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Valid Space Description in BIM for 3D Indoor Navigation

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ABSTRACT

The BIM paradigm, supplied by appropriate standards like IFC, became unavoidable in recent construction projects. Several applications (e.g. indoor navigation, energy analysis ...) find in it a source of information on which they can rely. However, practices reveal that BIM models are not always directly reliable for applications and the latter have to ensure the validity of the data by their own. In the case of indoor navigation, the calculations will highly rely on the IfcSpace objects describing the rooms, in addition to their spatial relationships with their surrounding components. Unfortunately, it is common to face IFC models in which IfcSpace objects contain wrong geometric and topological description. In this paper, the authors discuss the issues related to BIM models validation for indoor navigation. Furthermore, they present a method to generate valid indoor spaces in IFC models. The approach relies on the structural components of the building (walls, slabs, etc.) and uses topological operations, supported by the combinatorial map data structure, to produce watertight space volumes.

KEYWORDS

Building Analysis, Building Model, GIS, IFC, IfcSpace, Simulation, Space Generation, Standard, Validation

1. INTRODUCTION

Building Information Modelling is most probably set to become the paradigm that will dominate the world of 3D building modelling in the near future. It is increasingly adopted in the construction industry due to several of its advantages. The most prominent one is probably the solution it provides to the interoperability issue between the numerous actors involved in a building construction process. Indeed, almost all of them need to rely on an abstraction of the building at some point for different purposes (visualization, planning, simulation, quantity takeoff, etc.). Due to their different points of view, the same building can be represented multiple times and differently, leading to laborious and error prone collaborations. The BIM paradigm makes it possible for the actors of the construction process to collaborate easier, by gathering all the needs of all the experts in a single model (Isikdag et al., 2012).

The most renowned open BIM standard is the Industry Foundation Classes (IFC) released by the International Alliance for Interoperability (IAI), now known as BuildingSMART Alliance (BuildingSMART, 2015). The IFC standard provides an elaborated description allowing to semantically and geometrically describe building components, as well as their spatial relationships. A huge amount of building components is considered through approximately a thousand of classes. IFC is adopted by the biggest architectural design software products, followed by more and more applications that rely on it to extract specific information and perform specific tasks.

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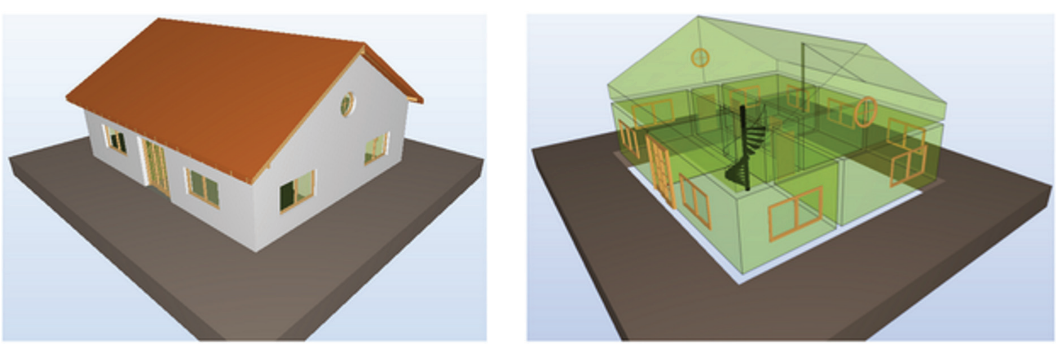
Geometry, semantics and topology are the main information necessary to pretend to a reliable and flexible 3D indoor navigation system. By gathering all of them, IFC models are of big interest for that application domain. Thanks to the description of the indoor space partitions (known as the IfcSpace class), the openings and the spatial links between them, it is possible to create a basic connectivity graph, in a straightforward manner, which could support path computation. Figure 1 provides a good illustration of an IFC model and its original space units. Simply by taking the spaces as nodes and considering the intermediate elements linking the spaces (windows, doors, stairs, etc.) as the edges of the graph, a network covering the connectivity of the indoor space can be made. This concept is widely accepted by many applications and adopted by the OGC standard IndoorGML (Lee et al., 2014).

However, similarly to all BIM based applications, if indoor navigation relies on the information stored in an IFC model, the correctness of its operations will depend heavily on the validity of the provided information as well. Therefore, valid geometry, topology and semantic in the IFC models is fundamental. Since IFC is mainly a semantic oriented format, the focus made on the latter makes it less exposed to error, compared to geometry and topology. In order to limit that problem, the IFC standard includes rules for the description and the implementation of its classes. For example, the spatial information definitions rely on the ISO 10303-42, which corresponds to the geometric and topological representation definitions of the STEP standard (Pratt, 2001).

Unfortunately, practices show that rules of the standards might not be respected and validity issues on the described objects hamper the optimal use of BIM models. 3D models for indoor navigation need the indoor spaces to be represented as closed volumes with planar surface boundaries made of consistently oriented faces. But it is common to have open volumes, inconsistent orientation of the object faces or intersecting volumes. On the other hand, since they are not mandatory, the IfcSpace objects may not even be represented, in some models. All those issues represent a serious limitation to IFC-based indoor navigation.

In this paper, we investigate the validity requirements of geometric and topological information for indoor navigation against the rules specified by the IFC standard. We also study the current situation of the means set to improve the production of valid IFC models. Furthermore, we present an approach allowing to automatically create geometrically and topologically valid IfcSpace objects in an IFC model. Starting from the geometry of the structural components of the model, we identify the contact surfaces between them and bring out the layout of the indoor spaces that they enclose. Our approach relies on the combinatorial map data structure that allows us to perform topological operations while insuring the geometrical and topological validity of the resulting entities. In Section 2, we study the related work that has been produced in the direction of the usage of BIM in indoor navigation, and other applications, as well as their validity check and correction. In Section 3, we discuss and illustrate the representation errors related to IfcSpace objects. We explore the measures

Figure 1. Example of an IFC model of a house (left) and its IfcSpace objects (right). The openings and stairs which link the spaces are also illustrated.



that has been taken in order to ease the validation of the exchanged data through the IFC standard, and the few tools available to help going in that direction in Section 5. Then in Section 6 we present our approach to generate IfcSpace objects in IFC models. Finally, we conclude after a discussion and identification of the future improvements.

2. RELATED WORK

Several works in the literature of indoor navigation recognized the beneficial use of BIM models for such application. Indeed, efficient 3D indoor navigation highly relies on semantic information of the indoor environment and also on the geometric description of the components and their spatial relationships (Zlatanova et al., 2013). BIM models, particularly IFC, provide suitable information to support indoor localization, as well as automatically extracting navigation graphs. The latter requiring an organization of the indoor space in several space units (rooms) and the spatial relationships between them, that information is offered by the IFC models and can be directly exploited. Therefore, several works study the derivation of navigation graph directly on IFC models (Lin et al., 2013; Boysen et al., 2014) or modifications of them (Isikdag et al., 2013) for deriving paths for multi locomotion type (Khan et al., 2014) or support emergency response (Boguslawski et al., 2015).

Indoor navigation is not the only application that relies on IfcSpace entities. Indeed, applications such as facility management, lighting simulation, acoustics, etc. also rely on it. Furthermore, the Building Energy Modeling (BEM) domain is probably the most advanced field in the usage of IFC models to perform simulation (Bazjanac, 2008; O'Donnell, 2014). In BEM, IfcSpace objects as originally represented are not directly adequate for the calculation, they stand however as the basis for further preprocesses aiming at making them suitable for energy analysis (Hitchcock and Wong, 2011; Rose and Bazjanac, 2015). Nevertheless, the previously mentioned approaches assume availability of IfcSpace objects in their input IFC models. Thus, presence of valid space units is a crucial requirement for their usage.

Thus, validity checking of the IFC models has been an early concern in BEM. Bazjanac (2008) emphasized the impact of invalid models and failure to their checking in the simulation processes relying on them. Daum and Borrmann (2013) introduced a method for validating the spatio-semantic consistency of IFC models based on the usage of the Query Language for Building Information Models (QL4BIM). They aimed at preventing the lack of consistency between the semantic and the geometric part of the BIM models. In Geographic Information System (GIS), Ledoux (2013) proposed a thorough study on the validity of solid objects representation in 3D GIS against the standards defining them. The author went through the full definition of valid solid according to ISO standards (ISO 19107), discussed cases that should not be allowed in GIS models and introduced a validation methodology. He also pointed out the importance of the usage of adequate data structure for such validation task. The problems raised in (Ledoux, 2013) are very similar to the situation in BIM. Both BIM and GIS domains have concerns about geometric and topological validity of their object representation, even though they rely on different standards as we will see later.

Because of the dependency of the cited applications to the IfcSpace objects, their presence is critical in the input models. Since the existence of IfcSpace is not mandatory, it is commonly not created, which leads to a serious limitation for those applications that need it. These spaces are created at a later stage. While no study in indoor navigation addresses the issue yet, van Treeck and Rank (2007) introduced an approach based on graph theory and allowing to extract air volume bodies out of BIM models for building energy simulation. The method relies on the geometric, topological and semantic information that are assumed available and valid in the input models and they derive four graphs that are used for the calculations. Diakité et al. (2014b) introduced an approach dedicated to topological and semantic enrichment of CAD and GIS models starting from their geometry. Their approach allows producing similar results to that of van Treeck and Rank (2007) with the advantage to rely on one single data structure that gathers all the necessary information.

While the direct conformity of IFC models (or BIM in general) to specific applications is in reality less trivial than expected, we focus in this paper on the geometric and topological requirements that an IfcSpace objects should meet to support indoor navigation. We identify the definition of a valid IfcSpace and we discuss the issues related to it in practice. We extend the approach of Diakité et al. (2014b) to adapt it to the IFC context and propose a method to create valid space objects. We rely on one combinatorial data structure known as combinatorial map (Damiand and Lienhardt, 2014) which guarantees the geometric and topological validity of the results while being able to handle all the required information in a unified model.

3. ISSUES RELATED TO SPACE REPRESENTATION IN IFC MODELS

3.1. How Spaces Should be Represented in IFC Model

Spaces are defined in the IFC standard as follow: "A space represents an area or volume bounded actually or theoretically. Spaces are areas or volumes that provide for certain functions within a building." (Liebich, 2004). They are described by the IfcSpace class and can represent indoor spaces as well as outdoor ones. In the former case, they are associated to the building stories and in the latter, to the building site. Similarly to several other IFC classes, IfcSpace objects can have multiple geometric representations: foot print (2D), swept solid, constructive solid geometry (CSG) and boundary representation (B-Rep).

Among all the representations, the B-Rep is the most used one due to its wide range of geometric capabilities and its implicit topological structure linking its primitives: vertices, edges, faces, etc. (Pratt 2004). Applications such as indoor navigation are more related to the GIS domain, where generally, B-Rep is the dominant geometric paradigm to represent 3D geometries, like it is the case for the most prominent GIS standard, CityGML (Kolbe et al., 2005) and IndoorGML (Lee et al., 2014). Thus, B-Rep representation of the IfcSpace objects is convenient; we will focus on it in this work and we refer to it anytime the geometry of an IfcSpace is mentioned.

The IFC standard relies on the ISO 10303-42 definition that specifies the geometric and topological characteristics of solids (Liebich, 2004). Therefore, an IfcSpace corresponds to a manifold solid described as follow: "A manifold solid B-rep is a finite, arc wise connected volume bounded by one or more surfaces, each of which is a connected, oriented, finite, closed 2-manifold. There is no restriction on the genus of the volume, nor on the number of voids within the volume." The bounding surfaces of the solid in question correspond to planar faces of class IfcFacetedBrep and are defined as follows: "A faceted B-Rep is a simple form of boundary representation model in which all faces are planar and all edges are straight lines. […] has to meet the same topological constraints as the manifold solid B-Rep." Such definition of a solid is close to the definition used in GIS and that is based on the ISO 19107 standard, as discussed in (Ledoux, 2013). In summary, an IfcSpace should be characterized by: a closed volume made of a set of planar, oriented and connected 2-manifolds of surface genus 0. Faces do not intersect except along their boundaries (i.e., edges). Each edge along the boundary of a face is shared by at most one other face in the assemblage. The assemblage of edges in the B-Rep does not intersect except at their boundaries (i.e., vertices) (BuildingSMART, 2015). Furthermore, the IfcSpace should be represented by one or more closed shells which shall be disjoint, then should include no volume intersection and all Euler formulas need to be satisfied (Liebich, 2004).

In summary, the previous definition of an IfcSpace object is in accordance with what is needed for 3D indoor navigation. Unfortunately, despite the standard definitions and the implementation guides (discussed in the following section) produced to orient toward proper models, it is still common to face wrong geometric and topological descriptions of the IFC objects in general. As discussed by Ledoux (2013), the standards exist but software designers may fail to refer to them to ensure the production of correct models. In the next subsection, we will illustrate some common errors on IfcSpace objects.

3.2. Illustration of Invalid Representations of IfcSpace Objects

At the early stage of 3D indoor navigation, it was enough to rely on the semantic of IfcSpace objects defined in an IFC model in addition to their spatial relationships to extract navigation graph. But there is so much more that BIM models can bring to support finer indoor navigation that new research on that field is demanding more than just the basic representations of the spaces. For example, finer subdivision of the indoor spaces into functional subspaces is investigated to allow more flexible navigation systems (Zlatanova et al., 2013, Diakité and Zlatanova, 2016).

But as soon as one tries to perform advanced geometric operations on the IfcSpace entities, unexpected problems are often faced, such as the wrong orientation of the faces composing the surface boundary, face overlap or intersection inside a same IfcSpace, non-simple shells, etc. Figure 2 illustrates the problem induced by the wrong orientation of the faces.

Indeed, when the orientations are not consistent among the faces composing a B-Rep solid, the shell of the latter cannot be unified to form one unique closed manifold, due to topological incompatibilities. It becomes impossible to identify what is the inner and the outer part of the solid. Yet such configuration is forbidden in the definition of the standard, and even precisions are given in the orientation that the surfaces should adopt: the normal vector of each face should point outward, meaning from the boundary of the solid towards its exterior (Liebich, 2004).

In the example of Figure 2 (bottom row), it can be seen that the IfcSpace volume, composed of several faces (triangles in this case) is subdivided into three subset of faces. Only the faces sharing coherent orientation can be topologically connected to form one single surface component. Such an object is not conform to a solid and cannot be used, as it is, to perform advanced analysis operations or simulation.

Another common wrong description of the IfcSpace objects is with non-simple shells due to surface overlapping or intersections, and sometimes volume intersections as well. Figure 3 illustrate

Figure 2. Illustration of an IfcSpace containing wrongly oriented faces. The upper row provides views of the concerned space volume in the IFC model. The bottom row shows the B-Rep of the space and the three unconnected surfaces subsets composing its boundary.

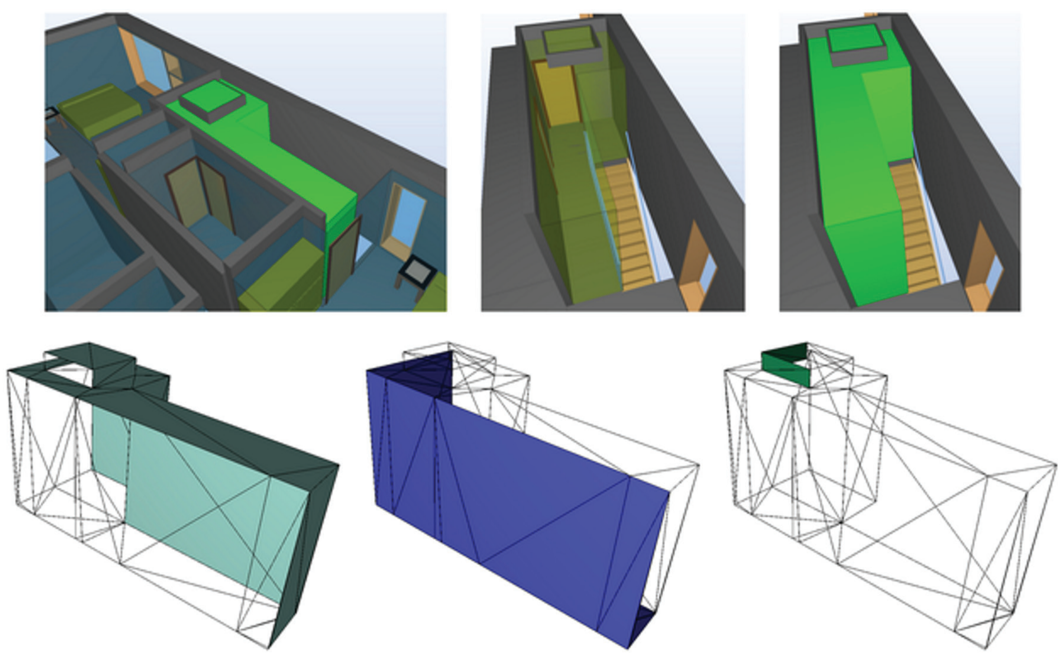
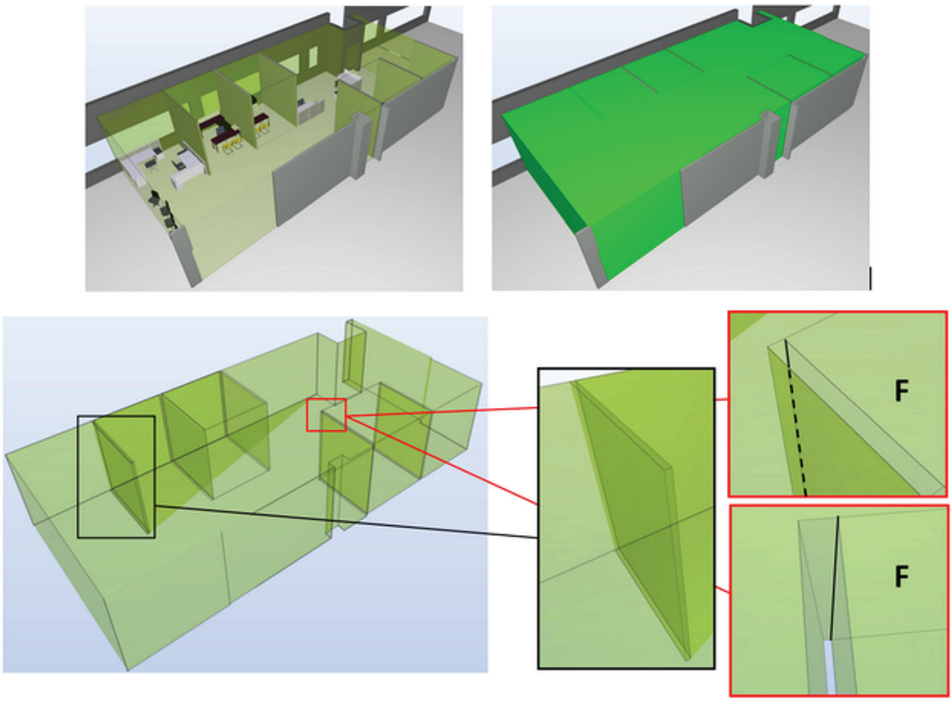


Figure 3. Illustration of errors related to the description of the surface shell. The top row shows a part of an office building with the structural elements, the furniture and the corresponding IfcSpace (top-right image). The bottom row offers zoomed views on the identified defects: inner volume similar to a volume intersection (middle frame) and an incoherent surface intersection (the two right frames, the bottom one being a top view). The bold lines in the right frames correspond to an edge that is shared by more than two faces, including the face F that should not exist.



the case of a complex office building on which one single IfcSpace is defined to cover a big subspace (top row). The enlarged views provided in the bottom row expose the geometric and topological errors that are not conform to the standard. The first case (bottom-middle frame) corresponds to a surface closure contained inside the space shell and that takes the shape of a wall (that can be seen on the top-left image). The correct shell should completely exclude the volume occupied by the wall, which is clearly not the case.

Furthermore, at parts where the walls are properly excluded from the IfcSpace volume, there is still a surface overlapping or a surface intersection. As shown in the two bottom-right frames, the layout of the wall is clearly out of the space volume, but still the face F remains. Because of the latter, the bold edge is shared by three faces instead of the maximum of two, as specified in the standard. Therefore, faces in the same configuration than F should be removed from the space volume, for them to be geometrically and topologically valid.

3.3. About the Origins of the Geometric/Topological Error in the Models

The origin of the problems discussed earlier can be diverse. Besides the well-known computer's floating precision issue that may affect the process, problems can be originated from both sides, the designer and the design software used to make it. Designer might have introduced errors due to wrong modeling of the objects. For example, the designer may not ensure that a wall he made is touching properly the slab, the ceiling or another neighboring wall. This will logically end up in situations such as illustrated in Figure 3 (bottom-middle frame). On the other hand, the design software may not have provided tools to check the correctness of the model and thus to support the designer in building models according to the standard.

This is not a simple issue, since the goal of the software is to avoid constraining too much the designer for the latter to fully express her/his inspirations. But when it comes to building model that are supposed to respect defined standards, the solution would be that both the designer and the software are aware of the rules to produce the resulting models in the best way.

While on the model designer side we can only suggest a better education and training in accordance to the standards, at the software design side tools can be provided to, at least, make the design of the IFC software product conform with the standards and also detect and prevent problems. In the following section we will go through the available means that helps to go in that direction.

4. CURRENT STATE OF THE IFC MODELS VALIDITY CHECK

As mentioned earlier, the geometric and topological validation of IFC models is not a new concern. But because of the important amount of classes that defines the IFC standard, the description complexity of a given construction can be very high. As users of such model will most likely be experts in specific domains, they will only be interested in specific classes. Therefore, for a validation purpose, it seems more reasonable and probably easier to proceed by application-based approaches instead of a global approach. We discuss in this section the measures that have been taken to help in proper implementation of IFC models, and we explore the few tools available to support this.

4.1. Model View Definitions (MVDs)

In order to supervise and simplify the exchanges, MVDs are set between actors of the construction industry and between software designers. BuildingSMART defines a MVD as "a subset of the IFC schema, which is needed to satisfy one or many Exchange Requirements of the AEC industry" (BuildingSMART, 2015). Hence, the international group proposes few official MVDs (e.g. the IFC2x3 Coordination View, the IFC4 Reference View, etc.). In parallel to the definition of the specifications, BuildingSMART has set certification processes allowing to certify that a given software's implementation is IFC compatible or not. An exhaustive list of certified software products as well as those for which the certification is still in progress is provided. The process involves cross verification of the software developers, BuildingSMART teams as well as user organizations. Therefore, the certification process considerably contributes to the improvement of the validity of the exchanged data.

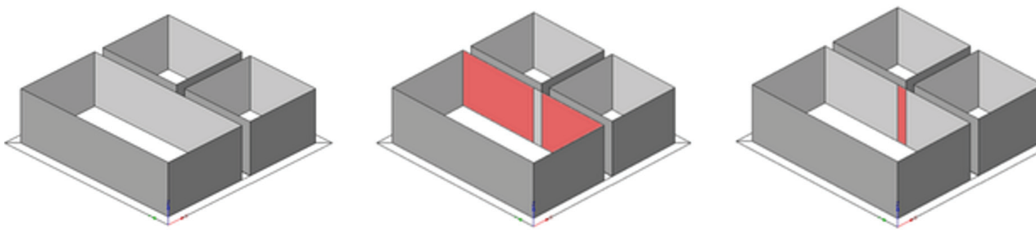
MVDs can be extended by add-on views to fulfill additional needs for particular exchanging schemes. One example of such extension is the Space Boundary add-on view that is an extension of the IFC2x3 Coordination View. However, to our knowledge, no add-on view is considered in the current official certification process.

4.2. Space Boundary Add-On View (SBV)

The SBV provides a guide for implementation that was originally introduced to define support for exchange between architectural and building service modeling software and the thermal analysis software products. These latter mainly rely on the so-called thermal boundaries that correspond to specific surfaces of the building components. The usefulness of space boundaries (SB) goes beyond the scope of thermal analysis because the same concept is also needed by applications such as energy and lighting simulation, facility management, quantity takeoff as well as indoor navigation. Therefore, the SBV tries to cover all the common needs of those applications by introducing two different level of space boundaries.

The 1st level SB is illustrated in the Figure 4, left. It is more general and for a given space, do not consider the influence of opposite spaces that are separated from it by a wall or a floor. The 2nd level SB emphasizes the special cases needed by thermal analysis. It then considers the influence of the opposite spaces to a given one (Figure 4, middle) as well as the presence of physical elements instead of spaces (Figure 4, right).

Figure 4. Space boundary levels as defined in (Weise et al., 2009). Left: SB level 1. Middle and right: SB level 2a and 2b (also called the 3rd level SB).



For indoor navigation, the 1st level SB is indeed enough, because only the boundaries that outline the room spaces are sufficient. Nevertheless, to link the spaces the openings are required (for example two spaces will be linked by a door or a window), or the virtual boundaries between two spaces (boundaries that do not correspond to physical elements of the building). However, the SBV fits well to the BEM related applications in general. A tool named Space Boundary Tool (LBNL, 2014) allows generating SBs for such applications. But it requires as input a validated IFC and cannot process when IfcSpace objects are missing in the building model.

4.3. Limitations of the MVDs

While the MVDs stand as guidelines for data exchange, they do not guarantee more than instructions regarding the adequate formatting and the filling of the proper classes inside the IFC structure. For example, in the SBV, agreements are made on the classes that can have SBs (IfcWall, IfcFloor, etc.), it is set that only one level SB can be represented in an IFC model, etc. Furthermore, some geometric and topological constraints are also considered. For example, SBs of a space shall result into a closed shell independently from the SB levels, to form a watertight entity (Weise et al., 2009).

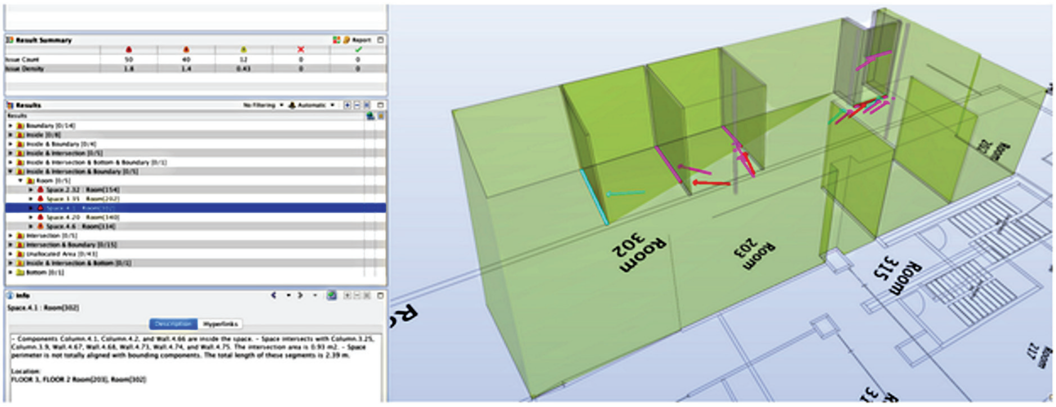
However, all these defined agreements and constraints may not be respected during the design of an IFC model. Indeed, in one hand the add-on views are not part of the BuildingSMART certification process, and on the other hand, it is clearly specified, for the SBV, that middleware, preprocessor or quality checker should be in charge of checking the consideration of the defined constrained. Therefore, a further validity check is still necessary and has to be provided by the third-party software products using the IFC file for a specific application.

4.4. Checking Tools

There are several tools listed as IFC file validating in the BuildingSMART webpage dedicated to IFC related toolboxes (BuildingSMART, 2016). Unfortunately, most of the free ones are limited to syntactic conformity check. But among the commercial products, some provide more extended checking possibilities. One of the most renowned is Solibri Model Checker (SMC) by Solibri (2016) that allows checking the conformity of IFC models according to MVDs by setting rules based on the latter. Most of the official MVDs can be natively found in the software. Several rules are dedicated to the spaces. We tried the "Space Validation" rule that checks the correctness of space geometry and location.

Figure 5 shows the results of the validation on the office model in Figure 3. On the IfcSpace illustrated in the latter, SMC detected and listed all the structural elements intersecting with the space. It also detected incoherence in the space boundary (apparently compared to the perimeter of its 2D projection). Nevertheless, while the pointed errors confirmed our expectations, it seems that the rules are limited and still do not completely cover the geometric and topological requirements specified by the standards. Indeed, the problems related to the non-conformity of the surface boundary to the B-Rep solid definition are not (at least explicitly) treated. Similarly, the test on the IfcSpace in Figure 2 could not detect the wrong orientation of the faces. It seems that those constraints are clearly missing in the define rules.

Figure 5. Results of the space validation rules. SMC could detect all the intersecting volumes with the IfcSpace and that all the perimeters do not fit to the bounding components.



Therefore, we introduce in the following section our approach to automatically generate indoor spaces that correspond to IfcSpace objects, in order to fill the non-existing ones or simply replace the wrong ones in IFC models.

5. AUTOMATIC GENERATION OF INDOOR SPACES

The previous sections helped us to point out the non triviality of directly relying on IFC models for applications such as indoor navigation. Generating automatically the proper IfcSpace objects can help to overcome the issue of their non-representation as well as their non-validity. We present here our approach to generate IfcSpace objects from IFC models. Similarly to van Treeck and Rank (2007), we assume that the IFC file contains valid geometry of the building structural components such as walls, floors, roofs, etc. Indeed, such assumption can be afforded because if the structural elements were to arrange as well, the models would be less interesting for the applications in term of efficiency and time of labor. Thus, all the components should correspond to 3D solid objects and spatial contact between them must be assured. We will first briefly introduce few key notions regarding 3D combinatorial map (3-map) that is the data structure supporting our approach. The formalism of the 3-map allows us to extract the air volumes that correspond to the IfcSpace objects.

5.1. Combinatorial Maps

An nD combinatorial map (n-map) is an edge-centered data structure allowing to describe any quasi-manifold object regardless its dimension, thanks to a cellular subdivision (Damiand and Lienhardt, 2014). It is composed by a set of darts (the basic element composing the cells) and the relationships between them. A dart corresponds to a part of an oriented edge, plus a part of all the incident cells. An (i + 1)-cell is constructed by i-sewing the darts of a set of i-cell with the β_i link through their proper (i − 1)-cells. For example, a 2-cell (or face) is built by 1-sewing a set of 1-cells (or edges), to link them by β_1 through their common 0-cells (vertices). The darts and the β relations allow a n-map to represent the relationships between all the cells it contains. In addition to this, a n-map allows to associate attributes (that can be any type of information) to any cell. This property is used in a 3-map to associate to each 0-cells the given 3D coordinates of a point in R^3 to produce a so-called linear cell complex (LCC). But this can also be used to store information such as semantic.

The first step of the process consists in loading the geometry and topology of the building components in the LCC. Figure 6 illustrates the process on a simple IfcWall element. The initial faces F1, F2 and F3 (the other faces are not discussed for simplicity) are decomposed into edges

(a_1, …, a_{10}) that form the corresponding 2-cells when they are properly linked between them by β_1. Hence the 2-cells are 2-sewed between them through the darts (b_1, …, b_{10}) of their common edges to obtain the final 3-cell of Figure 5 (right). All the solids representing the structural elements in the IFC are therefore imported in the LCC, which will become at this stage a complex of several spatially unconnected 3-cells. For the sake of simplification, the doors and the windows that can be composed by several superfluous geometric features, only their IfcOpening elements are considered. This result in simple box volumes that generally insure the spatial contact with their surrounding spaces. Similar simplification was adopted by Rose and Bazjanac (2015) as well.

5.2. Generation of the Indoor Spaces

Our approach to generate indoor spaces can be decomposed in 3 main steps. Starting from the structural elements of the building described in a given IFC file, we proceed to:

- The explicit creation of the contact surfaces between the components
- The explicit topological linking of the touching elements
- The duplication of the faces corresponding to the space boundaries and their linking to form closed volumes

We discuss each steps in the following subsections.

5.2.1. Creation of the Contact Surfaces Between the Components

The IfcSpace objects correspond to the spaces that are bounded by the walls, roofs, floors and other structural components. But they can also be spaces outside of the building that are bounded by virtual boundaries (Liebich, 2004). In this work, we limit our interest in indoor spaces for indoor navigation purpose. Therefore, to generate them, one needs to rely on the structural components and find the corresponding boundaries delimiting them. For this reason, the contact between the components is crucial, as it allows to determine the space extremities. In Diakité *et al.* (2014a), an approach allowing the topological reconstruction of 3D building components was introduced. After reconstruction of the 3-cells, the latter were linked between them through a process involving the explicit modeling of their contact surfaces.

Figure 7 shows the steps of the process on two overlapping faces, represented with their oriented darts (b and b') and that are assumed to belong to two different volumes (3-cells). The 2D view is preferred for sake of simplicity. The principle of the explicit representation of the contact surface(s) between the two faces is based on a cutting approach that creates the contact surface as separated

Figure 6. LCC representation of an IfcWall. From left to right: original faces of the IfcWall; corresponding 2-cells composed by their 1-cells;reconstruction of the wall volume by 2-sewing the 2-cells;final wall 3-cell (volume).

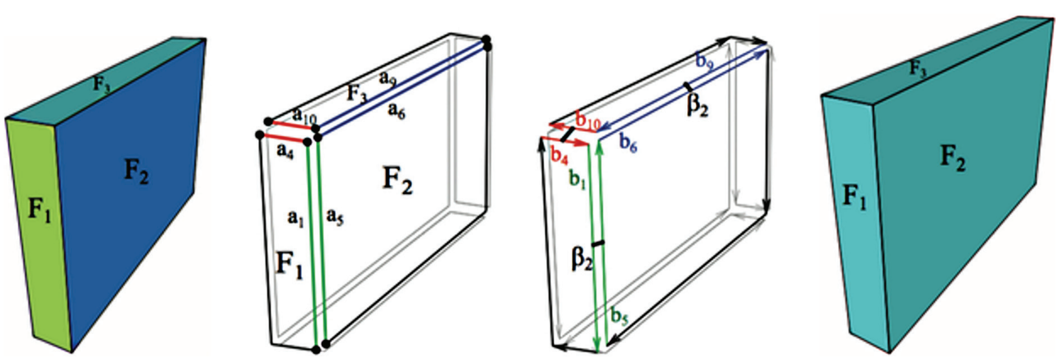
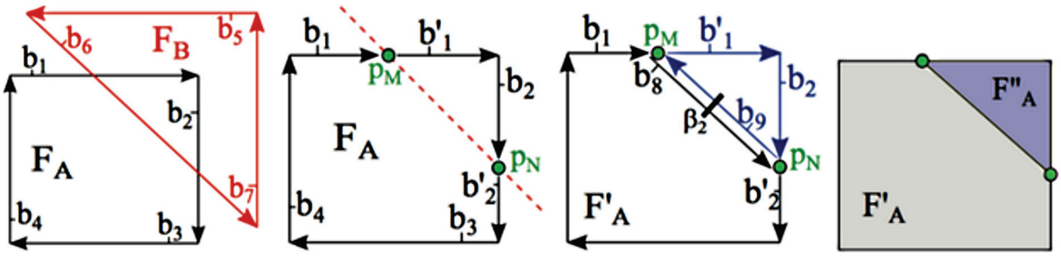


Figure 7. LCC representation of an explicit contact surface modeling between two 2-cells F_A and F_B, belonging to two different 3-cells (only the cut of F_A is illustrated). From left to right: F_A and F_B overlapping; detection of the intersecting points P_M and P_N; insertion of P_M and P_N on F_A; F_A becomes split into F'_A and F''_A.



2-cells on both overlapping faces. Focus is made on the cut of the layout of F_B from F_A, but the exact same process will be held on F_B based on the layout of F_A. That approach is used here on the IFC entities such that the boundaries of the spaces will be explicit as well.

5.2.2. Explicit Linking of the Touching Elements

The 3-map formalities allow the explicit representation of spatial relationships between cells thanks to the β links. For two 3-cells to be linked by β_3 in a 3-map, they need to share at least a common 2-cell that stand as their contact surface (Diakité et al., 2014a).

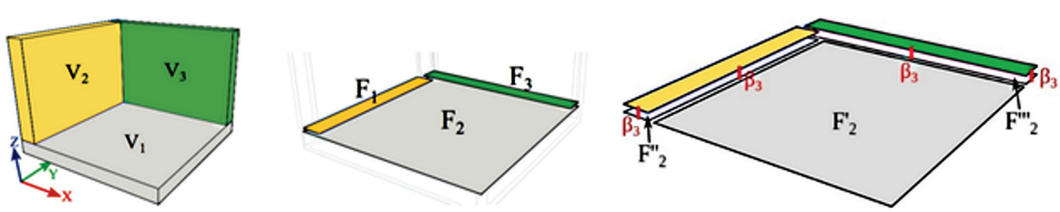
Thus, all 3-cells having contact surfaces are 3-sewn through their corresponding common 2-cells resulting from the different face cutting. An illustration is provided in Figure 8 where the face F_2 belonging to the slab (V_1) is split into three faces F'_2, F''_2 and F'''_2, with the two latter corresponding to the contact surfaces between the slab and the walls volumes V_2 and $V_3$and still are part of V_1. Thus, the $\beta_3$links can then be built between the three volumes via their common overlapping 2-cells.

5.2.3. Detection of the Space Boundaries and Creation of the Space Volumes

Thanks to the previous step, any touching building elements are explicitly linked in the 3-map data structure. It then becomes straightforward to recognize the 2-cells corresponding to space boundaries. Indeed, since contact exists only between physical building components, surfaces of a given component, that has no contact with any other component can be assumed to be in contact with the air (Diakité *et al.* 2014a). Therefore, such 2-cells that contain 3-free darts (darts that has no β_3 links)are duplicated and linked between them to form closed watertight volumes (Figure 9).

Similarly, to the approach of van Treeck and Rank (2007), the outer shells are also generated since the faces at that side are also in contact with the air (Figure 9, right). The spaces generated by our method correspond to the 1st level SB of the SBV. We discuss the implementation details of the approach and present the results of our experiments on IFC models of buildings.

Figure 8. Example of three volumes V_1, V_2, V_3, that can be seen as two walls and a slab (left), the creation of their contact surfaces (middle) and their β_3 linking through the contact 2-cells (right).



6. IMPLEMENTATION AND EXPERIMENTS

6.1. Implementation

The entire framework presented in the previous section has been implemented in the C++11 language and is supported by several libraries. The Computational Geometry Algorithms Library (CGAL Project, 2016) provided several geometric algorithms and is the basis of the operation's implementation. We particularly used its Linear Cell Complex package that provide an implementation of the combinatorial map data structure; the latter is the basic data structure that supports all our operations while handling at the same time the geometry, the topology and the semantic information of the original IFC models. The IfcPlusPlus library (IfcPlusPlus, 2016) provided a complete parser for IFC2x3 and IFC4 formats.

6.2. Experiments

In order to test our approach in a configuration that fit to the preconditions, we built a single floor IFC model containing four rooms and one corridor that is a final number of 5 spaces. SketchUp Pro 2016 have been used to design the model and export it as IFC. We have also experimented our implementation on several IFC models obtained from different sources (e.g. the Open IFC repository (Amor, 2012)), and we faced few issues that are discussed in the next subsection.

As it can be seen in Figure 10 showing the screenshot of the IFC viewer, no IfcSpace element exists in the initial model. We therefore apply our approach by first importing the walls, the roof, the slabs and the openings in our LCC tool. The furniture elements were ignored during the model's loading. Thanks to the 3-map data structure used, the semantic information of the components was kept, so each type of building element is represented by a single color as illustrated in Figure 11 (top left). The roof has been hidden to allow visualization of the indoor environment.

The fingerprints of the walls and doors on the slab surface (Figure 11, top right) illustrate the identified contact areas. The latter allowed to determine the 2-cells belonging to the rooms (the outer shell volume has been hidden for sake of visibility). The generated volumes (bottom) show the space corresponding to the air volumes enclosed by the structural components. They are watertight 3-cells and explicitly contain their contact surfaces with their surrounding components (doors, windows, etc.). At the end of the process, the spaces will correspond to the only 3-cells of the LCC that have no semantic information attached to them, as they are just generated. Therefore, it is straightforward to assign them the desired attributes in the structure, in order to prepare their export in a new IFC file eventually.

Figure 9. Projection view of the duplication process of the 3-free faces of the walls W_1, W_2, … (left) and their linking by β_2 (middle) to obtain closed volumes corresponding to room R_1, R_2, …, as well as the outer envelope (right).

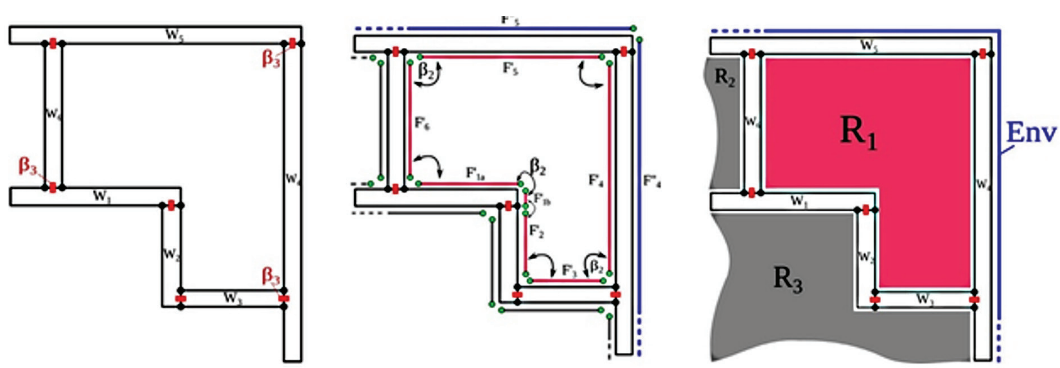


Figure 10. View of the IFC model test using Solibri Model Viewer (Solibri, 2016)

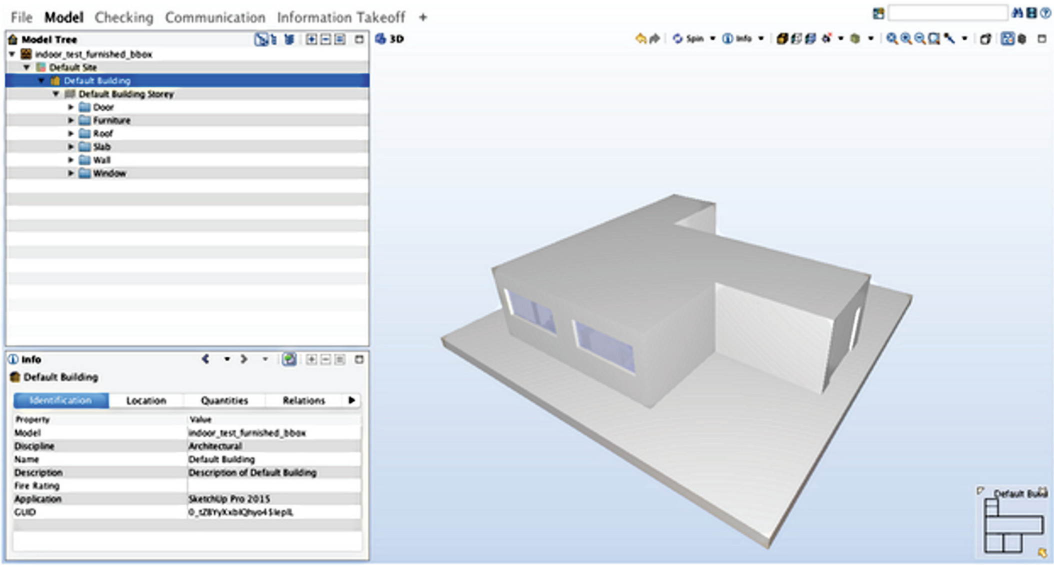
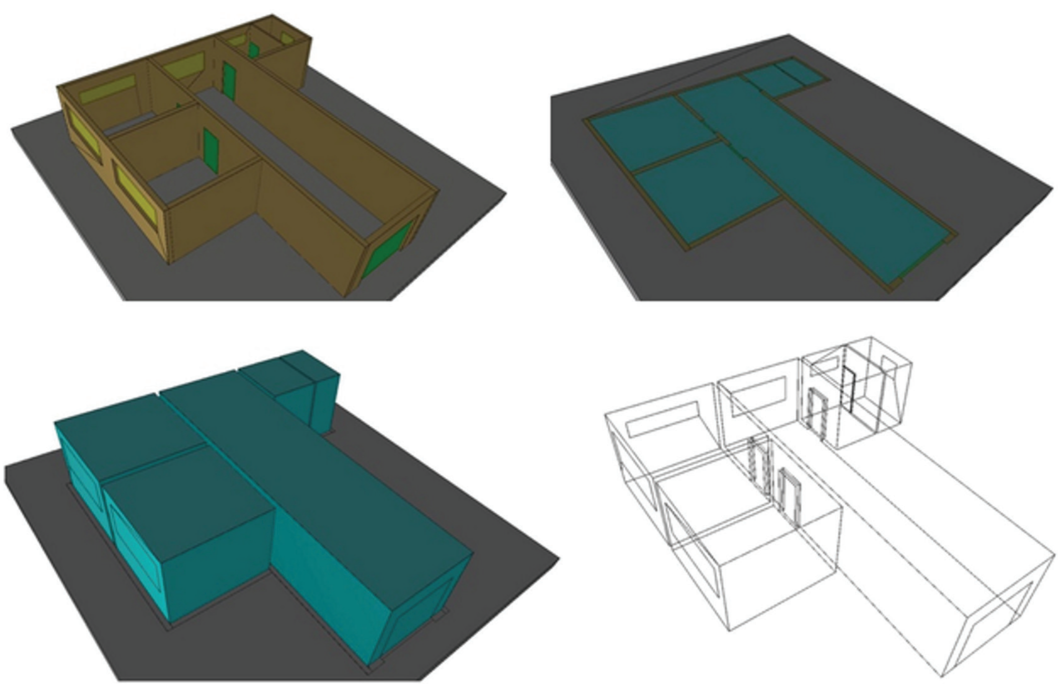


Figure 11. Generation of spaces from the structural components of the IFC model. Imported IFC components in the LCC tool (top left); reconstructed contact surfaces and identification of the space boundaries on the slab (top right); generated space volumes (bottom left) and their wire frame view (bottom right).



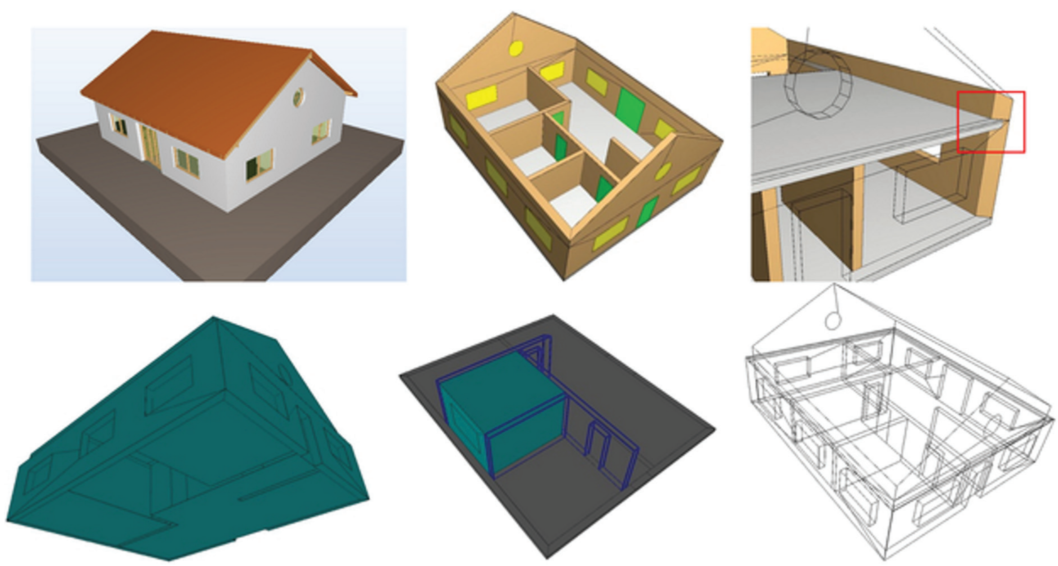
6.3. Discussion

Our approach to generate IfcSpace is straightforward and relies on a simple topological concept. Its implementation does not require exhausting efforts and is made easy by the freely available libraries cited in the implementation details. While it does not need big effort to be set, its benefits are huge for all applications relying on BIM model that require an explicit description of the spaces. Indeed, IfcSpace objects are necessary to several user applications, yet there is, to our knowledge, no available third-party tool allowing to generate such spaces when they are missing. It is the case for example for facility management, energy simulation, acoustic or indoor navigation on which we focus in this paper.

However, some limitations have to be considered with our approach. A first one is the validity of the geometric representation of the input model on which the method relies to deduce the spaces. Wrong configuration will lead to wrong generated spaces, as illustrated in Figure 12. There is a volume intersection between a slab and some walls on the studied IFC model (top-right). Therefore, wrong boundaries are considered for the enclosed air volumes (bottom-left). The only space volume that could be correctly reconstructed (bottom-middle) is properly surrounded by components that just touch but do not intersect.

Another aspect to consider is the high possibility of geometric computation failure of the operations. This is mostly due to the precision issues involved in the process. Indeed, the explicit reconstruction of the contact surfaces between the structural components implies several geometrical operations that are sensitive in 3D (for example segment-segment or point-segment intersection, coplanar face checking, etc.). A precision threshold is then required in most of the calculations, but the automatic deduction of such threshold remains a challenge. In our experiments a precision of 10e-3 appeared to be convenient.

Figure 12. Failure cases of the IfcSpace generation due to wrong representation of the structural components in an IFC file. Top row: original IFC model (left), corresponding LCC (middle), zoom on the intersection between the slab of the first floor and the side walls (right). Bottom row: wrongly generated space that aggregates almost all the spaces of the building (left), single correctly reconstructed space (middle) and wire frame view of the generated spaces (right).



7. CONCLUSION

We discussed the checking of the validity of BIM models for their direct usage by third-party applications, with focus on indoor navigation. To overcome missing or wrong IfcSpace objects, we introduced an approach allowing to generate indoor spaces that are needed as input data to such applications. Our method relies on a topological approach supported by the combinatorial map data structure and provides watertight volumes of the air spaces from the layout of the structural components of the input building model (walls, slabs, roofs, etc.) and their spatial relationships. We implemented and tested our approach on IFC models and generated spaces corresponding to IfcSpace objects.

This work is the first step of what can be seen as a supporting tool aiming at making BIM models fully suitable for indoor navigation. The analysis of the standard definitions and the current status of the validity check of the IFC models helped us to precisely identify where the challenging issues are. Nevertheless, several improvements can be considered in future work. For example, a further correction level could be considered by involving Boolean operations to overcome the intersecting volumes issue. More IFC models should be tested to see the cases that are not considered or properly handled by the approach. Finally, with the fast development of fine grained 3D indoor navigation, we could also consider the elaboration of an add-on view dedicated to the IFC standard, or study how the specific needs of indoor navigation can fit to already existing MVD (e.g. the SBV).

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