

Consistency constraints and 3D building reconstruction

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ABSTRACT

Virtual architectural (indoor) scenes are often modeled in 3D for various types of simulation systems. For instance, some authors propose methods dedicated to lighting, heat transfer, acoustic or radio-wave propagation simulations. These methods rely in most cases on a volumetric representation of the environment, with adjacency and incidence relationships. Unfortunately, many buildings data are only given by 2D plans and the 3D needs varies from one application to another. To face these problems, we propose a formal representation of consistency constraints dedicated to building interiors and associated with a topological model. We show that such a representation can be used for: (i) reconstructing 3D models from 2D architectural plans (ii) detecting automatically geometrical, topological and semantical inconsistencies (iii) designing automatic and semi-automatic operations to correct and enrich a 2D plan. All our constraints are homogeneously defined in 2D and 3D, implemented with generalized maps and used in modeling operations. We explain how this model can be successfully used for lighting and radio-wave propagation simulations.

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1. Introduction

Before construction, buildings are often virtually represented in 3D so as to design a site and conduct studies related to lighting, heat transfer, radio-waves propagation, and so on. These environments are composed of a set of 3D geometric primitives with various types of additional information to expand their use: adjacency relationship between volumes, object types, or material properties used for building construction.

Many simulation programs cannot rely on commercial modeling software because their internal structure is not available. Consequently for each scene, the user has to manually pre-process the model in order to make it compatible with the required representation. This is why some integrated prototypes both build a 3D model and apply the simulation process [1]. However, the representation is not sufficiently generic for being used in different applications. To our knowledge, there is no common framework for both modeling indoor scenes and applying various types of simulations.

In this paper, our aim is to propose a representation of buildings homogeneous in 2D and 3D, taking geometry, topology and semantics consistency into account. The model should be generic enough to be used in as many applications and simulation systems as possible. To do this, we formally define a set of

constraints adapted to most common buildings. Generalized maps (G-maps [2]) are used as a topological basis and our definitions rely on their terminology. We also propose a semi-automatic reconstruction pipeline for generating 3D buildings from 2D architectural plans (see Fig. 1). Our main contributions are:

- a formal description of constraints providing a generic representation of geometry, topology and semantics of architectural indoor environments;
- the use of these constraints for automatically reconstructing 3D buildings from 2D vector plans, including topology and semantics;
- a set of semi-automatic operations used to detect and correct errors in the 2D plans before 3D construction.

The resulting scenes can be edited with a general modeler based on G-maps [3]. In addition, cell and portal structures often used in the context of large buildings [4–8] can be naturally produced from our structure. We have also produced files for radio-wave propagation simulations used in our laboratory [9,10] (Section 7).

This paper is organized as follows. Sections 2 and 3 present the existing methods in 3D architecture and describe G-maps. Section 4 presents our consistency constraints. Section 5 provides the 2D processing of an architectural vector plan. Section 6 explains how we detect and correct errors. Sections 7 and 8 present and discuss our results.

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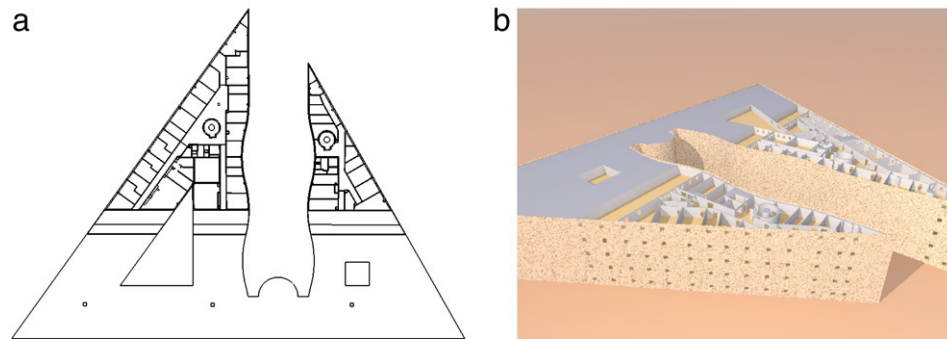


Fig. 1. (a) Building 2D plan; (b) 3D reconstruction with proper topology and semantics.

2. Related work

Topological models

We wish to represent large buildings, actually corresponding to 3D topological objects, made up of vertices, edges, faces and volumes which do not necessarily have regular shapes. Many topological models have been proposed in the literature for handling different classes of subdivisions (oriented surfaces, manifold, non-manifold, etc.) in any dimension. Examples of such structures are adjacency graphs [11], ordered models (as defined in [12]), 2D or 3D edge-based models [13–15] or higher-dimensional models [12,2].

Adjacency graphs (such as [11]) do not allow multi-incidence (see [2]). Moreover, the topological correctness of the model is difficult to express [16]. This is the reason why ordered models have been introduced. They are mainly defined with a single type of basic elements and links between these elements [12,2].

For the reasons explained above, we choose an ordered topological model. Complexity studies have shown that for 2D and 3D manifold (surface subdivisions or volume subdivisions), costs for representing an ordered model and an incidence graph are comparable [17]. This is even more true when taking geometry, photometry and other attributes into account.

Buildings are composed of volumes (floors, walls, rooms, etc.) sharing faces. Topologically speaking, it corresponds to 3D orientable manifolds. In [18], it has been shown that models defined to represent 3D manifolds are comparable either to 3D map (for orientable ones without boundaries) or to 3D Generalized maps (for orientable or not orientable ones, with or without boundaries). Generalized maps are defined homogeneously in any dimension, so that operations implemented in 2D can be naturally extended in 3D or in higher dimension.

Analysis of architectural bitmap images

Several methods have been proposed for reconstructing 3D buildings from existing images of 2D architectural plans (i.e. bitmap images) [19,20]. Bitmap images contain low-level geometrical and semantical information and before reconstruction, the first step is extracting richer information. However, the vectorization process usually employed to this task does not provide any topological information.

Even though the 3D reconstruction can be achieved with these methods, none of them does provide any topological information. However, these types of analyses are complementary to our work since much semantic information can be automatically deduced from images.

Google Earth [21], the French National Geographic Institute (IGN) [22,23] and other authors [24–26] also propose frameworks used to rebuild the geometry of real urban scenes based on various types of images (satellite, aerial, ground, etc.). Again, no topological information is produced with these approaches.

3D building analysis

Some authors have also proposed to extract topological information from a list of polygons, making it possible to reduce visibility calculations for lighting simulation and visualization. Airey et al. and Teller et al. [5,6] propose a binary space subdivision method (Binary Space Partitioning or BSP) while Meneveaux et al. [27] propose a method using rules for extracting rooms of buildings. These subdivision schemes produce a set of regions called *cells*, separated by openings (*portals*); the topological description corresponds to adjacency relations between 3D cells. However, this model does not provide any incidence/adjacency relations between lower-dimensional elements.

Building modelers

Fradin et al. [28] propose a building modeler for manually designing complex indoor scenes. The topological structure relies on *G*-maps, with hierarchy and multi-partitions, also adapted to various types of simulations [8,29]. The topological basis is also *G*-maps, but does not include any consistency constraints specifically related to architecture. Moreover, the operations defined in this modeler are designed so that the user has to construct the whole 3D building manually, without the benefit of using existing 2D data.

Several industrial software [30,31] propose to design 2D plans and/or 3D buildings. Many operations are provided such as: walls, stairs, or doors drawing; boolean operations; extrusion, revolutions and so on. However, even though those software allow us to construct 2D plan and 3D buildings simultaneously, they still do not provide any topological representation nor consistency control (superimposed walls, disjoint segments, and so on).

Many actors in architectural business need to share information for formalizing electronic documents. To this end, the IFC (Industry Foundation Classes) have been proposed recently. Since the first version appeared in 1997, more and more applications have employed this formalism. However, the associated file format essentially contains semantical information; it has not been defined for representing low-level topological relationships, which are necessary for many modeling operations such as those described in this paper.

Procedural modeling

Procedural systems which do not require any manual intervention have been used to produce urban scenes. Several authors propose applications for randomly constructing realistic (but not real) virtual cities and facades [32–35]. Unfortunately, these programs only produce cities and buildings geometry, without topology. In addition, reproducing a real environment is not possible due to the random processes applied.

Discussion

Many tools are dedicated to the (re)construction of 3D architectural environments. Some of them are dedicated to simulation, but

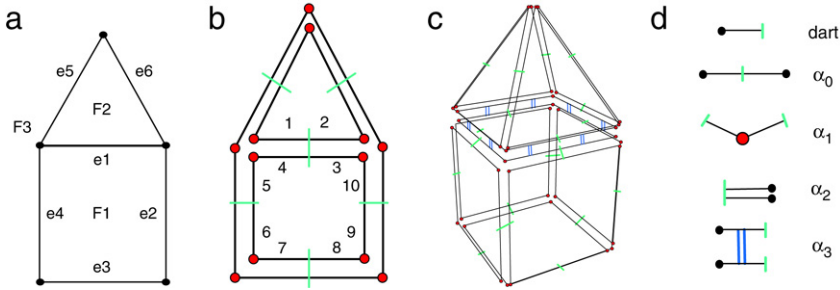


Fig. 2. G-Map representation: (a) a 2D object containing 3 faces, 6 edges and 5 vertices; (b) corresponding generalized map: the set of darts $\{1, 2, 3, 4\}$ represents the edge e_1 , the set of darts $\{3, 4, 5, 6, 7, 8, 9, 10\}$ represents the face F_1 ; (c) 3D object composed of 2 volumes represented with 3G-map, volumes are linked by α_3 ; (d) symbolic representation of involutions. In most cases, α_0 links are not represented for the sake of readability.

no generic model is currently provided for general purpose applications. Furthermore, without any topological structure nor consistency constraint, reconstructing a 3D building from 2D plans for producing topology requires many manual processing that cannot be done automatically. To our knowledge, the only application that provides topological information is the one proposed in [28]. However, no specific constraint is defined for the building structures so as to detect and correct errors in models.

3. Generalized maps

We wish to represent buildings made up of volumes (floors, walls, rooms, etc), each of them being an orientable 3D object. We need a subdivision of space into volumes, faces, edges and vertices, defined by their boundaries in any dimension. G-maps offer an implicit representation of cells with efficient operations since a local modification in the map is automatically propagated to the incident cells.

The rest of this section gives the main definitions and properties of n-G-maps. They can be found in [2,18] and are included here for the convenience of readers unfamiliar with G-maps.

Definition 1 (Generalized Map [2]). A generalized map in dimension $n \geq 0$ (or n-G-map) is an algebra $G = (D, \alpha_0, \dots, \alpha_n)$, where:

- D is a finite set of darts;
- $\alpha_0, \dots, \alpha_n$ are involutions;
- $\alpha_i \alpha_j$ is an involution $\forall i, j$ such that $0 \leq i < i + 2 \leq j \leq n$.

From a single type of basic elements (called *darts*) and involutions¹(called α) defined on these darts, generalized maps represent object cells and adjacency/incidence relationships. 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 link between two vertices, α_1 links two edges, α_2 links two faces and α_3 links two volumes (Fig. 2).

Two darts d and d' are i -sewed if $\alpha_i(d) = d'$ with $d \neq d'$, and d is i -free if $\alpha_i(d) = d$. An *orbit* is described by a dart and a set of involutions. It provides the set of all darts that can be reached by any composition of the given involutions: given dart d , the orbit $\langle f_1, \dots, f_k \rangle(d)$ corresponds to all the darts obtained starting from d , and using any composition of all the involutions f_1, \dots, f_k .

Definition 2 (i -cell). Let $d \in D$, $N = \{0, 1, \dots, n\}$ and let $i \in N$. The i -cell incident to d is the orbit $\langle \alpha_0, \dots, \alpha_{i-1}, \alpha_{i+1}, \dots, \alpha_n \rangle(d) = \langle \alpha_0, \dots, \alpha_{i-1}, \alpha_{i+1}, \dots, \alpha_n \rangle(d)$.

An i -cell is a particular orbit composed with all involutions except α_i . Two cells are disjoint when their intersection is empty, i.e. when no dart is shared by the cells. In Fig. 3, i -cells which compose a 3G-map are represented with their corresponding orbit.

The *degree* of an i -cell C is the number of distinct $(i + 1)$ -cells incident to C (for instance, the vertex degree is the number of edges incident to it).

Definition 3 (Dangling Elements). $\forall i \in [1, 2]$ the i -cell C_i is a *dangling* cell iff the degree of C_i is 1 and if one of its incident $(i - 1)$ -cell C_{i-1} is also of degree 1.

In Fig. 4a, E_1 is a dangling edge since it is incident to a one-degree vertex and its degree is also equal to one; E_2 is not dangling, because even if its degree is one, it is not incident to a one-degree vertex (see Fig. 4b).

On the basis of G-maps representation, we have used a 3D topological modeler, comprising many operations such as sewing two cells along a face or more complex operations like sweeping or corefining [3]. We associate G-maps with linear embeddings because the reconstruction process starts with a set of segments corresponding to the 2D plan geometry.

4. Consistency constraints for 3D buildings

For each type of simulation using buildings, specific attributes are required by the program (adjacency relationship between volumes, object types, or materials properties used for building construction). However, the general building structure remains the same in most buildings, so that generic rules can be defined for various applications. Such a model should:

- correspond to a structured representation;
- ensure consistency of topology, geometry and semantics;
- reduce as manual processing of buildings as possible when 2D data already exists.

G-maps alone are not sufficient for representing an architectural model with semantics, topology and geometry such as neighbourhood relationships or volume thickness. This is why we propose additional consistency constraints, that can be used for various applications: reconstruction from 2D plans, error detection and correction, model modifications, and so on.

Our set of constraints is dedicated to building models. Each constraint is defined as a geometrical, topological and/or semantical property. In this section, we firstly focus on the space subdivision representation of buildings; secondly, we express constraints in terms of elements thickness; thirdly, we enrich the model with semantical rules.

4.1. Space subdivision

We need to represent objects of the real world, corresponding to disjoint volumes: rooms are defined as volumes, as well as walls, doors, windows. This is why we use a 3D space subdivision. The model must be oriented and composed of closed volumes, faces and edges. Furthermore, elements cannot be superimposed. This representation corresponds to a closed and oriented 3D *partition*.

¹ An involution f is a one-to-one mapping such that: $f^2 = Id$.

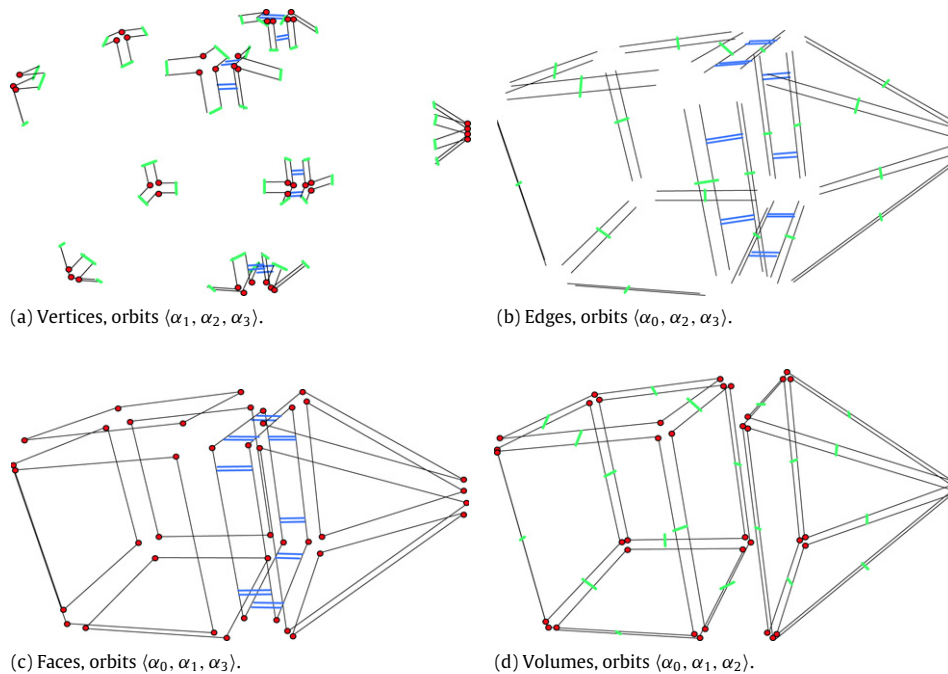


Fig. 3. Each cell can be obtained from a dart and an orbit: $\langle \alpha_1, \alpha_2, \alpha_3 \rangle$ for vertices, $\langle \alpha_0, \alpha_1, \alpha_3 \rangle$ for edges, $\langle \alpha_0, \alpha_1, \alpha_3 \rangle$ for faces and $\langle \alpha_0, \alpha_1, \alpha_2 \rangle$ for volumes.

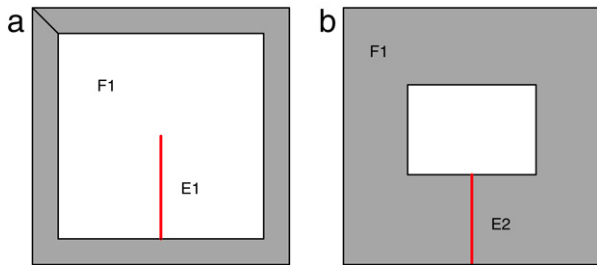


Fig. 4. (a) Dangling edge: E_1 is inside face F_1 . Its degree is 1 and it is incident to a vertex of degree 1; (b) E_2 is a degree 1 edge which is not dangling.

Property 1 (Space Partition of \mathbb{R}^3). Let C_i^1 and C_i^2 be two i -cells of a partition P with $i \in \{0, 1, 2, 3\}$; $C_i^1 \cap C_i^2 = \emptyset$ or $C_i^1 \cap C_i^2 = \{C_j | j \in \{0, 1, 2\} \text{ and } j < i; C_j \in P; C_j \text{ be incident to } C_i^1 \text{ and to } C_i^2\}$.

Fig. 5 gives example of models that do not comply with this property. It shows two distinct faces with various embeddings.

Fig. 6 shows configurations with several distinct faces in \mathbb{R}^2 . In Fig. 6a, F_1 and F_2 are two open faces that do not cover \mathbb{R}^2 thus not corresponding to a space partition. In Fig. 6b, F_1' and

F_2' are the complement of F_1 and F_2 and their intersection is not empty (it is a face): this configuration also does not correspond to a space partition. Fig. 6c illustrates three closed faces where F_3 is the complement F_1 and F_2 . The union of F_1, F_2 and F_3 covers \mathbb{R}^2 and the intersections are composed of edges and vertices included in the partition. This configuration is thus a space partition, complying with Property 1.

Note that with Property 1, a model composed of several connected components is not a space partition (see Fig. 6a and b). With 3G-maps, a model is composed of a single connected component iff: $\forall d \in G, d \in \langle \alpha_0, \alpha_1, \alpha_2, \alpha_3 \rangle(d')$ until $d' \in G$.

Property 2 (Closeness). The model is closed in all dimensions.

For a G-map, this property is equivalent to: $\forall d \in G$ and $\forall i, 0 \leq i \leq 3, \alpha_i(d) \neq d$ (a closed G-map has no free dart).

Property 3 (Orientation). The model is oriented.

G-maps can be used to represent objects orientable or not. For buildings, we specify that the model is oriented. When a 3D connected oriented model is represented by a G-map, the orbit $\langle \alpha_0 \alpha_1, \alpha_0 \alpha_2, \alpha_0 \alpha_3 \rangle(d)$ contains one out of two darts of the G-map.

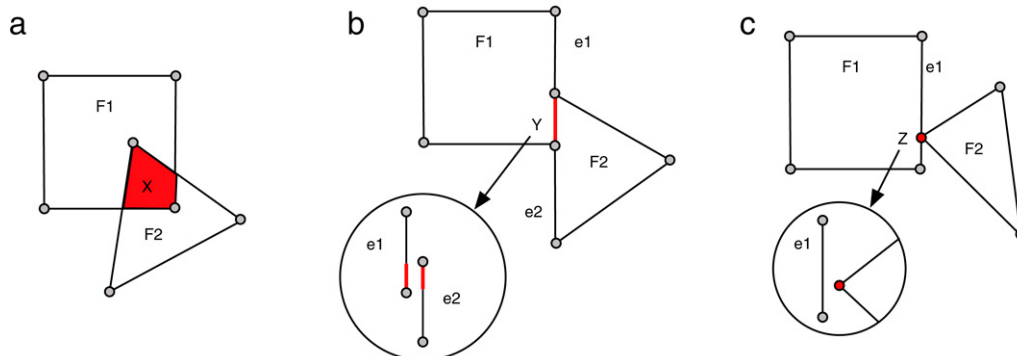


Fig. 5. Series of configurations with distinct faces F_1 and F_2 composed of the set of cells $S = \{f_1, f_2, e_1, \dots, e_7, v_1, \dots, v_7\}$: (a) the geometrical intersection of F_1 and F_2 is a face X that does not belong to S ; (b) identically, $F_1 \cap F_2$ is an edge Y that does not belong to S ; (c) $F_1 \cap F_2$ is a vertex Z that is not incident to F_1 .

Fig. 6. Space partition property: (a) F1 and F2 do not cover \mathbb{R}^2 ; (b) the intersection of F1' and F2' is not empty (it is a face); (c) a model made up of a single connected component which complies with Property 1.

Fig. 7. Dangling cells: (a) in 2D the dangling edge E_1 does not represent a thick object; (b) 3D example with a wall having no thickness, represented by a dangling face.

Then, this orbit cardinal is equal to half the number of darts in the G-map.

$$\text{Let } d \in D, |\langle \alpha_0 \alpha_1, \alpha_0 \alpha_2, \alpha_0 \alpha_3 \rangle(d)| = |D|/2.$$

With a G-map, this property can be ensured using a boolean mark for each dart indicating the orientation and verifying: $\forall d \in D, \forall i, 0 \leq i \leq 3, \text{orientation}(d) = 1 \Leftrightarrow \text{orientation}(\alpha_i(d)) = 0$.

4.2. Volumes and thickness

We are mainly interested in a structured representation of the main building work in 3D: doors, windows, walls, stairs, rooms, and so on. In practice, each element must be defined with a significant thickness: flat volumes/edges or dangling faces/edges (see Fig. 7) cannot appear in a real world model.

Property 4 (Dangling Elements). *A partition of \mathbb{R}^3 representing a building does not contain any dangling edge or face.*

With G-maps, the degree of dangling faces and edges is 1. Furthermore, a dangling edge contains at least one dart d such that $\alpha_1(d) = \alpha_2(d)$, and a dangling face contains at least one dart d such that $\alpha_2(d) = \alpha_3(d)$.

4.3. Semantic constraints

In applications concerning building simulations or modeling, the type of each volume should be precisely defined. This is why we have identified several semantic key markers matching objects common to most buildings (walls, rooms, stairs, etc.). Their number can easily be increased depending on application needs. Our basis set of marks contains the following elements:

-WALL	-STAIR	-ROOM	-FACADE
-DOOR	-WINDOW	-CEILING	-GROUND

Property 5 (Semantical Markers). *Each volume should be associated with one (and only one) basis key marker.*

Note that the FACADE describes the infinite volume outside the building, and each of its faces is incident to the building WALL, WINDOW, DOOR, CEILING or GROUND volumes.

With G-maps, this property implies that all the darts belonging to the same 3-cell have the same semantic:

$$\forall d_1 \in D, \forall d_2 \in \langle \alpha_0, \alpha_1, \alpha_2 \rangle(d_1), \text{semantic}(d_1) = \text{semantic}(d_2).$$

Property 6 (Neighbourhood Constraints). *Volume neighbourhood must comply with the constraints given in Table 1.*

Using G-maps allows us to detect semantical inconsistencies. Each face is incident to 2 volumes and volumes are connected by an α_3 involution. Then, with G-maps, semantic consistency is controlled with the following property: $\forall d \in G, \text{Table 1}[\text{semantic}(d), \text{semantic}(\alpha_3(d))] \neq \text{error}$.

Two neighbour volumes can have the same semantic markers in several cases: architects sometimes separate walls or ground volumes deliberately. For instance, when two walls are not built with the same material, a face must exist between the two corresponding volumes.

Property 7 (Building Facade). *The outside volume is unique, infinite and complementary to the set of building volumes; the building facade corresponds to the (interface) faces between outer wall volumes and the outside volume.*

With G-maps, this property implies that all darts with semantic facade are contained in the same volume:

$$\forall d_1, d_2 \in D, \text{with } \text{semantic}(d_1) = \text{FACADE} \text{ and } \text{semantic}(d_2) = \text{FACADE}, d_1 \in \langle \alpha_0, \alpha_1, \alpha_2 \rangle(d_2).$$

Note that when two houses are adjacent, there is only one shared wall. The facade is defined all around the whole building (corresponding to the two houses). If each house is modeled independently and linked later, the common walls and facades should be merged to compose a single volume. In addition, for several floors the corresponding facade faces are linked, producing one single facade volume.

5. Building reconstruction and constraints compliance

This section describes our 3D reconstruction system, with the assumption that 2D digital plans do not contain any error: no superimposed elements, no dangling edge, no semantic inconsistency. Without any error, the process is automatic. In

