GEOMETRICAL AND TOPOLOGICAL ISSUES FOR COUPLING DIMENSIONALLY REDUCED MULTIZONE MODELS WITH HIGH-RESOLUTION CFD TECHNIQUES

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ABSTRACT

In this paper we emphasize a technique based on graph theory that allows for deriving both a *dimensionally reduced object model* required for setting up a thermal multizone model and a *geometrical model* for defining a single or multiple CFD domains in a building model together with *incidence matrices* correlating these models. The incidence matrices are an essential precondition for establishing a runtime coupling between both approaches such as automatically providing a CFD model with boundary conditions obtained during a thermal multizone simulation and vice versa. We thereby start from a CAD or a building product model. The algorithm is basically applicable to any building energy simulation tool.

INTRODUCTION

The topic of coupling dimensionally reduced with high-resolution modeling techniques is a complex challenge in the scope of building energy simulation. The problems range from topological and geometrical issues of a building model, numerical issues with respect to the inherent multi-physics characteristics up to the analysis and visualization of results and the evaluation of local thermal comfort criteria. The application of detailed simulation tools is often avoided in the design process because of the costs associated with the definition of numerical models. Moreover, sharing (simulation) data between different platforms is a time-consuming and error-prone process.

Concerning the first issue, we developed a technique based on graph theory that allows for interpreting the geometrical, topological and semantical data of a building (product) model and furthermore for *automatically* extracting indoor air volume bodies and hulls contained within the model. Exemplary, Figure 1 sketches a single floor of an office building with corresponding air volume bodies obtained by our algorithm (four in this case).

Therefore, we identify a structural component graph, a graph of room faces, a room graph and a relational object graph as aids and we explain algorithms how to obtain these relations (see below). Knowing about these relations, it is straightforward to derive both

- a dimensionally reduced object model and
- a geometrical (B-rep) model

together with incidence matrices relating models and components. The object model serves as input for setting up a thermal multizone model while the B-rep model with attributes is required for a corresponding CFD (computational fluid dynamics) model definition. The incidence matrices are an essential precondition for establishing a runtime coupling between both approaches such as automatically providing a CFD model with boundary conditions obtained during a thermal multizone simulation and vice versa. Figure 2 shows the sequence of operations within this discretization process.

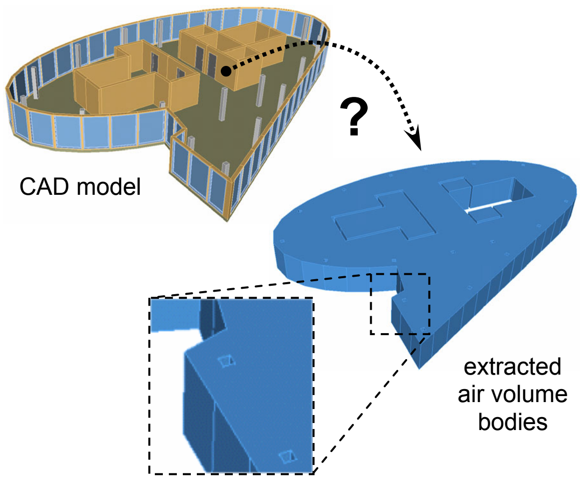

Figure 1: Single floor of multi-storey office building and corresponding set of (here) four air volumes

For the CFD part, we developed a parallel code based on the hybrid thermal lattice Boltzmann method proposed by (Lallemand and Luo, 2003) for simulating 3D turbulent convective flows of Boussinesq-incompressible Newtonian fluids. The code is based on Large-Eddy simulation (LES) and has been extended by a Smagorinsky subgrid scale turbulence model for both the fluid flow (Krafczyk et al., 2003) and the heat flux (van Treeck, 2004) and has been validated with respect to Nusselt number correlations for various Rayleigh numbers (van Treeck et al., 2005). A space-tree based discretization technique (Wenisch et al., 2004) allows for transforming the geometrical B-rep model of a zone air volume obtained by the above mentioned algorithm into a voxel model of the computational domain. The latter serves as input for our CFD solver.

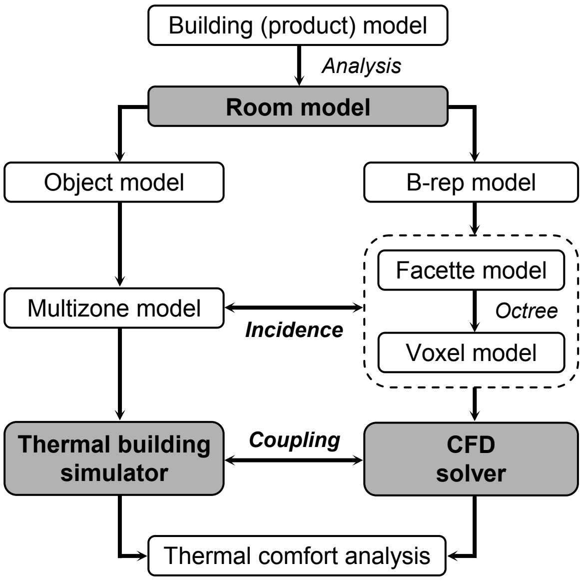

Figure 2: Sequence of operations within the discretization process

Starting from previously proposed algorithms by (Beausoleil-Morrison, 2000) and (Hensen, 1999), a partitioned solution approach has been developed in order to establish a coupling between our CFD code with a thermal multizone model (van Treeck, 2004). For the thermal building simulation, we use the simulation environment SMILE (Nytsch-Geusen et al., 2001) which is extended by a software interface developed by our project partners accordingly. The coupling is explicit, i.e. for a distinct time interval of a multizone simulation, say a whole day in steps of one hour or less, the CFD simulator is provided by appropriate boundary conditions and quasi-stationary solutions of the average velocity and temperature fields are evaluated while using last available solutions as initial conditions each. For a detailed review it is referred to (van Treeck, 2004).

In this paper, we emphasize the topological and geometrical key aspect. The approach is generally applicable to *any* building energy simulation software which provides a software (or at least a file) interface and to *any* CFD solver which supports the ACIS file format (Corney and Lim, 2001) or an STL (stereo lithography file) format. The software technique makes use of an XML-based object-oriented data structure based on the document object model provided by the QT library (QT, 2005). The structure is exchanged between components either via a file interface or by streaming data using a socket communication.

GRAPH DEFINITION

Independently if geometrical informations are obtained from a building product model or directly from a three-dimensional CAD model, a major problem of handling these informations is the *interpretation and preparation* of these data with respect to dedicated tasks such as building energy or structural simulation.

As previously shown in (van Treeck and Rank 2004), we identify four graphs necessary in order to analyze the topological structure of a building and the relations between its individual components.

It should be stressed that these graphs are not provided by a CAD model, even if a building product model or a parametric system is considered. If any, informations available are relations describing mutually connected wall components together with blending shapes or associative links between AEC objects, both of course useful for the design process.

With respect to building energy simulation, the task is therefore to *detect* indoor air volumes rather than drawing new objects manually, to *semantically identify* components together with their interconnections and to *relate* hierarchic models among eatch other.

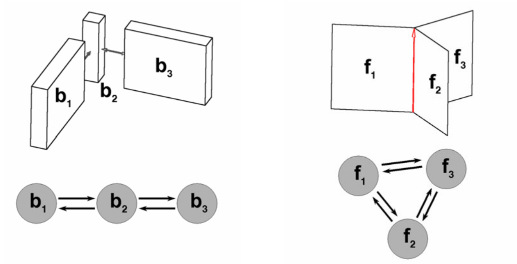

Figure 3: Structural component graph (left) and graph of room faces (right)

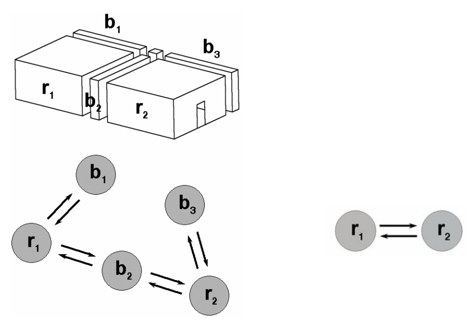

Figure 4: Relational object graph (left) and room graph (right)

Given the geometrical model of a building, we create a *structural component graph* (cf. Fig. 3)

$$G_B = (M_B; R_{PC}) \quad , \quad R_{PC} \subseteq M_B \times M_B \qquad (1)$$

which defines the relation R_{PC} of plane connections between the set of all B-rep volume bodies M_B. Precondition is the decomposition of the entire model into a so-called *connection model*, which is described in the next section. Using the local regularity of a radial-edge data structure, the topological relations R_{NF} between all faces of the solid model M_F can be derived by the *graph of room faces* (cf. Fig. 3)

$$G_F = (M_F; R_{NF}) \quad , \quad R_{NF} \subseteq M_F \times M_F \tag{2}$$

being necessary in order to extract a set of minimum closed B-rep bodies of the model, each representing an indoor air volume. Thereby, the sense of orientation is an important property of faces. Using these relations, we determine the *room graph* (cf. Fig. 4)

$$G_{AV} = (M_{AV}; R_R) \quad , \quad R_R \subseteq M_{AV} \times M_{AV} \tag{3}$$

by partitioning G_F into equivalence classes and subsequent condensation, which is described below. Knowing the set of indoor air volumes M_{AV}, we classify components of M_B. For example, walls can be identified as being outside, interzonal or inside walls. The latter analysis requires the definition of the relation R_I, which defines adjacencies between components M_B and air volumes M_{AV}, and can be expressed by the *relational object graph* (cf. Fig. 4)

$$G_I = (M_B, M_{AV}; R_I) \quad , \quad R_I \subseteq M_B \times M_{AV} \quad . \tag{4}$$

The following sections describe the fundamental procedure to derive these relations.

MODEL DECOMPOSITION

Prior to the analysis, the model is decomposed into a so-called *connection model* M_B. As we already presented the whole decomposition algorithm on the last IBPSA conference (van Treeck et al., 2003), we shall repeat the connection model definition only.

The solid B-rep model $\Omega \subset \mathbb{R}^3$ is obtained by transferring the geometry contained in an IFC building product model (IFC, 2005) using a toolbox system into a solid B-rep model, see (van Treeck et al. 2003) for details.

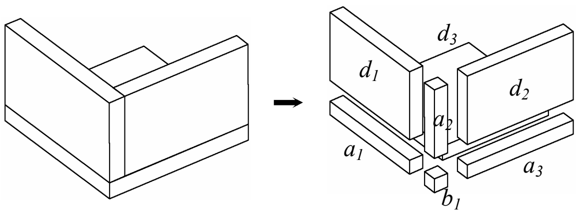

Figure 5: Decomposition into connection model

At locations with coinciding elements of Ω, components are decomposed into so-called coupling objects M_K and difference objects M_D, each representing a rigid body $\subset M_B$. The set of coupling objects can be further subdivided into a set M_{K1} of connection bodies of the base model and the set M_{K2} of connection bodies of the connection model (see Fig. 5) with

$$M_{K1} \cup M_{K2} = M_K \subset M_B \text{ and } M_K \cup M_D = M_B \, . \tag{5}$$

Having r coupling elements a_i of the base model with $i=1,...,r$, s coupling objects b_i of the connection model with $j=1,...,s$ and t difference objects d_k with $k=1,...,t$, we can write

$$\begin{aligned} \bigcup_{i=1,\dots,r} a_i &= M_{K1} \subseteq M_K \quad , \\ \bigcup_{j=1,\dots,s} b_j &= M_{K2} \subset M_K \quad \text{and} \\ \bigcup_{k=1,\dots,t} d_k &= M_D \subseteq M_B \quad . \end{aligned} \tag{6}$$

The resulting model is obtained by a recursive decompositioning algorithm which makes use of boolean operations. Distinguishing mark of the connection model is that local intersections between difference objects result in common edges and/or nodes only. Links between connection objects can be expressed by the symmetric and undirected relation R_{PC}.

AIR VOLUME EXTRACTION

Based on the connection model definition and the structural component graph, we now extract the set of minimum closed and non-closed B-rep shells M_{AV} contained within a model, i.e. indoor air volumes, hulls and, as side effect, also improperly modeled regions. The idea is to recursively analyze adjacency relations between the set of faces M_F of all objects being part of the set M_B.

In order to extract air volumes, various techniques are commonly used. A well-known method makes use of the definition of the polygonal shape of a ground plane. The area obtained is extruded using a sweeping model. A different approach utilizes an algorithm to find the convex hull based on a set of vertices, which e.g. is obtained from surrounding faces. The deficiencies of these techniques are obvious. In the former case, a unified room height is assumed and connections between rooms cannot be taken into account. The latter method is restricted to convex bodies; shapes with reentrant angles are not permitted. However, especially buildings are 'affected' by e.g. inclosed columns and typically non-convex shapes. We think that the techniques mentioned are *not suitable* to derive a room graph or to supply simulation tools with appropriate data (e.g. for the meshing process required for an indoor air flow simulation).

The analysis based on graph theory presented in this section allows for identifying closed and non-closed bodies contained within a model, independently whether being convex or non-convex or whether existing in a manifold or non-manifold environment. In order to reduce complexity, we shall consider plane faces only. It should be mentioned that the algorithm is universally valid, because the analysis is of intrinsically topological nature. As the full algorithm is given in (van Treeck, 2004), we restrict this section to the key issues.

- We start from a set of faces M_F provided by all objects being part of the set M_B.
- The sense of orientation of all faces M_F is inverted, i.e. the direction of face normals is reversed, in order to find indoor air volumes rather than describing rigid bodies now.
- The B-rep model is collapsed into a radial-edge data structure (Corney and Lim, 2001). This has two reasons. Firstly, instances of vertices, edges and faces shall exist exactly once at same locations. Vertices are conflated in an ε-environment to smooth inaccuracies due to round-off errors. Secondly, the radial-edge structure allows for arranging topological coedge elements with respect to the geometrical alignment of their dedicated faces.
- Faces with plane connections denoted by the structural component graph are removed because these faces do not contribute to the range of air volume bodies.
- Coinciding curves are detected and further decomposed.

Key issue of the subsequent analysis is the definition of a relation R_{NF} (indicating 'next neighboring' faces) that strongly depends on the topological and geometrical configuration of the face elements in space. We follow the principles of the definition of rigid bodies, i.e. we require that surfaces are closed shells, faces possess an orientation (law of Möbius) and that faces are not allowed to intersect with themselves (Bungartz et al., 2004) but we additionally intend to find smallest volumes respectively.

Essentially, we formulate two criteria, a topological and a geometrical one. Concatenating both criteria yields a symmetric, anti-reflexive and unweighted graph of room faces. In the sense of graph theory we now extract connected components of this graph.

For example, Figure 6 shows the graph of room faces of an air volume body with inclosed column. A face in the model corresponds to a node in the graph having links to adjacent faces. The top face marked is connected to eight faces: the four edges of the outermost polygon are in contact to the 'outside walls' while the four edges describing the hole are connected to the faces of the penetrating column.

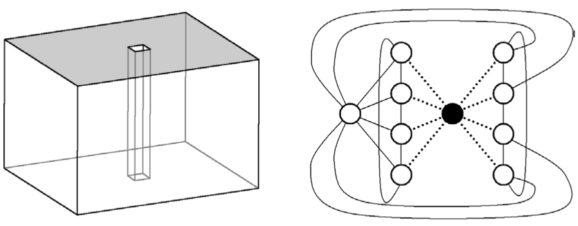

Figure 6: Graph of room faces of indoor air volume with inclosed column

The *topological criterion* for a connection component describing a closed air volume body requires that each edge of each face has exactly one connection to another face where leaf vertices are not permitted and that components are cyclic connected.

In order to obtain the set of *smallest* volumes contained in the model, a *geometrical criterion* shall ensure to get immediately next neighboring faces spanning the smallest volume possible if more than two faces are connected by a common edge. Furthermore, the face orientations must fit to each other in order to describe valid B-rep bodies, with all face normals e.g. pointing to the exterior side. This complex geometrical analysis which makes use of a radial-edge data structure is described in (van Treeck, 2004) in detail.

However, it can be shown (van Treeck, 2004) that a closed B-rep shell describing either a room air volume or a hull is represented by a basic cyclic connected component of the graph of room faces G_F if the mentioned topological and geometrical criteria are fulfilled. Therefore, the graph G_F is partitioned into n basic equivalence classes $[\lambda_i]$ with $i=1,...,n$ using an appropriate equivalence relation (cf. Pahl and Damrath, 2001). This equivalence relation is obtained by evaluating the refexive-transitive hull of the relation $R_{NF} \subseteq M_F \times M_F$.

Moreover, the set of faces of the solid model M_F can be condensed which yields the reduced graph G_{AV} that we denote as *room graph* (cf. Fig. 4).

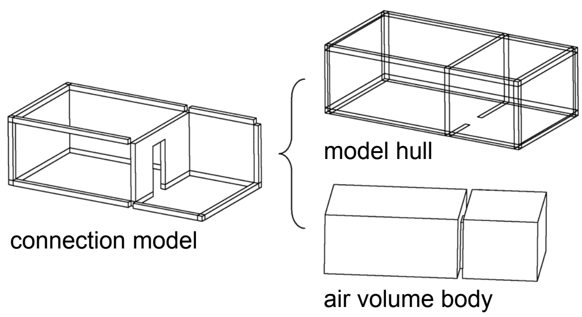

Figure 7: Air volume extraction of model with two rooms being connected by open door

For example, Figure 7 shows on the left-hand side the part of a connection model of two rooms being connected by an open door. Accordingly, the graph analysis yields (a) the model hull and (b) the corresponding air volume body, see right-hand side of Figure 7. In order to distinguish between hull (half space) and air volume ('valid' B-rep body) we apply the Gauß integral theorem for computing body volumes. We would like to mention that this allows for further detecting modeling inaccuracies such as non-closed shells. These patches can be highlighted by a wireframe model indicating (and especially locating) the cause of an improper zone configuration.

The algorithm makes use of the object-oriented data structure of the geometrical model and is implemented using a depth-first search tree in C++. For the whole mathematical derivation and implementational aspects it is referred to (van Treeck and Rank, 2004) and (van Treeck, 2004).

SAMPLE MODEL

Unlike manually assigning components with their function, the knowledge of the structural component graph, the set of air volumes and thus the room graph establishes the basis for further analysis of the model. This will be demonstrated using the sample model given in Figure 8. Figure 9 shows the decomposed model and Figure 10 the set of air volumes obtained.

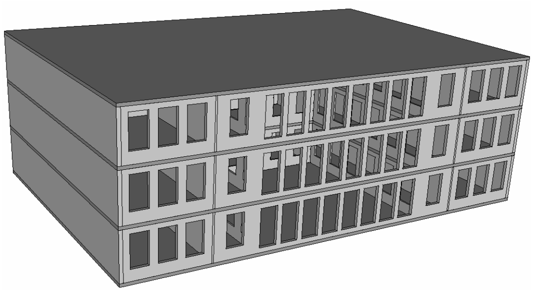

Figure 8: Sample model with inner courtyard

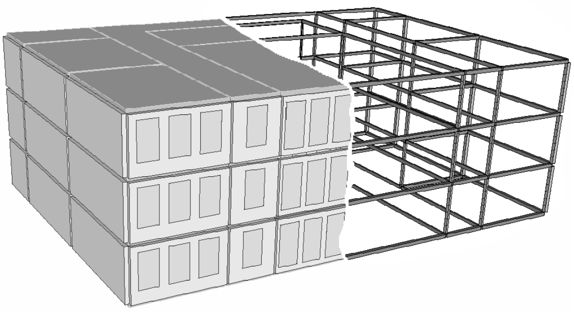

Figure 9: Decomposed model with difference and coupling objects, respectively

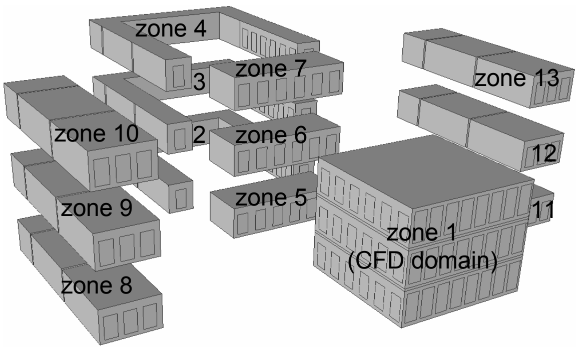

Figure 10: Extracted air volumes and aggregation to zones, e.g. zone 8 is composed of three air volumes

Air volume bodies itself can be aggregated in order to form contiguous areas. Intuitively, handling air volume bodies given by the building design and current configuration is the most native way for defining zones. A CAD user *visually understands* the building structure rather than just 'storing' self-defined lists of walls and objects in a dialog box.

INCIDENCE MATRIX

Given the set of air volumes M_{AV} and the model hull, the relational object graph G_I with its incidence matrix $R_I \subseteq M_B \times M_{AV}$ can be established (cf. Fig. 4). R_I is a heterogeneous binary relation formed by regular pairs (c_i, $[\lambda_j]$) of components $c_i \subset M_B$ and air volume bodies $[\lambda_j] \subseteq M_{AV}$ if both objects are in plane contact respectively. In our software, the identification of objects is accomplished by assigning unique unified identifiers to objects.

COMPONENT IDENTIFICATION

With the relational object graph it is straightforward to analyze components of the connection model with respect to their semantics and to store these informations in the model using body and face attributes. Structural components such as walls, slabs or plates can be identified being *external, outside, internal, interzonal* (or *invalid*) elements as shown in Figure 11.

In the following we consider components $M_D \subseteq M_B$ of the difference model only. Clearly, this corresponds to using internal dimensions in the setting of thermal building simulation and implies the utilization of linear thermal bridge heat loss coefficients in simulations in order to eliminate the error introduced by this simplification.

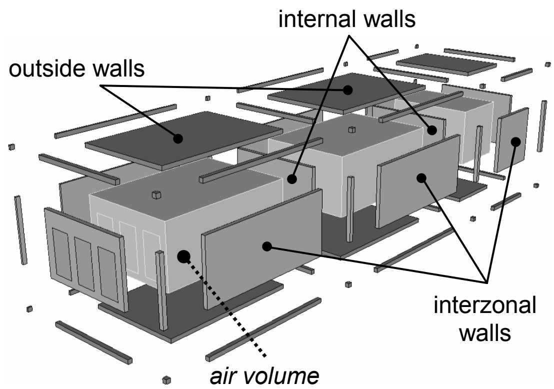

Figure 11: Identification of components

In order to set up boundary conditions in simulations, interfaces between air and components are characterized by attributing the objects' faces accordingly. Face attributes are *{ambient, airvolume, none, invalid}*, depending on a next neighboring entity. The algorithm for the identification is given in (van Treeck, 2004).

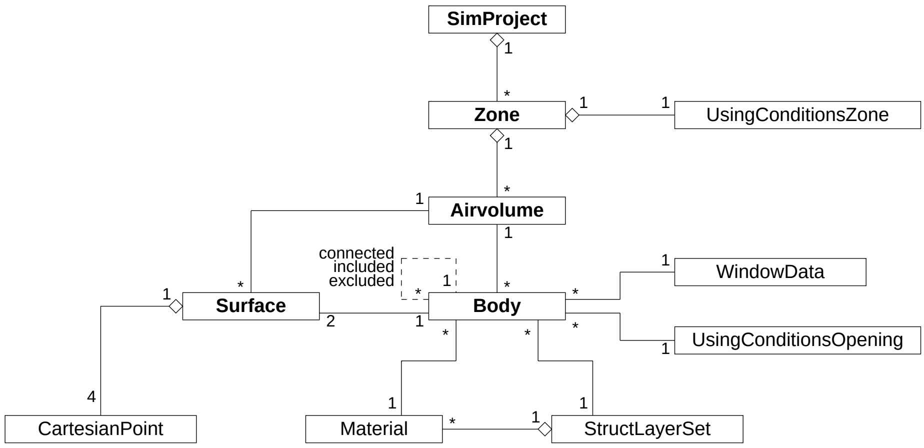

Figure 12: Multizone object model

OBJECT MODEL

Knowing the relational object graph G_l, we can reduce the model complexity by deriving an object-oriented model in order to set up a thermal multi-zone building simulator. Buildings are hierarchically structured systems and are usually organized in storeys, rooms and building components. We drop this view by recognizing zones as aggregations of air volume bodies.

The layout of the object model was choosen according to the work of (Nytsch-Geusen et al., 2001), i.e. in parts similar to the system architecture of the building model in the simulation environment SMILE, and is shown in Figure 12.

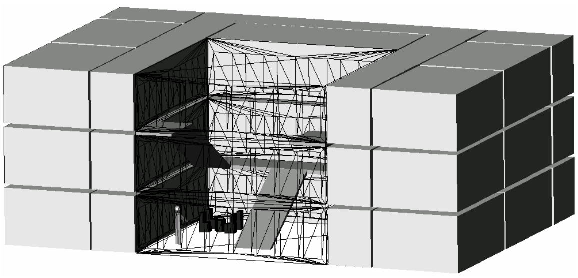

Figure 13: Facetted surface mesh of CFD domain with staircase and occupants

Thereby, a simulation project aggregates a number of zones, where the latter aggregate one or more air volumes. Air volume objects know about the corresponding set of adjacent bodies and their semantics. Structural elements itself are composed of a multi-layered structure with individual materials each. Although part of the geometric model, we additionally store the surface geometry and vertex coordinates. This allows for directly transferring the object model only and without further exchange of the B-rep model for establishing and a multizone model and linking it to one or more CFD domains.

LINKING TO A CFD DOMAIN

Limited by computing capabilities, a detailed CFD computation is applicable at single zones such as an inner courtyard and within distinct time intervals only. Figure 13 shows the formation of air volumes and the facetted surface mesh of the CFD domain, i.e. the atrium with staircase and occupants inside.

As the thermal building model supplies CFD with appropriate boundary conditions (and as the case may be vice versa), both models are linked using the relational object graph.

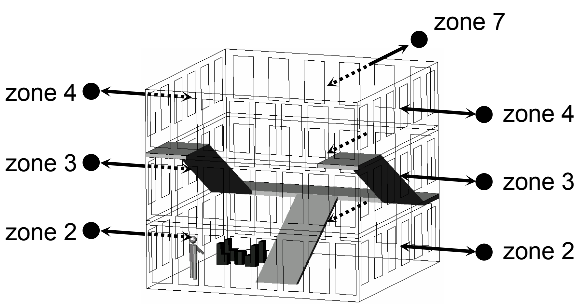

Figure 14: Links between dimensionally reduced object model and geometrical model

More precisely, the surface of the object's layer next to the flow model is to be linked to the computational domain. In our specific case, the latter is a voxel model obtained by a space-tree discretization (compare to Fig. 16) starting from a facetted surface mesh. Our CFD solver is based on the hybrid lattice Boltzmann method and requires a uniform cartesian grid as input (cf. van Treeck et al., 2005). Having a facetted surface mesh (which can be easily derived from the B-rep model), the discretization process takes a few seconds computing time only. This is regarded as one of the major advantages of this technique, especially if applied to computational steering applications as demonstrated in (Wenisch et al., 2004).

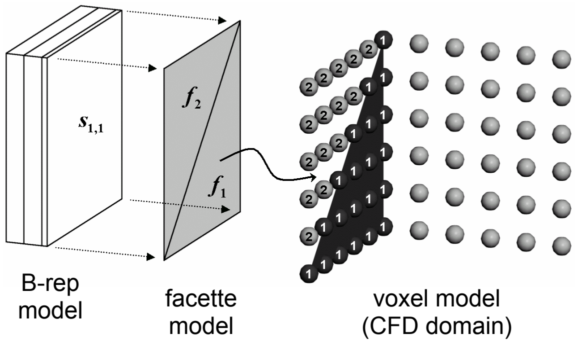

Figure 15: Link between B-rep model and voxel model (CFD domain)

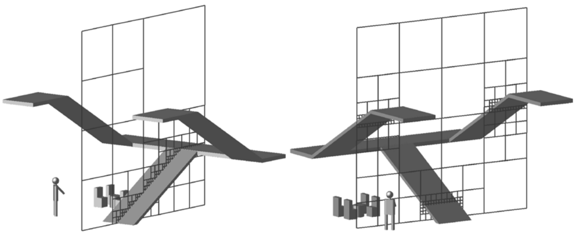

Figure 16: Vertical cut through octree discretization (quadtree representation, levels 0 to 6 displayed)

With given boundary conditions, a CFD simulation can be initiated. For example, Figure 17 depicts streamlines injected to the averaged velocity field for the case of turbulent natural convection in the courtyard at a moderate Rayleigh number of 10^8.

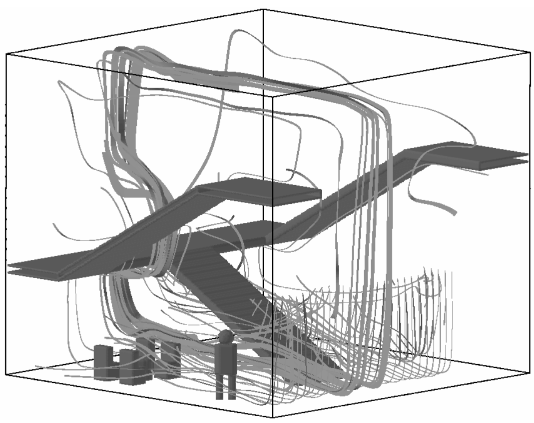

Figure 17: Natural convection in inner courtyard induced by boundary conditions computed by a thermal multizone simulation (streamlines are injected at horizontal plane at front fassade)

For a complete discussion it is referred to (van Treeck, 2004).

CONCLUSION

In this paper, we discussed algorithms for the analysis and interpretation of building (product) model based geometry in order to support the linking of computer aided design tools with numerical simulation techniques. In order to interpret the geometrical, topological and semantical data of a building model, we identified a structural component graph, a graph of room faces, a room graph and a relational object graph as aids and we explained algorithms to derive these relations. The technique allows for deriving a dimensionally reduced object model together with a geometrical model and for relating both models hierarchically.

Building simulation is one of the most important aids in the scope of energy-efficient building design, in predicting energy consumption of buildings and in estimating thermal comfort. Although restricted to distinct time intervals, limited areas and relatively small Reynolds and Rayleigh numbers, also CFD becomes a meaningful tool in engineering practice. As mentioned in the first section, the application of these simulation tools is often avoided because of the costs associated with the model definition and the cumbersome process of sharing and exchanging data between applications. With the integrated technique on-hand, we would like to contribute to this situation as we furthermore expect that three-dimensional modeling techniques will substitute the still primarily applied draft-oriented two-dimensional modeling approach in the near future.

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NOMENCLATURE

G_{AV} room graph

G_B structural component graph

G_F graph of room faces

G_I relational object graph

M_{AV} set of air volume bodies

M_B connection model

M_D set of difference objects

M_F set of faces

M_K set of coupling objects

R_I component / air volume relation (incidence)

R_{NF} relation of next neighboring faces

R_{PC} relation of plane component connections

R_R relation defining room adjacencies

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