SEMANTIC AND TOPOLOGICAL REPRESENTATION OF BUILDING INTERIORS
An Overview

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Abstract: Software related to urban environments has experimented a considerable growth over the last years. This trend makes necessary the creation and management of urban models, both for cities and building indoors. There exists a huge variety of proposals dealing with the geometry, topology and semantics of building indoors. In this paper we give an overview of a number of recent works from several research areas such as Geographic Information Systems (GIS), Building Information Models (BIM), Building Product Models (BPM) and Computer Aided Design (CAD) tools and propose a reference architecture which gathers the analyzed features.

1 INTRODUCTION

Building indoor information is needed for multiple applications covering diverse areas such as GIS, BIM, spatial databases or CAD. Each area uses different approaches to represent the information; for instance, the most extended standard used to manage BIM information in construction is the Industry Foundation Classes (IFC) model. Even within the same research area, a wide range of partial views of the same model can be found, depending on the specific application. A classification of models and application areas would be useful to have a starting point before considering the development of new approaches.

2 BIM AND GIS MODELS

In 1992, Björk (Bjork, 1992) introduces an object-oriented model to represent semantic data of buildings. His work focuses on the definition of a schema including information about spaces and their enclosing entities (walls, columns, doors and windows), being a precedent of the Industry Foundation Classes (IFC) standard.

On the other hand, in the last years GIS systems require more and more information about indoor of buildings. Some works have researched on this topic. Isikdag et al. (Isikdag et al., 2008) propose use case scenarios to implement Building Information Models (BIM) in a geospatial environment. Van Berlo and Laat (Van Berlo and de Laat, 2010) introduce an implementation of the conversion from IFC to CityGML. Cerovsek makes an exhaustive research study about BIM technology (Cerovsek, 2010). This work offers a number of recommendations about how BIM models should evolve in order to make easier the development and standardization of BIM tools.

3 2D MODELS

Franz et al. (Franz et al., 2005) analyze building models under two different points of view: cognitive sciences and architecture. They summarize various existing graph-based models used in both areas, and discuss the transfer of models between them.

Lamarche and Donikian (Lamarche and Donikian, 2004) propose a method to represent the topology of an indoor space for the simulation of crowds of humans. They compute a set of graph-represented convex cells using the constrained Delaunay triangulation of the floor plan. This set is then represented as a graph with nodes for the convex cells and edges for the neighbor convex cells (see Figure 1). This topological representation of the space allow them to identify passages, crossroads and dead ends in order to determine bottlenecks for pedestrians.

Plümer and Gröger (Pluemer and Groeger, 1996) utilize another formal representation for the aggrega-

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tion of 2D spatial objects: the nested maps, defined as planar graphs whose cycles are structured hierarchically, useful to model the hierarchical structure of closed spaces.

Hierarchical region graphs are used by Stoffel et al. (Stoffel et al., 2007) to model the structure of spatial regions and the inclusion relations among them. The data structure includes type parameters to specify the semantics of nodes (doors, windows, etc.) and graphs (rooms, walls, floors, etc.).

Li et al. (Li et al., 2010) represent rooms, lobbies, inner or outer walls, doors and windows using a set of labeled cellular units (free, occupied). A regular decomposition of the space is then made using a grid-graph. Algorithms from graph theory allow to solve some problems of space analysis and agent navigation.

Zhi et al. (Zhi et al., 2003) convert architectural floor plans into an object graph representing the structure of walls and openings, such that loops represent closed spaces. Since rooms are obtained as minimal loops, this work uses spatial vectors of loops to compute minimal area fundamental loops.

Hahn et al. (Hahn et al., 2006) deal with the real-time generation of building interiors. The main characteristics of the generator are: (1) the generation of building interiors is lazy, and (2) a set of rules is followed to ensure the correctness and realism of the results.

Merrell et al. (Merrell et al., 2010) use an approach based on bayesian networks to solve the generation of building interiors starting from high-level requirements. An architectural program is created after training a bayesian network with real data; then the architectural program is turned into a real floor plan by applying optimization over the space of possible building layouts.

4 2D MODELS WITH HEIGHT

Slingsby and Raper (Slingsby and Raper, 2007) deal with pedestrian navigation in 3D city models. After introducing a state of the art on 3D city modeling, pedestrian navigation and pedestrian access within buildings, this work proposes a model to represent navigable spaces in cities consisting of a 2.5D representation of building floors. In order to deal with irregular morphology of floors, they propose the use of four constraint elements: ramps, stairs, breaklines and offsets.

Tutenel et al. (Tutenel et al., 2009) propose a rule-based solver to generate indoor building scenarios automatically which works by using classes to represent 3D shapes (e.g. *Sofa*, *Table*, *TV*) with tags. They propose a rule layout planner, which consists of a backtracking mechanism executed to solve the placement of each object. The solver computes a set of possible locations for the current object according to the previously placed ones, assigning weights to them. Then, it selects the most feasible location.

The arrangement of furniture is also solved by Germer and Schwarz (Germer and Schwarz, 2009). However, they use a different approach in which agents are used to represent pieces of furniture. Each agent is responsible for placing and orienting itself properly, and finding a parent object. In order to achieve this, each agent has three possible states: (1) search, when it has not been processed, its parent has been lost or the search for its position has failed; (2) arrange, when the agent has found a possible parent; and (3) rest, when the arrange is finally successful.

Regarding building rendering, Van Dongen (Dongen, 2008) proposes a technique to simulate building interiors viewed from the street without any storage of geometry. While buildings are modeled using single cubes, the rendering process simulate the existence of rooms, objects and people using a ray-tracing algorithm with diffuse textures and billboard planes.

The structured floor-plan (Choi et al., 2007) consists of a high-level semantic structure which accomplishes with nine principles about object orientation of the model, existence of relationships among entities, managing of spatial information, levels of detail, and automatic creation of 3D models.

5 3D MODELS

Choi and Lee (Choi and Lee, 2009; Lee, 2001) propose a graph structure called *3D Geometric Network*, constructed using the Straight Medial Axis Transform. It represents the connectivity between rooms of a building. Geometric networks also model the 3D structure by means of adding edges between rooms from different floors.

Van Treeck and Rank (Van Treeck and Rank, 2007) represent the topology using a radial-edge structure (Weiler, 1988), which represents relations among vertices, edges, co-edges, loops, faces and bodies, and derives four different graphs: *structural components*, the *room faces*, the *relational objects* and *rooms*.

Borrmann and Rank (Borrmann and Rank, 2009) propose a set of spatial operators to determine the relative position between the bounding boxes of two 3D spatial objects among *above*, *below*, *eastOf*, *westOf*, *northOf* and *southOf*.

Billen and Zlatanova (Billen and Zlatanova, 2003) propose the dimensional model, a topological abstraction which analyzes complex relations between 3D objects using four *dimensional elements* (0-D, 1-D, 2-D and 3-D) for each spatial object.

Boguslawski and Gold (Boguslawski and Gold, 2010) deal with the problem of representing non-manifold CAD models using a data structure called Dual Half-Edge (DHE), consisting basically of two dual structures: a net of half-edges from solids and a dual structure of connected solids.

Clemen and Gielsdorf (Clemen and Frank, 2008) propose a systematic way to reduce the redundancy in geometric models using a generalized representation for models consisting of solids made up by faces contained in planes, half edges and nodes, and ensuring geometric constraints by referential integrity.

Van Berlo and Laat (Van Berlo and de Laat, 2010) collaborate with the introduction of an implementation of the conversion from IFC to CityGML. In order to achieve this, they introduce an extension for CityGML called GeoBIM. Therefore, the underlying geometric, semantical and topological models are the same in IFC and in CityGML.

A schema with four levels of detail is proposed by Hagedorn et al. (Hagedorn et al., 2009) to represent indoor building models. This schema has some similarities to CityGML; however the authors include features for indoor routing, not included in CityGML.

An example of the application of BIM for computer games with indoor scenarios can be found in (Yan et al., 2010). Yan et al. propose an architecture consisting of three modules: BIM, crossover and game. Information about the buildings is managed by the BIM module, while the crossover module is used to exchange information between the BIM module and the game module.

Topological houses proposed by Paul and Bradley (Paul and Bradley, 2003) constitute a purely mathematical abstraction to define houses. This formal definition allows to encode houses using two structures: PLA (points, lines and areas) and PLAV (PLA + volumes).

Finally, Xu et al. (Xu et al., 2010) propose a model including geometric, semantic and topological aspects of 3D City Models. To achieve this, a 3D city model is enriched with a thematic module which contains semantic and topological information; then the items of the thematic module are mapped onto the geometric model. This work also introduces a semi-automatic integration tool for the semantic enrichment process.

6 COMPARATIVE ANALYSIS AND DISCUSSION

In the above sections a number of papers from the literature have been reviewed. In this section we will propose a model which intends to serve as a linking point between low-level geometry, topology and semantics. Later, we will compare the reviewed works and discuss about the applicability of the cited models to different areas.

6.1 Our Proposal: A Three-module Framework

Our goal is to propose an architecture to represent building indoors accomplishing with the following requirements:

1. The model should cover different views of the same model: from low-level geometry of architectural drawings to high-level semantic information about the structural distribution and the connectivity among physical spaces (e.g. adjacency between rooms, between a room and an exterior area of the building, etc.).
2. All the views should be related, so that information from different levels can be mapped efficiently.
3. Other information models should be easily derived from our model.

In order to achieve the described requirements, we introduce a three-level architecture containing information about CAD drawings and topological structure of building indoor (figure 1).

The first module represents the input data of the framework and contains CAD architectural floor plans. They may include information about a variety of aspects such as structure, furnishing, plumbing, electricity, etc. together with meta-elements such as measurements and annotations. Due to the huge variety of possible models represented in CAD floor plans, we will propose a set of constraints on the range of input data. The second module contains the information relevant to represent the structure of a building interior, i.e., walls and openings, obtained as the result of semiautomatically filtering the information of the first module. The available low-level geometry elements (wall lines and opening blocks), are processed in order to obtain high-level information (walls, wall intersections and openings). The third module contains a topology graph derived from walls and openings. Its associated dual graph represents the subdivision of a building into closed spaces. Finally, the room structure gathers structural and semantic information (topology graph) and geometric information (wall lines).

An initial approach of our proposed model has been tested with real CAD floor plans with promising results:

- CAD floor plans have been processed semiautomatically in order to get semantic and topological features like walls, rooms (including their inner polygons and their contour).
- Geometric information from CAD floor plans is linked to semantic information obtained semiautomatically.
- We have successfully implemented modules which automatically export instances from our model to CityGML and COLLADA.

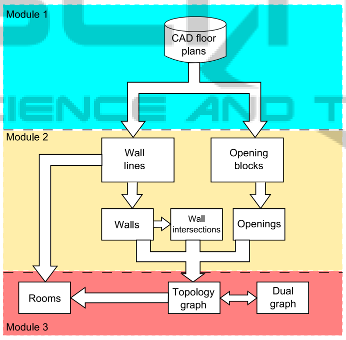

Figure 1: Framework based in a three-level architecture to represent building information models.

6.2 Comparative Analysis

Before presenting a summary of the main features of the reviewed papers (table 1), we introduce some previous considerations related with geometry, topological connectivity, topological adjacency and semantics.

6.2.1 Geometry

The majority of the reviewed papers include geometrical information as the basis of their models. However, they do not deal with geometry at the same depth. We distinguish among the following items:

1. Works that do not mention anything regarding geometry because they only focus on semantic issues. They appear in table 1 with a dash (-).
2. Works mentioning geometric elements without giving details of the underlying representation. They appear as *implicit*.
3. Geometric elements like vertices, edges, faces, regions, discrete cells or volumes appear abbreviated respectively as V, E, F, R, DC, VO.
4. Other works use spread models like IFC, CityGML, Geographic Markup Language (GML) or BIM's

6.2.2 Topology

We distinguish among connectivity and adjacency, when applicable.

1. Two spaces in a building model are topologically connected if there exists a door or a window between them. Thus, models with information about openings have topological connectivity. Connectivity is explicit if it appears represented in the model, and implicit if it can be deduced by analyzing the model.
2. Two spaces in a building model are topologically adjacent if they share at least one item (e.g. rooms sharing one wall). Adjacency is explicit if the model contains information about relationship between spaces, or implicit if the model does not contains this information, but it can be deduced analyzing the geometry.

6.3 Semantics

For each reviewed work, we specify which semantical items it contains, according to the legend: RO, O, PA, CR, S, T, W, L, C, CO represent respectively rooms, openings, passages, crossroads, stories, tags, walls, lifts, ceilings and corridors.

7 CONCLUSIONS AND FUTURE WORK

In this work we have analyzed a number of existing approaches to the problem of the representation of building indoor models. Initially, a set of criteria to classify the existing models have been introduced. According to these criteria, some works have been classified into three main groups: (1) 2D (2) 2.5D and (3) 3D.

Another topic covered in this paper has been the analysis of the wide range of building models according to geometric, semantic and topological features. This analysis allows us to state some conclusions:

- Due to the huge variety of existing representation models for building indoors, and the wide range of fields of application, it is quite complex to achieve

Table 1: Comparison between the overviewed works.

Group	Work	Geometry	Topology		Semantics
			Connectivity	Adjacency	
2D models	(Franz et al., 2005)	-	Implicit	Explicit	RO, O
	(Lamarche and Donikian, 2004)	Implicit	Explicit	-	PA, CR
	(Pluemer and Groeger, 1996)	V, E	-	Implicit	-
	(Stoffel et al., 2007)	V, E, R	Explicit	Implicit	RO, O, S
	(Li et al., 2010)	DC	-	-	T
	(Zhi et al., 2003)	V, E, R	Explicit	Implicit	R, O
	(Hahn et al., 2006)	Implicit	Explicit	Implicit	RO, O, S
	(Merrell et al., 2010)	Implicit	Explicit	Implicit	typed-RO, O
2.5D models	(Slingsby and Raper, 2007)	Implicit	-	Implicit	W, L, O
	(Tutenel et al., 2009)	Implicit	-	-	RO
	(Germer and Schwarz, 2009)	Implicit	-	-	RO
	(Dongen, 2008)	Cubes	-	-	W, C
	(Choi et al., 2007)	-	Explicit	Implicit	RO, O, S, W
3D models	(Choi and Lee, 2009)	R	Explicit	Explicit	RO, O, CO
	(Clemen and Frank, 2008)	V, E, F, P	Explicit	Explicit	-
	(Van Berlo and de Laat, 2010)	IFC, CityGML	Explicit	Implicit	RO, O, S, W
	(Paul and Bradley, 2003)	V, E, F, VO	Explicit	Explicit	W, C
	(Billen and Zlatanova, 2003)	V, E, F, VO	Implicit	Explicit	Buildings
	(Hagedorn et al., 2009)	GML	Explicit	Explicit	RO, O, S, W
	(Van Treeck and Rank, 2007)	B-Rep	Explicit	Explicit	RO, W
	(Borrmann and Rank, 2009)	VO	-	-	Buildings
	(Isikdag et al., 2008)	Implicit	Implicit	Implicit	O, S, W
	(Boguslawski and Gold, 2010)	V, E, F	-	Explicit	-
	(Yan et al., 2010)	BIM	BIM	BIM	BIM
	(Xu et al., 2010)	F, VO	Explicit	Explicit	RO, O, S, W, C
Our proposal		V, E	Explicit	Explicit	RO, O, PA, S, W, C

Legend: V=vertices, VO=volumes, E=edges, F=faces, P = planes, R=regions
DC=Discrete cells, RO=rooms, O=openings, PA=passages, CR=crossroads
S=stories, T=tags, W=walls, C=ceilings, L=lifts, CO=corridors

unified models. Thus, we consider unavoidable a thorough design of the problem to be solved, instead of the application of general approaches.

- In most of the reviewed works, there exists a lack of automation for getting building models, without regard of the field (BIM, GIS, Spatial Databases or custom models). Therefore, algorithms for the extraction of semantic information from CAD floor plans need to be developed. In this area, we have proposed some methods to recognize rooms semi-automatically from vector floor plans in AutoDesk© DXF format, obtaining promising initial results.

- The use of formal approaches is recommendable, since it allows to take advantage of demonstrated results. For example, a lot of works formulate a problem in terms of graphs. Thus, existing algorithms from graph theory can be applied without need to demonstrate the validity of the solution.

Some of our work (in progress) tries to solve the wall automatic recognition using graph theory.

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