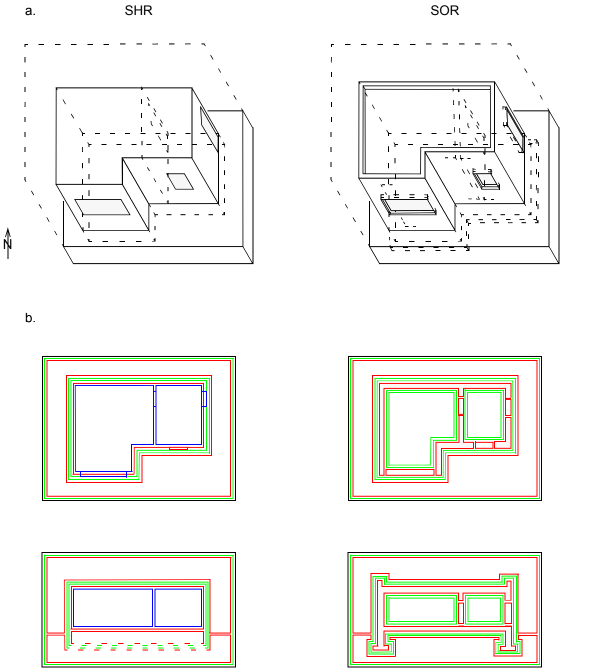

Figure 9. Example studio. a. axonometric view. b. floor plan and cross section (nested view).

First simulation session

The model is ready after these operations for energy use as well as thermal bridge simulation. An initial analysis with the thermal bridge analysis tool indicates 9.5°C indoor surface temperature at the joint between wall and roof elements (outdoor temperature: -10°C, indoor temperature: 18°C). This could, starting from relative indoor humidity values of over 69%, cause condensation and possibly mold growth at the space boundary (Figure 11). The building loads are summarized in Table 2.

Second simulation session

In response to the results from the first simulation session, the designer modifies the enclosure. The total building component volume is rearranged by resetting offset parameters in the SHR portion and new decomposition of the SOR portion of the model (Figure 12). A foam glass thermal insulation layer is added to the exterior wall and roof. Figure 12c shows a manipulation sequence that generates level 4 and a portion of the concrete/brick joint at level 5. Parallel and perpendicular partitioning operations are used, respectively. Again, the designer conducts energy use and thermal bridge analyses to obtain feedback on the performance impacts of these design changes. The results are summarized in Figure 13 and Table 3.

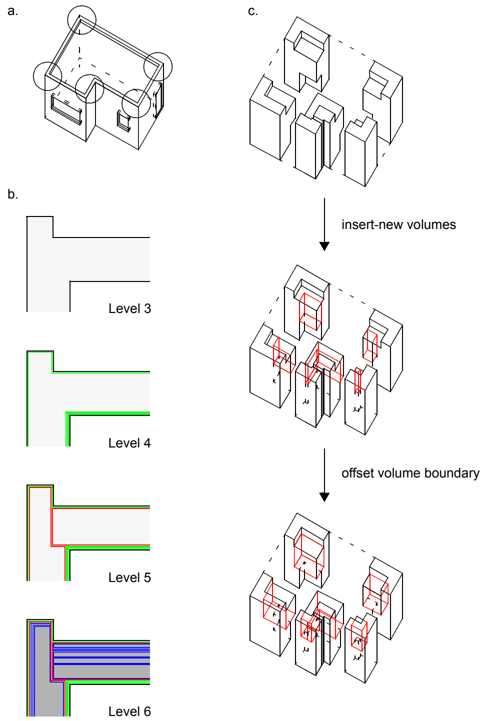

Figure 10. Decomposition of building enclosure volume. a. axonometric view, b. decomposition of roof section, c. intermediate steps generating level 5.

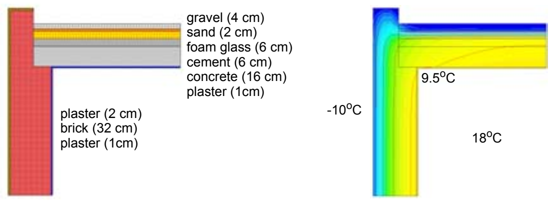

Figure 11. Cross-section and typical temperature profile for corner solution with brick exterior wall.

Table 2. Annual energy loads for brick enclosure alternative

UNIT	HEATING	COOLING	TOTAL
$kWh \cdot m^{-2}$	266	22	288

The space boundary temperature at the joint between wall and roof elements has increased to 13°C (same outdoor/indoor conditions), which is a significant improvement compared to the first solution. The modifications result in significant improvements in heating loads (47.9%), but cooling loads increase (149.4%). Overall energy loads are significantly reduced (55.8%), as is the risk of condensation.

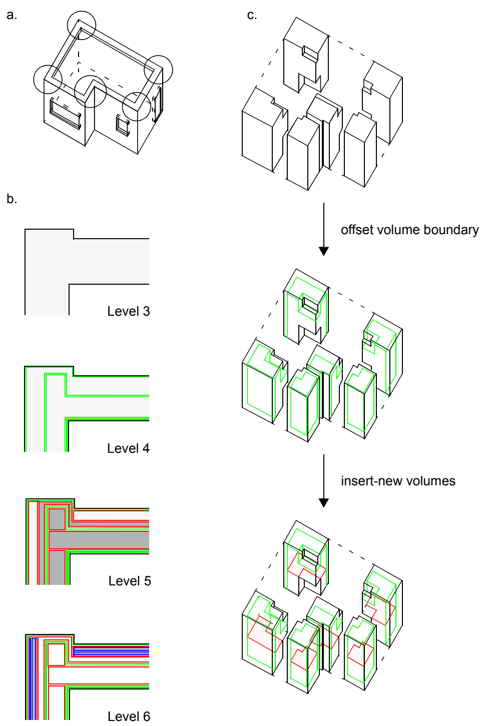

Figure 12. Decomposition of building enclosure volume. a. axonometric view, b. decomposition of roof section, c. intermediate steps generating level 5.

Figure 13. Cross-section and typical temperature profile for corner solution with insulated brick exterior wall.

Table 3. Annual energy loads for insulated brick enclosure alternative (base case: brick enclosure)

UNIT	HEATING	COOLING	TOTAL
kWh $\cdot$ m^{-2}	127	33	161
% base case	47.9%	149.4%	55.8%

CONCLUSION

A number of conceptual and implementation issues need to be addressed to demonstrate the viability and potential of the described representation framework in design practice. For a prototypical implementation, integration with a geometry modeling engine needs to be investigated. A preliminary analysis has shown that the basic geometry functionality underlying partitioning and offset operations are included in the application programming interface of solid modeling packages such as ACIS (Corney and Lim 2001). Furthermore, spatial queries for integration with simulation tools need to be defined and developed. Finally, integrity and consistency conditions need to be described more comprehensively to ensure robust operations.

REFERENCES

Augenbroe, G. (Editor) 1995. COMBINE 2 Final Report, Delft University of Technology, The Netherlands.

Corney, J., Lim, T. 2001. 3D Modeling with ACIS, Saxe-Coburg Publications, Stirling, United Kingdom.

Mahdavi, A. 1996. SEMPER: A New Computational Environment for Simulation-based Building Design Assistance. Proceedings of the 1996 International Symposium of CIB W67 (Energy and Mass Flows in the Life Cycle of Buildings), Vienna, Austria. pp. 467 - 472.

Mahdavi, A., Mathew, P. 1995. Synchronous generation of homologous representations in an active multi-aspect design environment, Fourth international conference, International Building Performance Simulation Association, Madison WI.

Paoluzzi, A., Sansoni, C. 1992. Programming language for variational geometry, Computer-Aided Design, 24 (7), pp. 349-366.

Papamichael, K., LaPorta, J., Chauvet, H. 1997. Building Design Advisor: automated integration of multiple simulation tools, Automation in Construction, Vol. 6, pp.341-352, 1997.

Pelletret, R, and Keilholz, W. 1999. Coupling CAD tools and building simulation evaluators, Sixth international conference, International Building Performance Simulation Association, Kyoto, Japan.

Physibel 2002. Voltra User Manual, Maldegem, Belgium.

Suter, G., Mahdavi, A. 1998. Generation and communication of design information: a building performance simulation perspective, Proceedings of the Fourth Design and Decision Support Systems in Architecture and Urban Planning, Maastricht, The Netherlands.

Suter, G., Mahdavi, A. 2002. Performance-inspired building representations for computational design, Sixth International Building Simulation (IBPSA) Conference, Kyoto, Japan.

Suter, G. 2003. Computer-based representations for building performance, Habilitation Thesis, Vienna University of Technology, Vienna, Austria (to be published).