Combining Geometry, Topology and Semantics for Generic Building Description and Simulations

Sébastien Horna, Guillaume Damiand, Abdoulaye Abou Diakité, Daniel Meneveaux

Combining Geometry, Topology and Semantics for Generic Building Description and Simulations

S. Horna [1] & G. Damiand [2] & A. Diakité [2] & D. Meneveaux [1]

[1] XLIM Institute, UMR CNRS 7252, University of Poitiers
[2] Université de Lyon, CNRS, LIRIS, UMR5205, F-69622 France

Abstract

2D and 3D virtual architectural models are the common ground of many studies, including environmental protection, energy saving, or human well-being. Building or urban environment simulations concern for instance heat transfer, lighting, and acoustics, each of them requiring physical parameters additionally to the geometric representation. Furthermore, geometry does not generally comply straightforwardly with physical parameters and users are forced to manually adapt the models before simulation. This paper proposes an overview of modeling and simulation studies that make use of topological representations, and discusses the advantages of a topological representation for various types of applications. Such a representation can be used not only to maintain the 3D model global coherence, but also to automatically retrieve walls, doors, or room volumes for instance. Based on the existing model of generalized maps, this paper also illustrates some examples of structure traversal that can be used for providing the users with adequate simulation data.

Categories and Subject Descriptors (according to ACM CCS): I.3.3 [Computer Graphics]: Building Simulation—3D Building Topology

1 Introduction

While many applications have been developed in the last two decades in the architecture community, a general representation that combines geometry, semantics and physical properties still remains difficult to define. This problem has been identified by the community for long, and Industry Foundation Classes (IFC) have been developed to tackle this problem. One remaining challenge concerns the practical use of this format since each property has to be managed by different software, depending on the application, and some information rely on the user expertise, which is unfortunately not sufficiently reliable for many application cases.

For instance, using a 3D scene directly from a geometric modeling tool for a specific simulation software does not provide directly all the practical information. One major question concerns the specific volumes required for the simulation. For instance, lighting simulation makes use of room volumes while accoustic simulation requires wall volumes. In addition, some adjacency information can be very useful for complex environments and out-of-core processing [JMA90, TFFH94, FMH05]. Due to the lack of data, the user has to edit often manually the 3D models for adding some new or differently structured geometry, and to make it compliant with the simulation software standards. Furthermore, if another type of simulation has to be performed, this manual processing is again required.

As shown by several authors [BC07, LCT07, KMKM07, CCSS07], topological representations can efficiently describe neighborhood and incidence relations in a building or a city and bring some very useful and efficient processing with some applications. For instance, it makes it possible to propagate straightforwardly some information from one volume to another one through an identified shared face.

This paper discusses the existing topological representations proposed by previous authors in Computer Graphics and Computational Geometry. It generalizes the use of one

Author version of paper "Combining Geometry, Topology and Semantics for Generic Building Description and Simulations; Horna S., Damiand G., Diakité A. A., Meneveaux D.; Proc. of 3rd Eurographics Workshop on Urban Data Modelling and Visualisation, Eurographics Digital Library, pages 13-18, November 2015, Delft, the Netherlands"

of them for several applications. We describe a topological model employed for more than two decades in computer graphics, and show in this paper that many applications in architecture can benefit from such a representation, from 2D modeling to 3D simulations systems, including 3D buildings update, lighting simulation, and structure export for accoustic, thermal or radio propagation simulation systems. More precisely, the contributions of this paper include:

- a state of the art of topological structures described in architectural representation and their advantages;
- a discussion about some data structure designed for computer graphics applications, with its advantages over ad hoc representations;
- the description of some export operations dedicated to various types of data used in simulation systems.

The remaining of this paper is organized as follows. Section 2 discusses the use of topology for architectural structures, and the existing models in the computer graphics community. Section 3 explains how some basic topological operators can be used to iterate through the different parts of a building and to provide simulators with various types of information. Section 4 contains examples of semantical and topological usage for different kind of simulation. Finally, Section 5 concludes and presents future work.

2 Topological Models and Architecture

Topological representations have been used for long in the computer graphics community since they provide some information that can be used efficiently for covering geometric objects, finding edges, faces or volumes of a given object part. They have been essentially developed for computational geometry purposes, but some ideas have been used by various authors in the architecture community.

2.1 Adjacency Needs for Simulation

Several authors have addressed the general question of simulation in the context of architectural environments, underlining the difficult issue concerning the 3D model representation [HL12, CH15, YBG15, Neg15], and the need for neighborhood information, volume or surface specification and physical properties.

For instance, the representation required for airflow or wind simulation is based on room volumes, portals and façade [vTR05, BC07, AMMB15]; heat transfer additionally requires some of the building structure information [SB05]: partition walls, ceilings, roofs, etc. Some approaches even focus on a detailed description of windows for heat transfer and energy saving [CAH*01, BPvdV05, CYK14], sometimes even including windows profile with double glazing and gas.

Some authors have identified several advantages in using topological information, for recovering adjacency and incidence information. For instance, in the context of heat transfer, incidence graphs have proven useful [RB15, vTR05, vTR07], and provided with semantical information: air volume, internal walls, outside walls, or interzonal walls. Bormann et al. propose directional operators and a spatial query language [BR09]. Some other authors have focused on topological reconstruction from existing 2D plans [DGF12, HMDB09], hierarchical modeling of buildings [FML06], or employed adjacency graphs, or more detailed topological representations for visibility and lighting simulation [JMA90, TFFH94, MBSB03, FMH05, MHA14].

The above models often rely on different type of adjacency graphs depending on the specific fields. Unfortunately, the definition of a generic adjacency graph valid for any type of building and any simulation remains a challenge. The next section discusses some topological models used for more than two decades with computational geometry algorithms, and one of them is chosen as an example. We show that such model can be used not only for geometric modeling, but also to export many types of information thanks to an efficient structure management and traversal.

2.2 Topological Models

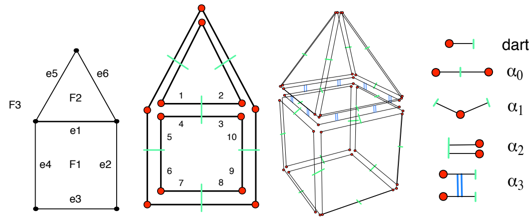
Topological representations have been employed in computer graphics for many years, including winged edges [Bau75], half-edges [Wei85], radial-edges [Wei88] combinatorial maps [Jac70, Vin83], generalized maps [Lie91, Lie94], mainly in the context of geometrical modeling or computational geometry.

The main interest of these topological models is to describe the topology of the objects, i.e. a subdivision in cells plus incidence and adjacency relations between these cells. Another interesting advantage is that many geometrical and topological operations are already defined for building and editing 2D or 3D objects [DL14].

Generalized maps as an example

Generalized maps (or n-Gmaps from now on, n being the used dimension) define the topological structure of geometric objects (object cells and adjacency/incidence relationships). They are based on a single type of basic element (called *darts*) and one to one involutions (called α) defined on these darts. Each involution α_i, with $0 \leq i \leq n$ (n being the dimension of the considered space) represents the adjacency relationships between *i-dimensional* cells. α_0 represents a link between two vertices, α_1 links two edges, α_2 links two faces and α_3 links two volumes (cf. Figure 1).

The object shape is described in a geometrical layer added to an n-Gmap; in practice, an Euclidean point is associated with each vertex of the n-Gmap. Due to its formal and mathematical definition, generalized maps allow to ensure consistency, and many authors use this structure for various operations [CD99, BSP*04, GSDL06]. They have also been used in the context of urban data topology compression [PGBM05].



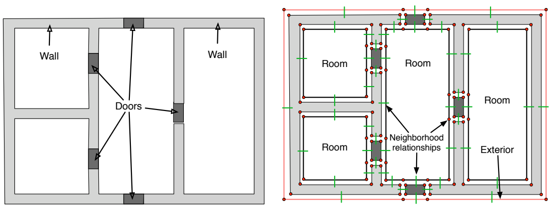
(a) (b) (c) (d)

Figure 1: *n-Gmap representations. (a) A 2D object containing 3 faces, 6 edges and 5 vertices. (b) Corresponding 2-Gmap: the set of darts {1,2,3,4} represents edge e_1, the set of darts {3,4,5,6,7,8,9,10} represents face F_1. (c) 3D object composed of 2 volumes represented with 3-Gmap. (d) Symbolic representation of involutions.*

Topology and architecture

Topological representations have been enriched by several authors with specific building information. For instance, hierarchical 3D modeling [FML06] or 3D building reconstruction from 2D plans [HDMB07], or specific semantic information retrieval [DDVM14], include semantical and physical data. Some of them have been used explicitely for lighting simulation [FMH05, MHA14], or radio-wave propagation [CVPA07].

In the real world, architectural environments correspond to oriented structures, with closed and disjointed volumes, faces and edges. Rooms, walls, doors or windows can be defined as a closed and oriented 3D partition (or 2D partition for plans) [HDMB07]. Each volume can also be identified using semantics such as ROOM, DOOR, WALL, GROUND, CEILING or EXTERIOR, and neighborhood constraints can be defined, depending on the application [HMDB09] (Figure 2 illustrates a scene complying to the topological model).



(a) (b)

Figure 2: *2D scene illustration complying the model properties. (a) Architectural plane representation. (b) Topological and semantics information: each face corresponds to one element (room, wall, ...); Topology represents neighboring relationships; Semantics specify types.*

Such a detailed representation provides a formal framework for 3D modeling, data analysis or error detection. Modeling operations can also be defined for editing the architectural structure: doors or windows addition, translation of windows, thickening of walls, etc. For the sake of efficiency, semantics and physical properties are directly attached to darts (in practice using pointers), allowing direct access to data. Various other strategies can be considered for avoiding redundancies (for example with removal and contraction operations [DL14]).

3 Iterating Through Building Parts

Based on this complete structure (topology, geometry, semantics), some low-level topological operators can be used to iterate through the different parts of the building. They consist mainly of iterators through specific parts of the model, mixing neighborhood relationw, semantics, and geometrical information.

The examples given in the next paragraphs show how various types of elements can be chosen (and for instance provided to some simulation tool) amongst the complete data structure. These examples can be extended for taking into account various types of information. Note that the topological structure can be seen as a graph, where each neighbor relation is labeled with a dimension.

Iterate through building volumes

The first example explains how it is possible to iterate through all the building elements, or through all the elements having a specific semantic. This can be done easily in a 3-Gmap, even if volumes are only implicitly represented, as shown in Algorithm 1. The main principle of this algorithm is to iterate through all the darts and to mark (with a Boolean) all the darts belonging to the same volume (i.e. considering all darts that can be obtained iteratively through α_i, with $i \neq 3$). Boolean marks ensure that each volume is considered/processed only once.

This Algorithm can be tuned easily to iterate only through volumes satisfying a given criterion, for instance room and/or wall volumes, by considering only darts satisfying the criterion.

Iterate through the faces of a given volume

As a second example, Algorithm 2 describes the iteration process through the faces of a given volume, from a given dart. This operation can be used for estimating the global area of a room, or for identifying the faces composing the facade of a building. The darts of a face are marked in the loop between lines 9 and 13 of the algorithm, and darts $\alpha_2(\mathtt{d}')$ are pushed in the stack since they may belong to faces not processed.

Walking through rooms

The last example developed in this paper uses various information. Algorithm 3 looks for a path between two given

Algorithm 1: Iterate through 3-Gmap volumes

```
Input: gm: a 3-Gmap.
Result: Run through all the volumes of gm.
P ← an empty stack of pointer to darts;
foreach dart d ∈ gm do
    if d is not marked then
        // process dart d which belongs to
           a new volume
        push(P, d);
        while P is not empty do
            cur ← top(P);
            pop(P);
            if cur is not marked then
                mark dart cur;
                // add darts in the same
                   volume, i ≠ 3
                for i ← 0 to 2 do
                    push(P, α_i(d));
unmark all darts;
```

Algorithm 2: Iterate through all the faces of a given volume in a 3-Gmap

```
Input: gm: a 3-Gmap; d: a dart.
Result: Run through all the faces of the volume containing d.
P ← an empty stack of pointer to darts;
push(P, d);
while P is not empty do
    cur ← top(P);
    pop(P);
    if cur is not marked then
        // process dart cur which belongs
           to a new face
        d′ ← cur;
        repeat
            mark dart d′; mark dart α0(d′);
            push(P, α2(d′));
            d′ ← α1(α0(d′));
        until d′ = cur;
unmark all marked darts;
```

rooms of the building, through doors. It uses the operator defined in Algorithm 2 to iterate on the faces of a given room volume, and gets through the door faces and volumes to find the adjacent room. The test is repeated recursively to find the path if it exists.

From a given face f represented by one of its darts, the algorithm looks at the semantic information of the adjacent volume, corresponding to $\alpha_3(f)$, line 5 in the algorithm. If a door is found, the dart of the second room around this door is obtained directly using $\alpha_3(\alpha_2(\alpha_1(\alpha_0(\alpha_1(\alpha_2(\alpha_3(f)))))))$ (with the shortcut $\alpha_{3210123}(f)$ used in the algorithm).

Algorithm 3: Walk in a building between two given rooms

```
Input: gm: a 3-Gmap;
       d: a dart belonging to a first room;
       d′: a dart belonging to a second room.
Output: true iff there is a path between rooms containing darts
        d and d′.
Result: Walk between the two rooms, it there is a path.
1  if darts d and d′ belong to the same volume then
2      // The path is found.
3      return true;
4  foreach face f of the volume containing d do
5      if α3(f).semantic = DOOR then
6          // Goes through the door
7          d″ ← α3210123(f);
8          if Walk(gm, d″, d′) then
9              return true;
10 return false;
```

The sequence of traversed rooms can easily be recorded during the algorithm, pushing a dart for each room and/or each door at the end of a list. Again, the method can be easily updated in order to account for specific constraints. For example, a test could be inserted in line 5 to pass through doors only greater than a given width, with the idea to estimate paths for wheelchairs.

4 Simulation Examples Using Topological Information

The representation described in the above section contains not only the geometric description, but also some important topological descriptors coming with iterators that can be extended and enriched. All the architectural structure volumes are defined. For instance the wall volumes are connected to the corresponding room volumes, and they can both be separately considered if desired according to an adequate algorithm.

Simulation tools are based on physical propagation (light, radio-wave, heat, sound, air, etc.) through architectural structures. The main differences concern the elements that should be accounted for during the propagation. Figure 3 illustrates an example of ray propagation through rooms, and the corresponding topological volumes. Ray propagation is made possible with the α_3 involutions that provide a direct link to the adjacent volumes during the propagation.

Among the existing simulation systems used for building and urban environments, the input data contain many types of information that can be quite different [HL12]. The following paragraphs provide three examples of simulation tools that make use of topological representations.

Lighting simulation

The literature concerning lighting simulation is vast, and various methods have been employed in the context of building

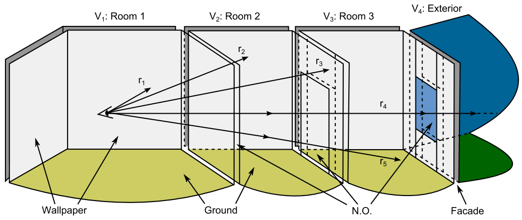
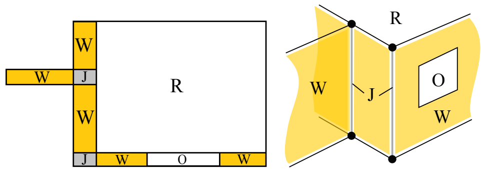


Figure 3: *Ray propagation through topology, geometry and semantics. Rays start from Volume V_1; they are propagated in the adjacent volume if they hit a non-occlusive (N.O.) face and stopped otherwise.*



(a) 2D view of volumes (b) Thin plate model

Figure 4: *Example of a room (R) surrounded by walls (W), containing an opening (O) and forming junctions (J).*

simulation, with some topological representation, such as radiosity [JMA90, TFFH94, MB99, MBSB03], photon mapping [FMH05] or path tracing [MHA14]. Lighting simulation requires room volumes and windows; opaque wall interiors can be ignored since the do not propagate light. Each volume can be identified with topological data structure using the appropriate volume record (room, doors and windows faces), and visited using Algorithm 2.

Radiowave propagation

Radio propagation simulation systems require room and wall volumes for transmission, they should also take into account edges for diffraction [VPE04, CVPA06]. In this case, the description of objects such as iron pillars inside the walls should be integrated in the topological representation, with their physical properties. With a topological model, they can be straightforwardly integrated, given the existing geometric modeling operations. Again, using semantics and topology, all these volumes and the corresponding faces can be straightforwardly identified using Algorithms 1 and 2 and given as input of simulators.

Acoustics

This last example shows how topology can also be used efficiently for modifying more deeply the building structure. Acoustic simulation systems also rely on room, opening and wall volumes, but they are used as interfaces within actual simulators (faces, and thin plate model, illustrated in Figure 4) [CST15]. The thin plate model corresponds to a flattening of all the walls/floors of the building structure, such that walls become faces, junctions become edges and rooms remain volumes; openings are parts of walls.

The thin plate structure can be obtained from a building model described by a 3-Gmap, iterating through all volumes. Algorithm 1 is applied to volumes associated with the semantic ROOM; all the corresponding faces are browsed thanks to Algorithm 2.

Similar operations are performed on volumes with semantic WALL, and a specialization of Algorithm 2 addresses the faces F linked to room volumes such that $\alpha_3(\mathtt{f})$.semantic $=$ ROOM. Those type of faces all around the wall volume are used to define the double-sided plates. In addition, faces F of wall volumes that are linked to other walls such that $\alpha_3(\mathtt{f})$.semantic $=$ WALL correspond to the wall-to-wall junctions.

5 Conclusion

The question of the structural and virtual representation of architectural models is of high importance for many applications. As mentioned by several authors, topology, geometry and semantics provide some important information for building and urban simulation and analysis. The different solutions proposed all agree about the necessity of having three levels of description (geometry, topology, semantics) for most applications.

In this paper, we illustrated how topological structures can be used as a basis to combine these three levels of information. Associated with topological operators allowing to iterate through some specific parts of a building, they can be used and specialized to produce input data required by many simulation systems.

The conclusion of this paper is that thanks to such combination of data structure, it is possible to address many different applications, starting from simulation algorithms and going to high level interactive building edition.

References

[AMMB15] AFLAKI A., MAHYUDDIN N., MAHMOUD Z. A.-C., BAHARUM M. R.: A review on natural ventilation applications through building façade components and ventilation openings in tropical climates. *Energy and Buildings 101*, 0 (2015), 153–162. 2

[Bau75] BAUMGART B.: A polyhedron representation for computer vision. In *Proc. of AFIPS National Computer Conference* (1975), vol. 44, pp. 589–596. 2

[BC07] BLOCKEN B., CARMELIET J.: Validation of cfd simulations of wind-driven rain on a low-rise building facade. *Building and Environment 42*, 7 (2007), 2530–2548. 1, 2

[BPvdV05] BOKEL R., PETERS B., VAN DER VOORDEN M.: Cfd-simulations of transparent coated and gas-filled facade panels. In *Building Simulation* (2005), pp. 91–98. 2

[BR09] BORRMANN A., RANK E.: Specification and implementation of directional operators in a 3d spatial query language for building information models. *Adv. Eng. Inform. 23*, 1 (Jan. 2009), 32–44. 2

[BSP*04] BRANDEL S., SCHNEIDER S., PERRIN M., GUIARD N., RAINAUD J.-F., LIENHARDT P., BERTRAND Y.: Automatic building of structured geological models. In *Proceedings of the Ninth ACM Symposium on Solid Modeling and Applications* (2004), SM '04, Eurographics Association, pp. 59–69. 2

[CAH*01] CURCIJA D., ARASTEH D., HUIZENGA C., KOHLER C., R. MITCHELL2 M. B.: Analyzing thermal performance of building envelope components using 2d heat transfer tool with detailed radiation modeling. In *Building Simulation* (2001), pp. 219–226. 2

[CCSS07] CHU G., CHEN T., SUN Z., SUN J.: Probabilistic risk assessment for evacuees in building fires. *Building and Environment 42*, 3 (Mar. 2007), 1283–1290. 1

[CD99] CAZIER D., DUFOURD J.: A formal specification of geometric refinements. *Visual Computer 15* (1999), 279–301. 2

[CH15] CLARKE J., HENSEN J.: Integrated building performance simulation: Progress, prospects and requirements. *Building and Environment 91*, 0 (2015), 294–306. 2

[CST15] CSTB: Acoubat, 2015. http://logiciels.cstb.fr/Acoustique-Acoubat. 5

[CVPA06] COMBEAU P., VAUZELLE R., POUSSET Y., AVENEAU L.: An optimization in computation time for the prediction of radio coverage zones. *Radio sciences 42, RS1003* (2006). 5

[CVPA07] COMBEAU P., VAUZELLE R., POUSSET Y., AVENEAU L.: An optimization in computation time for the prediction of radio coverage zones. *Radio sciences 42* (January 2007). 3

[CYK14] CHO J., YOO C., KIM Y.: Viability of exterior shading devices for high-rise residential buildings: Case study for cooling energy saving and economic feasibility analysis. *Energy and Buildings 82*, 0 (2014), 771–785. 2

[DDVM14] DIAKITÉ A. A., DAMIAND G., VAN MAERCKE D.: Topological reconstruction of complex 3d buildings and automatic extraction of levels of detail. In *Eurographics workshop on urban data modelling and visualisation* (2014), Eurographics Association, pp. 25–30. 3

[DGF12] DOMINGUEZ B., GARCIA A., FEITO F.: Semiautomatic detection of floor topology from {CAD} architectural drawings. *Computer-Aided Design 44*, 5 (2012), 367–378. 2

[DL14] DAMIAND G., LIENHARDT P.: *Combinatorial Maps: Efficient Data Structures for Computer Graphics and Image Processing*. A K Peters/CRC Press, September 2014. 2, 3

[FMH05] FRADIN D., MENEVEAUX D., HORNA S.: Out-of-core photon-mapping for large buldings. In *Proceedings of 16th Eurographics Conference on Rendering Techniques* (June 2005), pp. 65–72. 1, 2, 3, 5

[FML06] FRADIN D., MENEVEAUX D., LIENHARDT P.: A hierarchical topology-based model for handling complex indoor scenes. *Computer Graphics Forum 25*, 2 (June 2006), 149–162. 2, 3

[GSDL06] GRASSET-SIMON C., DAMIAND G., LIENHARDT P.: nd generalized map pyramids: Definition, representations and basic operations. *Pattern Recognition 39*, 4 (2006), 527–538. 2

[HDMB07] HORNA S., DAMIAND G., MENEVEAUX D., BERTRAND Y.: Building 3D indoor scenes topology from 2D architectural plans. In *GRAPP 2007* (Spain, Mar. 2007), pp. 37–44. 3

[HL12] HENSEN J. L., LAMBERTS R.: *Building performance simulation for design and operation*. Routledge, 2012. 2, 4

[HMDB09] HORNA S., MENEVEAUX D., DAMIAND G., BERTRAND Y.: Consistency constraints and 3d building reconstruction. *Computer-Aided Design 41*, 1 (2009), 13–27. 2, 3

[Jac70] JACQUES A.: Constellations et graphes topologiques. In *Proc. of Combinatorial Theory and Applications* (Budapest, Hungary, 1970), vol. 2, pp. 657–673. 2

[JMA90] J. M. AIREY J. H. ROHLF F. P. B.: Towards image realism with interactive update rates in complex virtual building environments. In *Symposium on Interactive 3D Graphics* (May 1990), pp. 41–50. 1, 2, 5

[KMKM07] KAROGLOU M., MOROPOULOU A., KROKIDA M., MAROULIS Z.: A powerful simulator for moisture transfer in buildings. *Building and Environment 42*, 2 (2007), 902–912. 1

[LCT07] LIN Z., CHOW T., TSANG C.: Effect of door opening on the performance of displacement ventilation in a typical office building. *Building and Environment 42*, 3 (07), 1335–1347. 1

[Lie91] LIENHARDT P.: Topological models for boundary representation: a comparison with n-dimensional generalized maps. *Computer-Aided Design 23*, 1 (1991), 59–82. 2

[Lie94] LIENHARDT P.: N-dimensional generalized combinatorial maps and cellular quasi-manifolds. *Int. Journal of Computational Geometry & Applications 4*, 3 (1994), 275–324. 2

[MB99] MENEVEAUX D., BOUATOUCH K.: Synchronisation and load balancing for parallel hierarchical radiosity of complex scenes on a heterogeneous computer network. *Computer Graphics Forum 18*, 4 (Décembre 1999), 201–212. 5

[MBSB03] MENEVEAUX D., BOUATOUCH K., SUBRENAT G., BLASI P.: Efficient clustering and visibility calculation for global illumination. In *AFRIGRAPH'2003 Proceedings* (Le Cap, Afrique du sud, Février 2003), pp. 87–94. 2, 5

[MHA14] MARIA M., HORNA S., AVENEAU L.: Topological Space Partition for Fast Ray Tracing in Architectural Models. In *GRAPP 2014* (2014), pp. 225 – 235. 2, 3, 5

[Neg15] NEGENDAHL K.: Building performance simulation in the early design stage: An introduction to integrated dynamic models. *Automation in Construction 54*, 0 (2015), 39–53. 2

[PGBM05] PRAT S., GIOIA P., BERTRAND Y., MENEVEAUX D.: Connectivity compression in arbitrary dimension. *The Visual Computer, numéro spécial, Springer Berlin Heidelberg 21*, 8 (Octobre 2005), 876–885. Pacific Graphics 2005, Macao, China. 2

[RB15] ROSE C. M., BAZJANAC V.: An algorithm to generate space boundaries for building energy simulation. *Engineering with Computers 31*, 2 (Apr. 2015), 271–280.

[SB05] STRAND R., BAUMGARTNER K.: Modeling radiant heating and cooling systems: Integration with a whole-building simulation program. *Energy and Buildings 37* (2005), 389–397. 2

[TFFH94] TELLER S., FOWLER C., FUNKHOUSER T., HANRAHAN P.: Partitioning and ordering large radiosity computations. In *ACM SIGGRAPH* (1994), pp. 443–450. 1, 2, 5

[Vin83] VINCE A.: Combinatorial maps. *Journal of Combinatorial Theory Series B 34* (1983), 1–21. 2

[VPE04] VAUZELLE R., POUSSET Y., ESCARIEU F.: A sensitivity study for an indoor channel simulation. *Annales des TÈlÈcommunications 59*, 5-6 (May 2004). 5

[vTR05] VAN TREECK C., RANK E.: Geometrical and topological issues for coupling dimensionally reduced multizone models with high-resolution cfd techniques. In *Building Simulation* (2005), pp. 1237–1244. 2

[vTR07] VAN TREECK C., RANK E.: Dimensional reduction of 3d building models using graph theory and its application in building energy simulation. *Eng. with Comput. 23*, 2 (Apr. 2007), 109–122. 2

[Wei85] WEILER K.: Edge-based data structures for solid modelling in curved-surface environments. *Computer Graphics and Applications 5*, 1 (1985), 21–40. 2

[Wei88] WEILER K.: The radial edge structure: a topological representation for non-manifold geometric boundary modeling. In *Geometric Modeling for CAD Applications*. Elsevier Science, 1988, pp. 217–254. 2

[YBG15] YANG Z., BECERIK-GERBER B.: A model calibration framework for simultaneous multi-level building energy simulation. *Applied Energy 149*, 0 (2015), 415–431. 2