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Cadastral data as a source for 3D indoor modelling

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ABSTRACT

Despite the rapid development of indoor spatial data acquisition technology, there are currently no solutions that enable large-scale indoor spatial data acquisition due to several limiting factors that characterize the indoor space. This fact, together with the rapidly growing need for indoor models, is the main motivation for our research. The focus is on the study of the appropriateness of existing cadastral data for 3D indoor modelling. Within the study, a framework for 3D indoor modelling has been developed, comprising a chain of processes, starting from initial cadastral data and ending with the OGC IndoorGML compliant document. The process chain is divided into three parts, which are described individually and supported by UML activity diagrams. The Slovenian Building Cadastre data represents the basis for the framework design and data assessment. The IndoorGML standard is used for final outputs, as it provides a standardized data model for the representation and exchange of indoor spatial information designed for indoor navigation and location-based services. The data storage options using a spatially enabled database are presented for storing 2D and 3D geometries. The stored data enables fully automatic IndoorGML document generation on request, while also taking advantage of all spatial database functionalities. The proposed approach is software independent and can be implemented with various spatially enabled software packages. In addition to 3D indoor data modelling, the framework represents a comprehensive method for assessing the usability of input data for the purpose of 3D indoor modelling. The assessment is done for the case of the Slovenian Building Cadastre. The assessment of the cadastral data suitability for 3D indoor modelling can be used for decisions regarding future steps towards a multi-purpose 3D real property cadastre. The presented concept can be applied in many countries worldwide that have a similar condominium registration system.

1. Introduction

The importance of 3D indoor models is growing due to a variety of applications, related in particular to location-based services and navigation (Afyouni et al., 2012; Yang and Worboys, 2015; Lin and Lin, 2018). We are often faced with locating points of interest (POI) and finding optimal paths to them, which can be effectively solved by using navigation principles. The navigation process requires two key components. The first one is positioning and the second one is spatial data, which provides the spatial context to the position information. Combining these two components, the navigation device can calculate an optimal route to the desired POI.

Recent technological developments in the field of geospatial data acquisition and outdoor positioning have made location-based services highly affordable and widely available on smartphones and other electronic devices (Huang et al., 2018). However, this is only true for the outdoor environment, as technologies for geospatial data acquisition, including remote sensing, and technologies for positioning, in particular Global Navigation Satellite Systems (GNSS), cannot be used in the indoor environment. As a result, there are a great number of highly developed and massively used location-based services (LBS) for the outdoor environment, such as Google Maps, Uber, Foursquare, Pokemon Go etc., and almost none for indoor space. Looking at the market of outdoor LBS, one can easily see the great potential of indoor LBS, especially because nowadays we spend a major part of our time indoors, whether working, resting, exercising, shopping, etc. The indoor navigation applications are of particular interest with regard to public buildings (e.g. hospitals, schools, universities, bus and railway stations, etc.) and shopping centres to facilitate POI searching for their visitors. Apart from that, several public services are potential users of indoor spatial data (e.g. police, emergency medical aid, firefighters, etc.). These services would benefit from indoor spatial data of every type of building, not just the public ones. Some studies have evaluated the indoor 3D spatial data and indoor navigation support for first responders in emergency situations (Lee and Zlatanova, 2008; Tang and Ren, 2012; Chen et al., 2014; Tashakkori et al., 2015). The potential has

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expanded even more in recent years with the increasing use of smartphones, which combine portability, computing power, data storage, connectivity and sensors.

Several technologies are being developed to enable efficient indoor spatial data acquisition using various combinations of passive image sensors and active ranging sensors (Gunduz et al., 2016; Kang and Lee, 2016; Liang et al., 2016; Jiao et al., 2017; Lee et al., 2017; Lenac et al., 2017). Indoor positioning is also a rapidly evolving field with some technologies already available and a lot of ongoing research activity (Vanclooster et al., 2016; Correa et al., 2017; Brena et al., 2017). The major common problem of both spatial data acquisition and positioning technologies related to the indoor environment that sets them apart from technologies for outdoors is that they are currently spatially very limited, i.e. they cannot be performed on a large scale. In practice, this means that each building must be individually equipped with an indoor positioning system, and a detailed as-built 3D model of the building interior structure should be available. In addition, the model has to include the topology information, i.e. an indoor space connectivity graph.

The complexity and consequently high costs of indoor spatial data acquisition noted above justify research on the usability of already acquired and stored data for existing buildings. The most detailed and comprehensive documentation about buildings is a construction plan. For older buildings, the drawings and documentation were provided and archived in analogue form, while for newer ones digital vector models are provided, and for some recently built ones also conforming to the standards in the fields of Building Information Modelling – BIM (ISO, 2018). Construction models that are provided within BIM in accordance with the Industry Foundation Classes (IFC) provide rich 3D geometry and semantic information, which can be used, analysed, enriched and updated by a large range of domains included in a building's lifecycle. This also includes the field of indoor LBS, which can benefit from the growing utilization of BIM in practice. Much recent research is therefore focused on integration of BIM and geospatial domains to fully exploit BIM potential in the geospatial domain and vice versa (Li and He, 2008; Chen et al., 2014; Hong et al., 2015; Deng et al., 2016; Diakité and Zlatanova, 2016a,b; Xu et al., 2017; Teo and Yu, 2017; Ellul et al., 2018). Currently, BIM has not yet been widely introduced operationally into the processes of building design, construction, maintenance, and facility management, but in the future, it has big potential to become a valuable data source for indoor LBS. The biggest issues surrounding the use of building construction documentation and data for indoor data extraction lie in their complexity, and in the fact that generally, they do not provide as-built information about new buildings (Atazadeh et al., 2017). Another possible source of data about buildings, albeit lacking in detail, is land administration data. Although their content, structure, degree of detail and entry regulations depend on each country's legislation, this data is generally centralized and easier to access compared to construction documentation.

This article focuses on 3D indoor modelling of buildings using cadastral data as an alternative data source to other indoor spatial data acquisition approaches. In this way, the article also aims to contribute to the idea of a multipurpose 3D cadastre (Tekavec et al., 2018), offering data modelling approach for indoor location-based services. We decided to use cadastral data from Slovenian Building Cadastre, as it has several advantages over other data sources in Slovenia, in particular, the centralized storage, availability and relatively uniform data content are the most important ones. Our aim has been to develop a framework for 3D indoor modelling which could be applied to Slovenian cadastral data. It is designed to generate 3D indoor models, compliant with IndoorGML standard, that provides a data model for indoor spatial information. The framework can be used for two purposes, either to generate 3D indoor models or to assess the input data suitability from the perspective of 3D indoor modelling. The latter can provide valuable information for decision making regarding the future changes of data models and processes in land administration systems. The article represents an extension of the research, published at 6th FIG Workshop on 3D cadastres (Tekavec and Lisec, 2018). The whole framework was thoroughly revised, and the proposed process has been modelled using UML activity diagrams. The research is supplemented with a comprehensive study on various options for data storage in a spatial database. Additionally, 3D data visualization options are presented and discussed.

2. Literature review

In recent years, the topic of indoor LBS has been experiencing intensified attention in research as the services and available technologies lag behind compared to the ones developed for the outdoor environment (Jensen et al., 2010; Gunduz et al., 2016). Important factors that facilitate research and development and ensure their consistency are international standards. There was no specific standard in the field of indoor LBS until the Open Geospatial Consortium (OGC) standard IndoorGML was introduced in 2014, aiming to harmonize and foster research and development. IndoorGML standard provides an open data model and XML schema for indoor spatial information (OGC, 2014). It covers geometric, topological and semantic aspects of indoor space. The origins of the standard date back to the year 2009, when the multilayered space-event model for navigation in indoor spaces was published by Becker, Nagel and Kolbe (2009). They defined key principles that are used in the IndoorGML standard. The standard follows the cellular space concept, according to which the indoor space is modelled as a collection of non-overlapping cells. This sets it apart from the other standards in the field of 3D modelling (e.g. CityGML, IFC) as they do not model the indoor space itself, but the building features (e.g. walls, windows), which, on the other hand, can also define indoor space. The most similar class, named IfcSpace, is used in IFC to represent empty spaces inside the building and can be used for linking the two standards (Teo and Yu, 2017). The overlap with other standards in the geometric part is solved with the possibility to add external references. However, 3D geometry can also be included in an IndoorGML document.

Topology is the key component of the IndoorGML standard, as it is vital for navigation applications (Lee, 2004). It is realized in the form of a Node-Relation Graph (NRG). The theoretical basis for derivation of NRG from the indoor space geometry is the Poincaré duality, where a k-dimensional object in N-dimensional primal space is transformed to an (N-k) dimensional object in dual space (Munkres, 1984). The topological relationships in IndoorGML are explicitly described using the XLinks concept of XML provided by GML. The referencing is realized using *href* attributes (*xlink:href* is used in the paper). Another important concept of the IndoorGML standard is a multi-layered representation (Becker et al., 2009). It allows the same indoor space to be modelled in several layers according to the cellular space concept and therefore allows for separate modelling of WIFI, RFID and other spaces related to indoor navigation (Fig. 1). The links between spaces are established via interlayer relations with different possible relations, such as within, contain, overlap.

With the introduction of the IndoorGML standard, the research community and developers got a data model to develop interoperable solutions for indoor LBS. Since then, several studies relating to this standard have been done on data acquisition, 3D modelling, visualization and applications. Seo (2017) developed a software for creating IndoorGML compliant models, which is is similar to our proposed framework in terms of data input and output. However several differences between them exist, which are discussed in section 5. Ryoo et al. (2015) compared the OGC standards IndoorGML and CityGML (OGC, 2012),

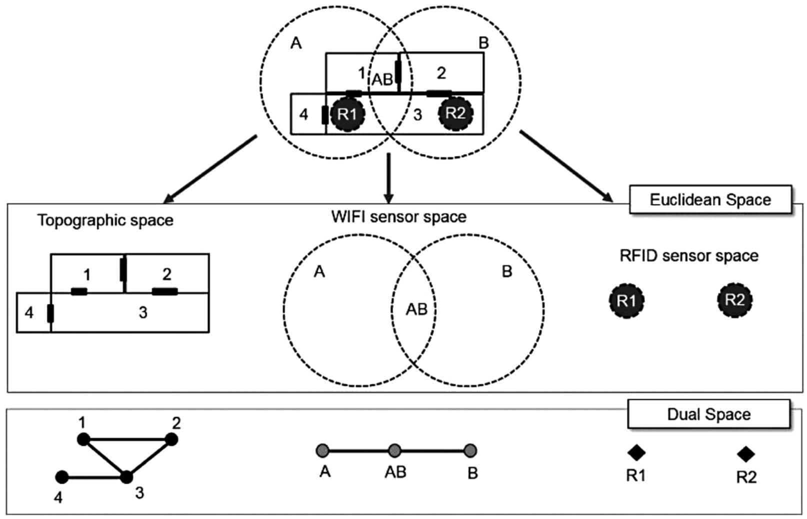

Fig. 1. IndoorGML multi-layered representation (OGC, 2014).

which both cover 3D modelling of indoor space in the GIS domain. Although they are similar in the 3D modelling aspect, the authors showed their differences, especially in their scope and applications. Typically for rapidly developing fields, there are a large number of remaining unresolved issues regarding indoor mapping and modelling. These issues are systematically analyzed and categorized into existing and future ones in Zlatanova et al. (2013). Recently Kang and Li (2017) emphasized the potential of the IndoorGML standard and encouraged the research community to include it in their research by proposing new features, developing new extensions and performing case studies. Research has also been conducted in relation to the data sources and modelling processes for obtaining IndoorGML compliant models (Khan et al., 2014; Mirvahabi and Abbaspour, 2015; Kim and Lee, 2015; Diakité and Zlatanova, 2016a,b; Teo and Yu, 2017). Indoor spatial information is related not only to physical structures but can also be combined with legal information (Zlatanova et al., 2016; Alattas et al., 2017). These studies deal with linking IndoorGML and LADM (ISO, 2012) mostly on a conceptual level. Alattas et al. (2018) further propose a database implementation of the conceptual link between LADM and IndoorGML. The main aim of linking is to analyse how legal information from LADM can improve the semantic properties of IndoorGML models and thus improve the process of indoor navigation. The cadastral extension is also mentioned as a candidate for the semantic extension of IndoorGML in Kang and Li (2017). The link between land administration and IndoorGML has therefore already been established and studied, but until now only at a conceptual level.

3. Research methodology and materials

The design of a conceptual framework for 3D indoor modelling based on cadastral data represents the core of the presented research. The framework is composed of a chain of manually or automatically performed processes, starting from initial cadastral data in the form of floor plans in raster format. The attention is given to minimize the need for manually performed activities, as they significantly increase the amount of resources needed for execution of the implemented framework. The OGC IndoorGML standard is used for final outputs. The framework consists of three main parts that are described in detail in Section 4.

The UML activity diagrams are used to summarize and clarify the framework (Figs. 3, 4, 7 and 14). The diagrams follow the division of the framework into three parts. Each diagram presents the activities and their links in the corresponding part of the framework. Aiming to design an applicable framework, we have tested each process using the input data from the Slovenian Building Cadastre in the form of a floor plan of a residential house. The data is in raster format, containing a floor plan for each storey (see also Drobež et al., 2017). Similar floor plans are usually included in the documentation for condominium registration in several other countries. GIS and ETL tools were used for the implementation of the framework. Besides the output in IndoorGML format, we developed options for 2D and 3D database data storage. The storage can serve as a final output or as an intermediate step from which the rest of the framework to obtain IndoorGML file can be done automatically on request at any given time. For the Slovenian study case, a usability analysis for 3D indoor modelling was further conducted, aiming to identify advantages and disadvantages of the data used throughout the process.

The framework is developed and illustrated based on the Slovenian Building Cadastre data. The Slovenian Building Cadastre was introduced in 2000 as a database for condominium registration in the Land Registry (see also Drobež et al., 2017). In the following years, up to 2006, photogrammetric acquisition of 2D outlines (outdoor) for all buildings was conducted for the whole country. In addition to building outlines, additional attributes were collected, including the ground height and maximum height. In 2006, the Building Cadastre was legally and operationally introduced and detailed registration of buildings and their parts (legal subdivision), together with floor plans, became mandatory. The Building Cadastre data is open and publicly available via the official website. The scanned building registration documentation with floor plans is not publicly available. However, it is available to the authorized land surveyors.

In this study, we have used floor plans from the building in the Building Cadastre, which have been available in raster digital form (Fig. 2) for more than a decade. The vector form of floor plans has been required for new cadastral entries since 2018. Mandatory content of floor plans are outlines of building parts for each floor. In many cases, the documentation contains more detailed floor plans with room outlines aiming to clarify the building division into building parts.

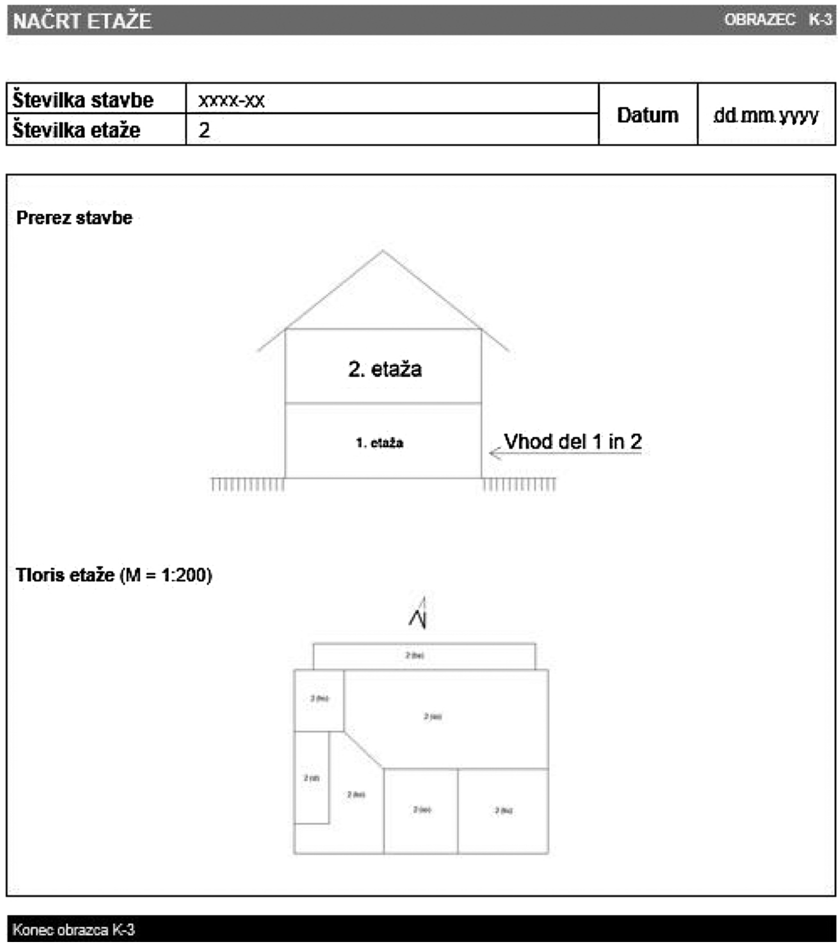

Fig. 2. Sample document of Slovenian Building Cadastre containing the building floor plan.

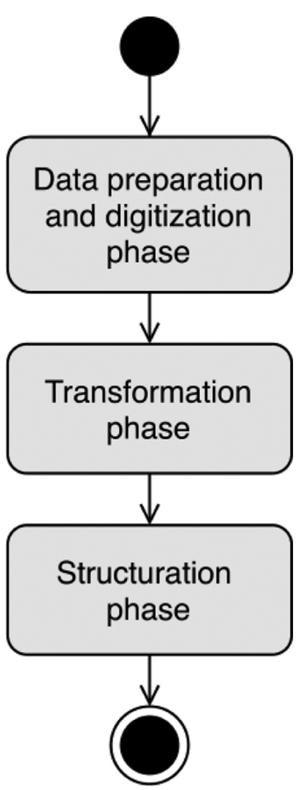

Fig. 3. Generalized UML activity diagram of the proposed framework.

4. Framework design

In this section, the entire process chain of the framework is described in detail. The framework is based on the research, published in Tekavec and Lisec (2018). The division into three parts follows the actual workflow of the framework implementation (Fig. 3).

4.1. Data preparation and digitization phase

In the first phase, all the data should first be acquired, prepared and then digitized. Additionally, the attributes, necessary for the execution of processes in the next phases, have to be added. Fig. 4 presents the processes that are executed in this phase.

For the implementation, we took raster floor plans of a residential house (with outlines of all rooms) modelled to fit into Slovenian Building Cadastre. Generally, two types of floor plans exist, depending on whether or not the wall thickness is considered (Fig. 5). The IndoorGML standard treats both concepts (thin-wall and thick-wall) as valid.

Based on the available digital raster image (floor plan), the geometry and topology (room connectivity) of indoor spaces can be obtained through digitization (Fig. 6). First, we scaled the raster images to represent the true extent of the building. For each floor plan, we created three spatial layers to be able to later align the digitized data to the IndoorGML data structure: a polygon layer for room geometry, a line layer for connections (graph edges), and a point layer for graph nodes. As the IndoorGML standard does not allow cell overlapping, each room outline digitized using the polygon feature, representing the basis for 3D cells, has to be checked for overlap with other polygons. This can be

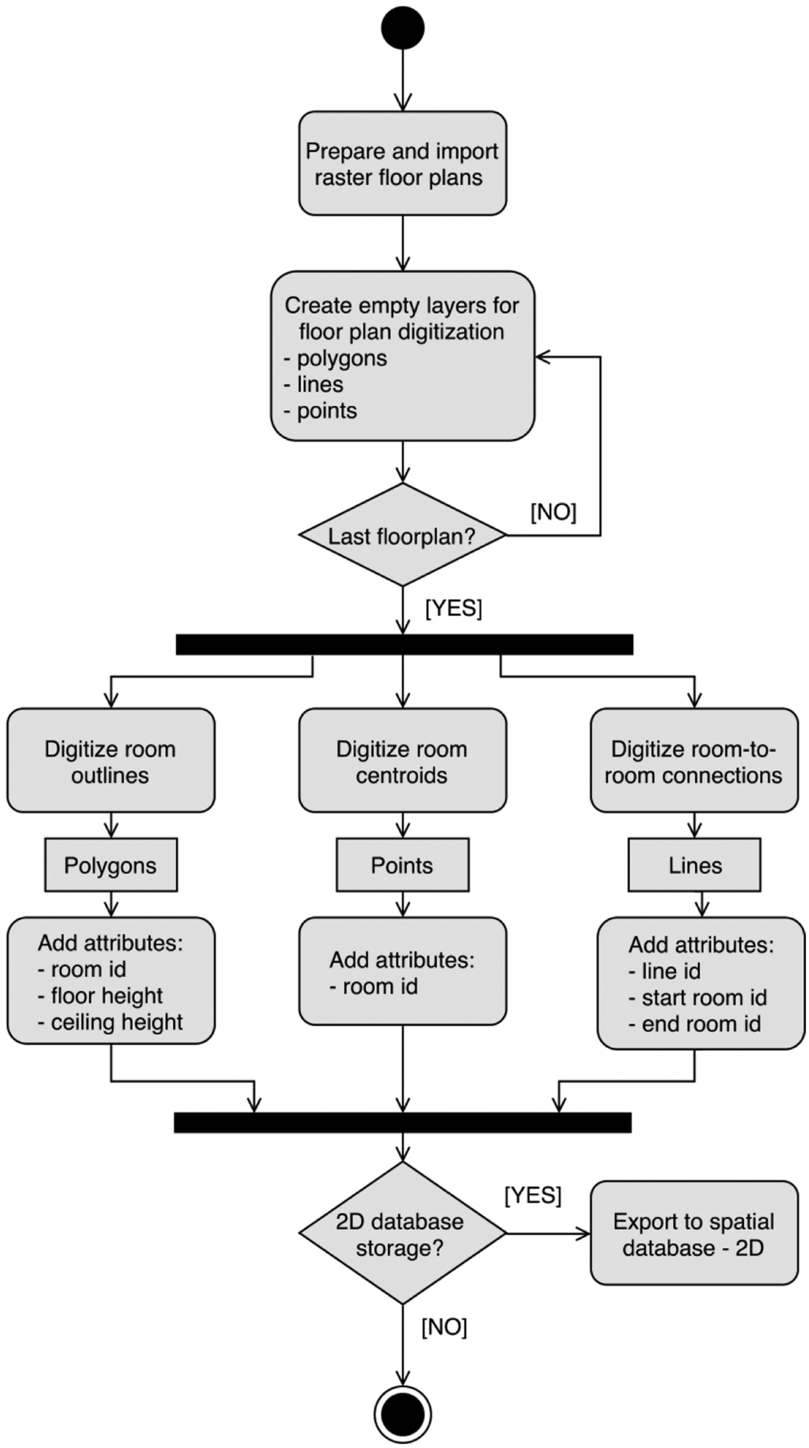

Fig. 4. UML activity diagram for the digitization phase of the proposed framework.

done automatically in QGIS software by the Topology Checker tool. To enable the construction of 3D cell spaces with the extrusion, the floor and ceiling heights have to be added for each floor. These attributes had not been available in Slovenian Building Cadastre until recently (2018) so the heights have to be measured and added manually. The heights can be relative, absolute or a combination of both. For absolute vertical positioning of the model, we need one height that has both relative and absolute height. Navratil and Unger (2013) provided a comprehensive overview of heights in land administration. It is worth mentioning that polygon extrusion could produce overlapping of 3D cells in cases where the floor and ceiling are not straight and horizontal.

Once the room polygons are created, points representing graph nodes can be created automatically as centroids, while lines representing graph edges have to be added manually if the floor plan does not include door openings. The possible connections between spaces can be automatically narrowed down to connections between neighbour spaces, but the actual connections still have to be added manually. Together with floor and ceiling heights, this represents significant manual input as it requires physical inspection of the building. If the floor plan contains the connection openings, they can be automatically identified using object recognition techniques on a raster image. Due to the duality concept, the points are given the same identifier as room

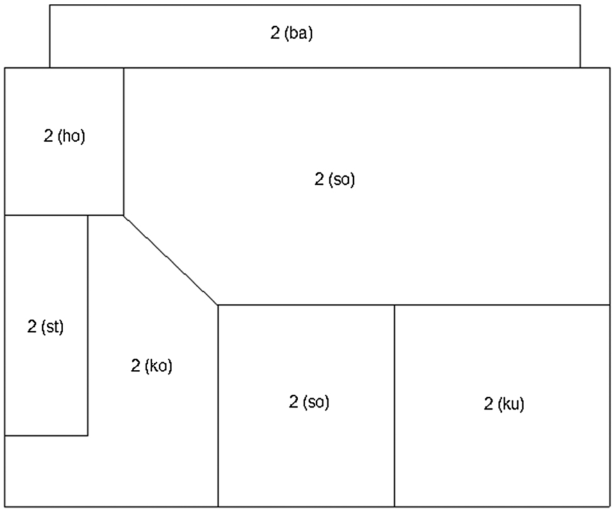

Fig. 5. Raster floor plan from Slovenian Building Cadastre following the thin-wall concept - the room annotations consist of building part number and room usage code in brackets.

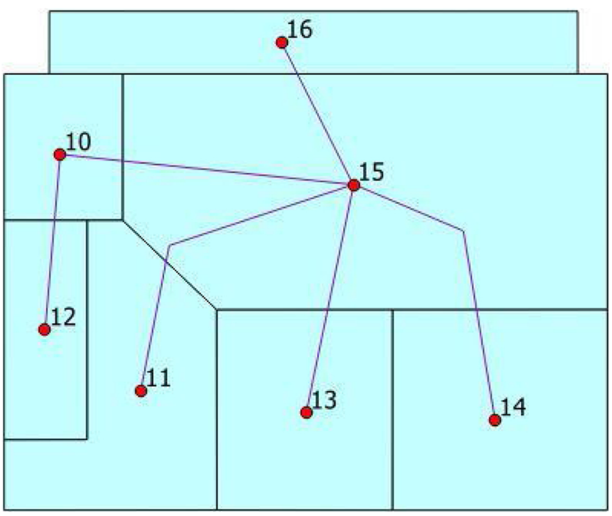

Fig. 6. Digitized polygons, line strings and points with identifiers.

polygons. Each line should be snapped to the start and end point with the start and end point identifiers added as attributes. The lines representing connections between rooms in different floors (stairs and elevators) have to be snapped to points on different layers with both point identifiers added as attributes. This enables the integration of separate connectivity graphs into one graph for a multi-storey building. While the positional alignment of floors does not affect the topology, it is still important to properly align the floor plans one above the other, to enable proper 3D visualization of geometry. The alignment can be automated if floor plans contain a common reference feature (outer perimeter, reference point, etc.). There are two options from the coordinate system perspective. We can use a local coordinate system for each building, or we can choose to digitize all layers in a common national or global coordinate system, as we did. If the local coordinate system is chosen, we need to establish a link to a national or global coordinate system. This can be a point with national or global coordinates of the local coordinate system origin. Here it has to be mentioned that the IndoorGML standard supports the conversion of coordinate reference systems via anchor node element.

4.2. Transformation phase

In the second phase, the data from the first phase goes through a set of transformation processes (Fig. 7). All layers of the same type, digitized separately for each floor, are first merged into one layer, followed by three different sets of transformations, one set for each feature type (polygon, line, point). Additionally, the options for 2D and 3D data storage are presented within this phase. At the end of this subsection, we present the option for 3D visualization of the data, which can be used to perform quality checks and for a clear representation of the modelled data.

The polygons representing outlines of the rooms are transformed into 3D cells with a process of extrusion using the height attributes. Each digitized 2D polygon, representing a room outline, is “lifted” to the floor height and then extruded to ceiling height, which forms a closed 3D cell. After extrusion, the orientation of faces has to be checked and then the cell can be assembled into solid geometry. The final phase of the transformation of polygons is creating IndoorGML specific attributes (Fig. 8). A unique id is assigned to each cell using a global counter. When generating the models separately (at a different time or as separate processes) the uniqueness of cell ids should be ensured by saving the last used id, using unique ids within the model combined with the building’s unique id, etc. The parent property and parent id attributes are static and contain information about the position and role in the hierarchy of the IndoorGML document. According to the concept of *Poincaré duality,* the cell and the corresponding node are connected. This connection is materialized with a duality *xlink:href* attribute. If we use the same numbering of cells and nodes (to obtain unique ids), only the node prefix has to be added to the numbering of cells to obtain a duality *xlink:href* attribute (“N1” for the node that corresponds to the “C1” cell).

The height values needed to position the nodes inside the linked cells in 3D space can be derived from the corresponding polygons. For implementation, we chose the mean value between the floor and ceiling height. The same types of attributes are added to nodes as to cells, with an additional connects *xlink:href* attribute that contains a list of all edges that are connected to a given node. This list was not included in the digitization phase, as the node can have any number of connected edges, so the connection information cannot be stored in the attribute table of nodes. Having the information about the start and end node for each edge acquired in the digitization phase, the list of all connected lines to each node can be created by joining the edge and node table. We implemented the list of connected edges by leveraging the list attribute option in FME Desktop software.

The edges are more challenging to put in the 3D environment than the nodes. The start and end height can be derived from node heights. As long as the connection between nodes is placed on a single level these heights are sufficient. When the two connected nodes lie on separate levels, the edge should change the height along its way.

Our solution simplified this problem using the start node height until the last line break and then changing the height to the end node height. This reduces the need for additional data input but can yield non-representative edges. Unique id, parent property and parent id attributes were also added to edges. We left out the duality *xlink:href* attributes used to link the edges and faces, as we do not provide modelling of cell connection surfaces (doors, windows) within our framework. If they exist in input data, they can be additionally included in the framework as a fourth digitization layer, transformed and written into the IndoorGML document as CellSpaceBoundary. The connects *xlink:href* attribute is sourced from the digitized line layer. The weight attribute determines the movement difficulty along the edge and represents key information in optimal path planning. The edge length and height difference can be used to automatically estimate the weight values, as they are available within the framework. However, more accurate values can be set if additional information or manual input is provided.

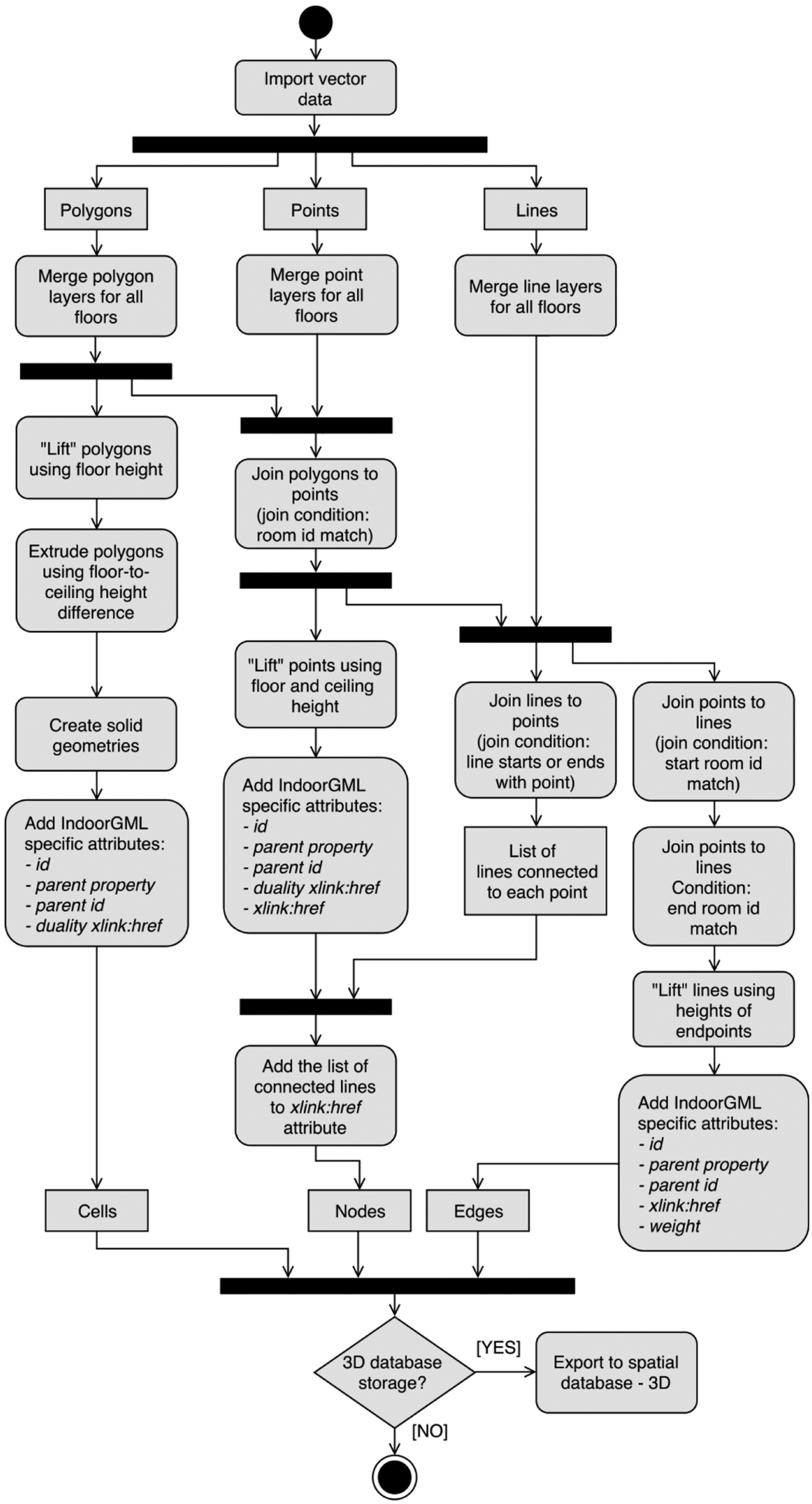

Fig. 7. UML activity diagram for the transformation phase of the proposed framework.

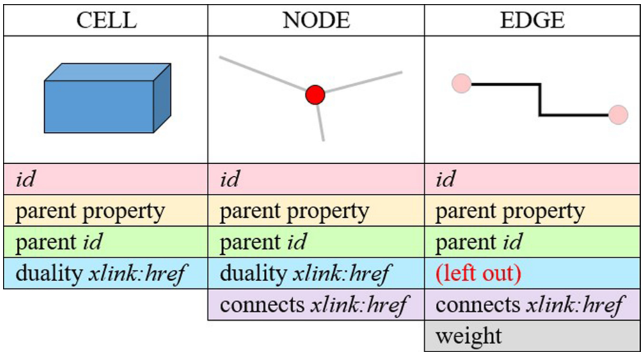

Fig. 8. IndoorGML specific attributes for each feature type (Tekavec and Lisec, 2018).

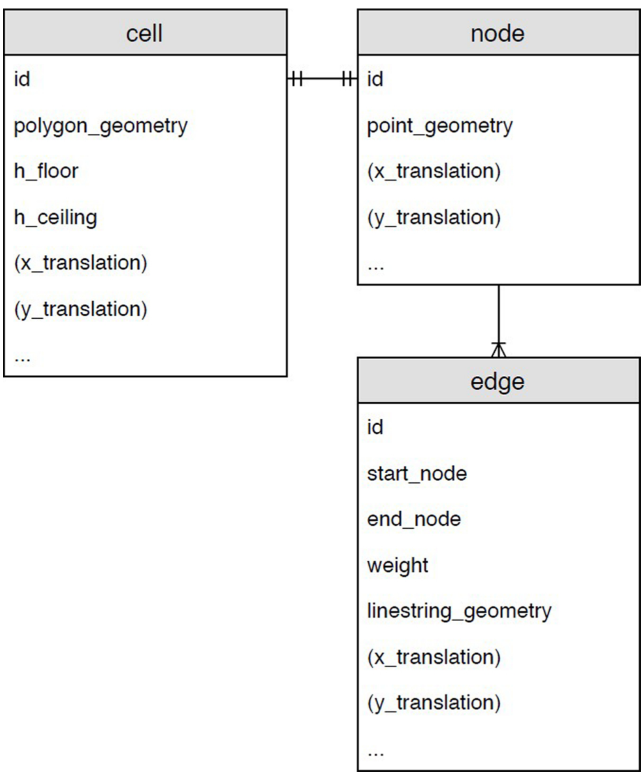

Fig. 9. The basic concept of 2D database storage.

4.2.1. Database data storage

The storage of the data in a database has many advantages compared to file-based data storage, especially from a data management and data dissemination perspective. Since the result of the proposed framework is in a file format, we propose two options of intermediate database data storage within the transformation phase. The storage is designed to enable fully automated creation of IndoorGML files. It can be seen as a breakpoint in the framework, from where the processes can be used only on request and data sourced from the database. The difference between options is the dimension of the stored geometries.

4.2.1.1. 2D database storage. Most of the databases support storing and management geometry following ISO SQL/MM-Part 3 (ISO, 2016) or OGC Simple Feature Access (OGC, 2010). They mostly support storage of geometry in the 3D space, but the functions for data management and analyses consider only two dimensions, with a few exceptions of some basic functions supporting 3D properties, e.g. Z-coordinate value retrieval. The 2D data storage can be performed right after the start of the transformation phase, as can be seen from the UML activity diagram for the data transformation phase (Fig. 7). Another option is storing the combined layers from the transformation phase. The stored geometries and attributes can be accessed and visualized by various GIS software, web services, etc. The basic concept of 2D database storage contains the

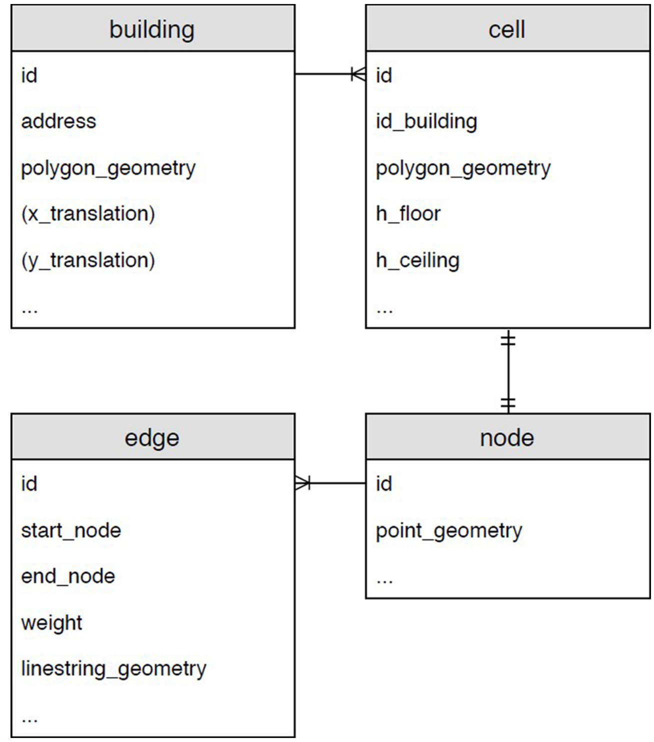

Fig. 10. 2D database storage with building table.

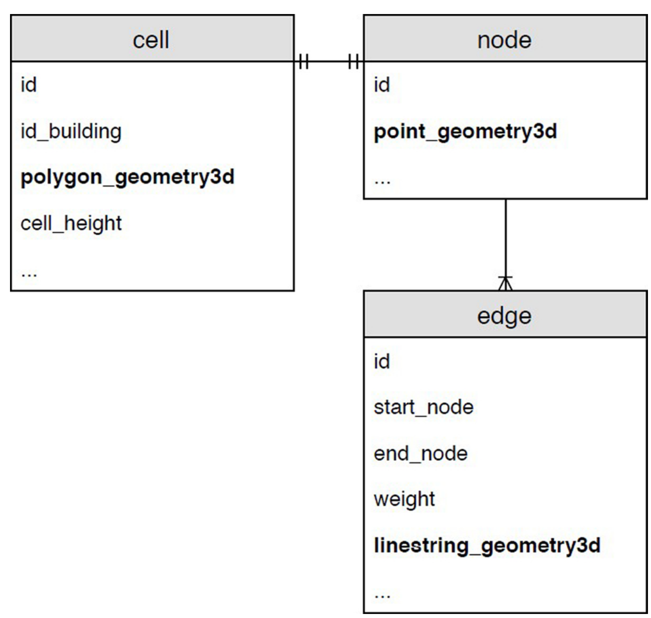

Fig. 11. The first level of 3D database storage.

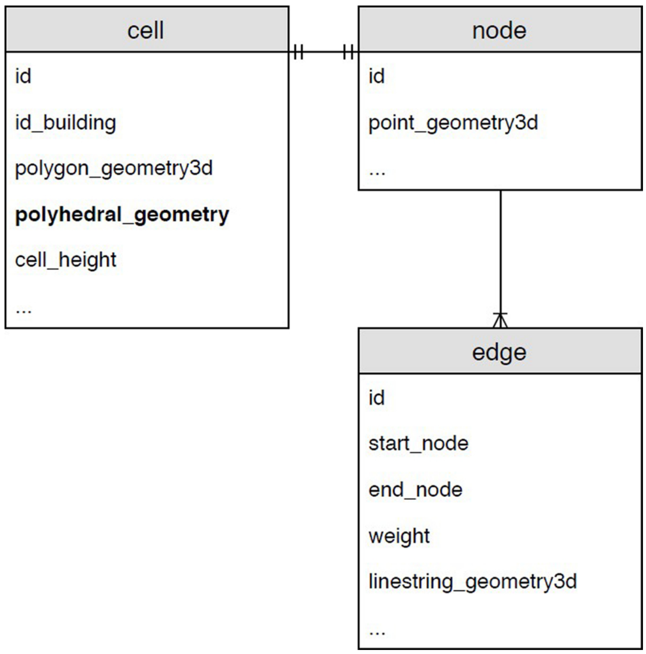

Fig. 12. Second level of 3D database storage.

cell, node and edge table (Fig. 9). Since the cells and nodes are related according to the Poincaré duality, the storage can be further simplified to store only the cell and edge table. In that case, node geometry and attributes would have to be derived from the cell table.

The brackets for x_translation and y_translation attributes indicate that these attributes are needed only when local coordinates are used. Instead, another point geometry column can be added. However, this can cause problems with some software that supports retrieval of only one geometry column per table. The "…" sign means that additional custom attributes can be added for each entity. By adding the building table (Fig. 10) related to official registers the data can be linked to address numbers and other data. The translation attributes if using local coordinates can also be stored in the building table. The rotation attribute can also be included but should be additionally accompanied by the rotation origin point. The 2D data storage is designed to allow fully automatic derivation of IndoorGML files, but not without additional processing.

4.2.1.2. 3D database storage. As mentioned in the previous section, most databases support storage of geometries in 3D space, including point, line string and polygon geometries. Some of the most advanced databases (Oracle Spatial, PostgreSQL with PostGIS) nowadays support storage of volumetric 3D geometries. Therefore, two levels of 3D database storage can be performed within the transformation phase.

The first level of 3D database storage can be performed when points, line strings and polygons are "lifted" onto the appropriate heights (Fig. 11). For cells, only one height attribute is now required for later extrusion. Also, the "lifting" of points and line strings with the polygon heights is not needed every time when deriving IndoorGML file out of the stored data. These geometries are also supported by most GIS software, web services, etc.

The second level of 3D database storage requires the support for volumetric 3D geometries. The open-source PostgreSQL database with PostGIS SFCGAL extension that offers state-of-the-art support for 3D geometries was chosen for our implementation. It can be performed after "lifting" of all features and extrusion of polygons into 3D solids. For nodes and edges, the storage is the same as in the first level, while cells are now stored as polyhedral surfaces, representing the outer shell of the solids (Fig. 12). To overcome the lack of current 3D support in GIS software, we propose a hybrid database storage, where "lifted" polygon geometry and cell relative height are still stored for cells.

4.2.2. 3D data visualization

Cells, nodes and edges modelled in 3D space open the possibility for their 3D visualization. The purpose of data visualization is often narrowed down to just being a tool for user-friendly and clear data presentation, but it is also an excellent tool to check data for inconsistencies and errors. Within our framework implementation, we used FME Inspector to inspect the results of each process of the transformation phase, as well as the end result – IndoorGML file. FME Inspector also allows visualization of the digitized layers and data stored in the database. To make the visualization of the data within the framework open and accessible, we propose the WebGL-based data visualization plugin for QGIS named Qgis2threejs. It takes 2D layers in QGIS and puts them in 3D space using height attributes (Fig. 13). The prepared visualization can be easily published to the web and opened in a web browser. We can further take advantage of QGIS advanced symbology capabilities to make data visualization as clear and descriptive as possible. The visualization has built-in commands for controlling 3D view, switching the layers on and off, adjusting transparency for each layer, and attribute-based labelling and access to feature attributes by their selection. Several studies deal with the challenges of 3D spatial data visualizations, such as occlusions, etc. (Shojaei, 2014; Wang, 2015; Zhou et al., 2015).

From version 3.0 on, QGIS has a built-in 3D viewer that has functionalities to visualize the spatial data in 3D. Currently, the 3D viewer does not provide sufficient functionalities to visualize volumetric objects representing indoor spaces, together with the connectivity graph. Also, the visualization is limited to QGIS software and cannot be disseminated online like the output of the Qgis2threejs plugin.

4.3. Structuration phase

In the final step, the transformed data is structured according to the IndoorGML structure and written into the IndoorGML document (Fig. 14).

The 3D cell solid geometry is assigned to a CellSpace element, node geometry to a State element and edge geometry to a Transition element. All geometries are encoded in GML (ISO, 2007). The parent id and parent property attributes enable the creation of *cellSpaceMember, stateMember* and *transitionMember* elements and their proper placement in the element hierarchy. The *duality* elements for CellSpace and State elements that establish links between them are created using duality *xlink:href* attributes. The *connects* elements for State and Transition elements are created with connects *xlink:href* attributes. These attributes contain a list of connected feature identifiers, solving the cardinality of the node – edge relation. The Transition element also get a weight element with a weight attribute assigned. All other IndoorGML elements and their attributes are created to comply with IndoorGML standard (Tekavec and Lisec, 2018).

```
<indoor:IndoorFeatures
     <indoor:primalSpaceFeatures>
          <indoor:PrimalSpaceFeatures gml:id="PS1">
               <indoor:cellSpaceMember>
                    <indoor:CellSpace gml:id="C1">
                         <indoor:Geometry3D>
                              GML Solid Geometry
                         </indoor:Geometry3D>
                         <indoor:duality xlink:href="#R1"/>
                    </indoor:CellSpace>
               </indoor:cellSpaceMember>
               …
          </indoor:PrimalSpaceFeatures>
     </indoor:primalSpaceFeatures>
     <indoor:MultiLayeredGraph gml:id="MG1">
          <indoor:spaceLayers gml:id="SL1">
               <indoor:spaceLayerMember>
                    <indoor:SpaceLayer gml:id="IS1">
                         <indoor:nodes gml:id="N1">
                              <indoor:stateMember>
                                   <indoor:State gml:id="R1">
                                        <indoor:duality xlink:href="#C1"/>
                                        <indoor:connects xlink:href="#T1"/>
                                        <indoor:geometry>


                                             GML LineString Geometry
                                        </indoor:geometry>
                                   </indoor:State>
                              </indoor:stateMember>
                              …
                         </indoor:nodes>
                         <indoor:edges gml:id="E1">
                              <indoor:transitionMember>
                                   <indoor:Transition gml:id="T1">
                                        <indoor:weight>1</indoor:weight>
                                        <indoor:connects xlink:href="#R1"/>
                                        <indoor:connects xlink:href="#R2"/>
                                        <indoor:geometry>
                                             GML Point Geometry
                                        </indoor:geometry>
                                   </indoor:Transition>
                              </indoor:transitionMember>
                              …
                         </indoor:edges>
                    </indoor:SpaceLayer>
               </indoor:spaceLayerMember>
          </indoor:spaceLayers>
     </indoor:MultiLayeredGraph>
</indoor:IndoorFeatures>
```

5. Discussion

Our framework was implemented using QGIS open source GIS software in the digitization phase, in which raster floor plans were digitized. For ensuing processes, we used the ETL software FME from SAFE software that supports 3D geometries and reading and writing IndoorGML files. For the input data, the raster floor plans from the Slovenian Building Cadastre were selected.

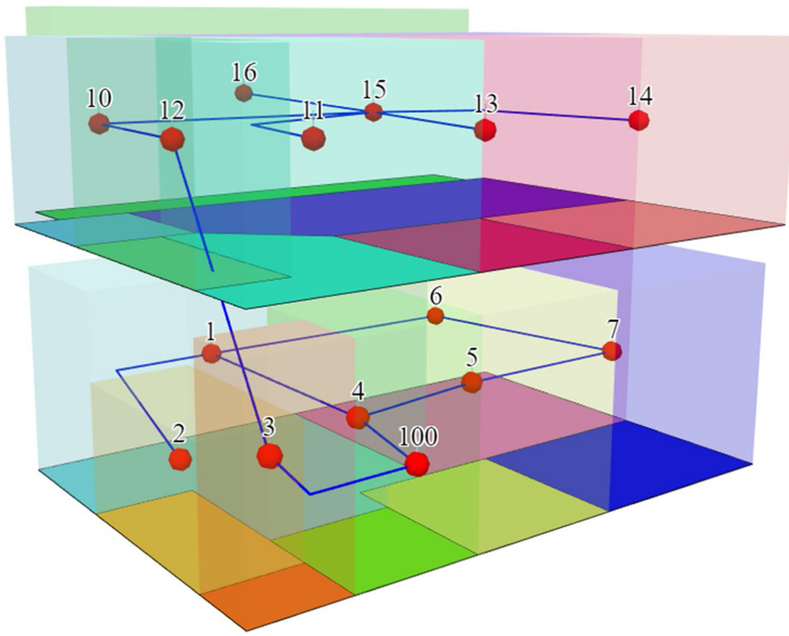

Fig. 13. 3D visualization of the transformed data (Tekavec and Lisec, 2018).

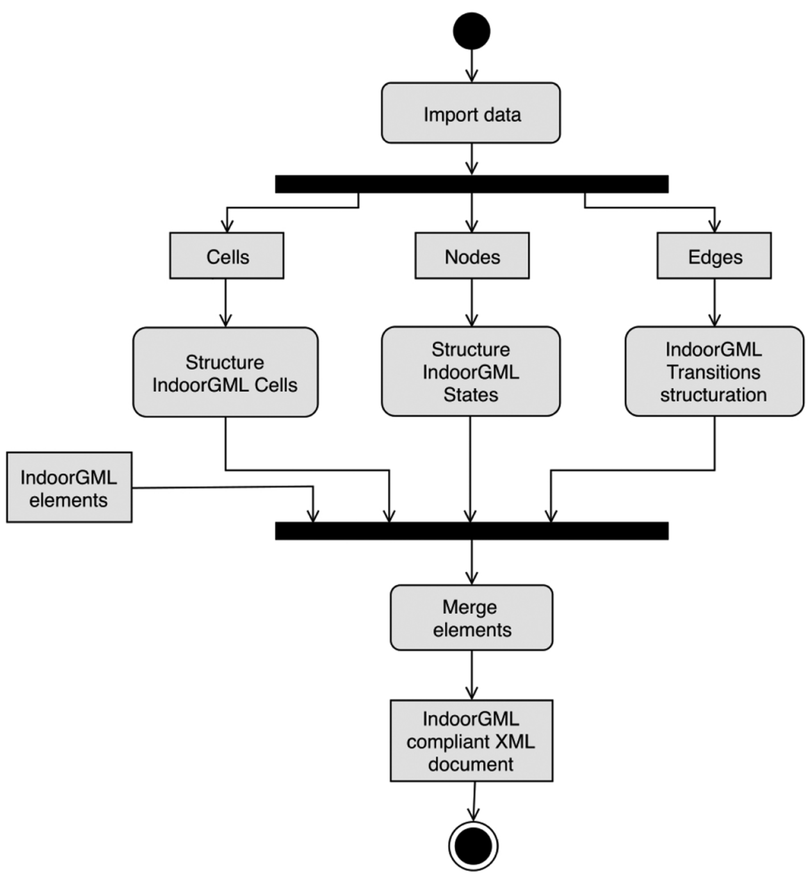

Fig. 14. UML activity diagram for the structuration phase of the proposed framework.

5.1. Data assessment

The presented framework can be used as a tool to identify the advantages and disadvantages of the (cadastral) data suitability for 3D indoor modelling. This is important the organizations, such as cadastral authorities that are responsible for the cadastral data, to devise the required changes in the data model if they decide to support 3D indoor modelling.

For the selected case, the Slovenian Building Cadastre, many advantages were identified in a very early stage of our research and were the reason why we considered using it for 3D indoor modelling. The data is centrally stored and maintained which makes it easily

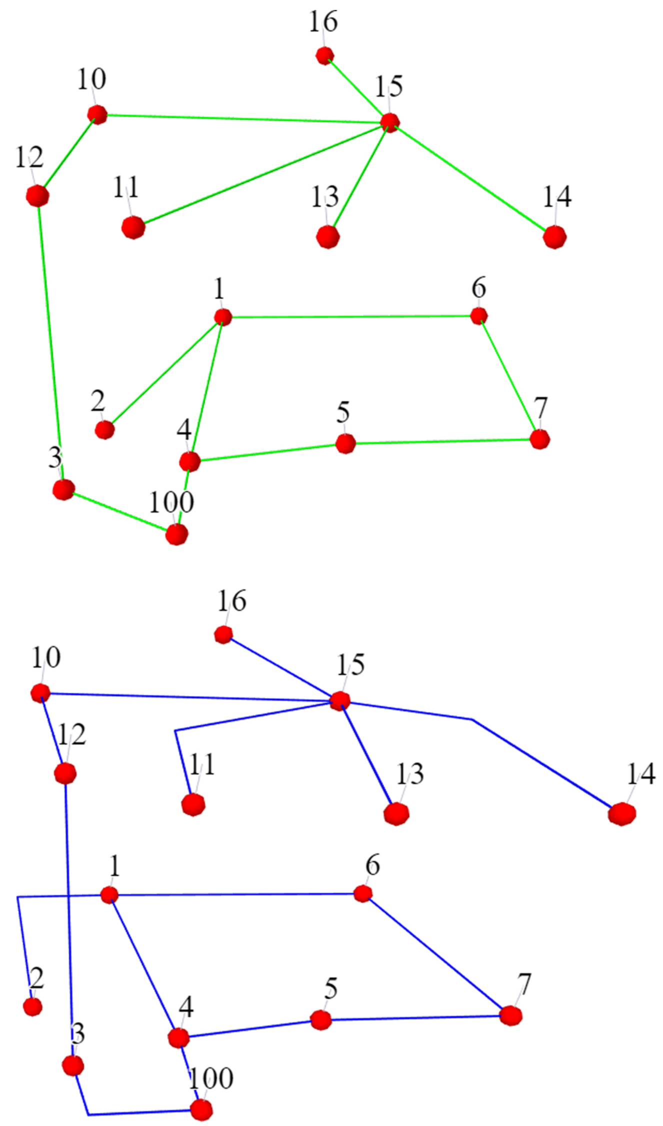

Fig. 15. Automatically derived graph from room polygons and room connection information (top) and graph containing digitized nodes and edges (bottom) (Tekavec and Lisec, 2018).

accessible, provided one has the access rights (attribute data is public, documentation is available to authorized land surveyors). In this aspect, the cadastral data is more useful than construction data, which is often hard to get access to and is not centrally stored. Another important advantage of cadastral data, compared to construction plans or data provided within BIM, is that the cadastre provides as-built data, while construction data often provides only as-planned information that can significantly differ from as-built data. As the Slovenian Building Cadastre provides a technical basis for condominium registration, the 3D indoor models derived from the cadastral floor plans can be directly linked to the established rights, restrictions and responsibilities in the building. The 3D model can be further linked to the Register of house numbers, allowing integration of indoor and outdoor navigation. In 2018, the Slovenian Building Cadastre introduced submission of floor plans in vector format together with floor heights which significantly reduces the manual input in the digitization phase of the proposed framework.

The disadvantages mostly originate from the fact that the data model for the Slovenian Building Cadastre was not designed to support 3D modelling and indoor graph derivation. Until 2018, the floor plans were submitted in raster format, requiring initial digitization. As already stated, since 2018, the floor plans are submitted in a vector format but are strictly limited to outlines of building parts, without the possibility to include room geometries. This significantly limits the usability of the floor plans for 3D indoor modelling. The paper focuses on using the building floor plans, which are not available for most of the buildings in Slovenia, as the full building registration is mandatory only since 2006. This is a significant limitation due to the fact that the proposed framework is not allowing a nationwide 3D indoor modelling.

5.2. Findings

The detailed description of processes needed to develop a 3D indoor model of a building based on cadastral data resulting in an IndoorGML document opens up several topics for discussion.

In the final IndoorGML document, we decided to use the 3D geometry of the cells. The only method to obtain 3D geometries that includes a reasonable amount of additional manual input is the extrusion of 2D polygons using floor and ceiling heights. While it is the most feasible approach, it also doesn't bring many advantages over 2D geometries. 3D geometries enable more realistic visualizations but have limitations, such as occlusions, that should be considered, like occlusions. The additional heights can be useful to determine if the height of the space enables navigation through it (some spaces can have very low ceiling). If the navigation graph is placed in 3D space, we can determine the height difference of the calculated route and thus get additional information about how demanding it is, as locomotion in a vertical direction is more demanding.

For the Slovenian case study, it has been shown that in the first part of the framework several missing data have to be added manually. Additional data are generally not cheap, and its acquisition is time-consuming, especially for the indoor environment. As already mentioned, progress has been made by introducing the floor heights and vector floor plans in the Slovenian Building Cadastre in 2018.

The inclusion of the information about which rooms are connected into the cadastral documentation would be a greater challenge, as it is far beyond the scope of the current land administration system. On the other hand, not much additional information would need to be collected and stored in the cadastral database. A basic connectivity graph without a detailed edge geometry could already be generated from room connections in tabular form. The nodes can be created automatically as centroids and then also edges, using the geometry of nodes and connectivity information from the table. Each edge is therefore constructed as a straight line using start and end node geometries. The algorithms for automatic generation of centroids can fail to place the centroid inside the polygon feature, but that can be automatically checked and manually corrected. Generated in such a way, a graph would have weak geometric properties, but its topology would be valid. Teo and Yu (2017) construct the connectivity graph the same way from IFC data and propose manual editing of the edges for complex and open spaces. Fig. 15 shows a comparison of an automatically generated graph from tabular room connectivity data and a graph generated with the digitization of nodes and edges. However, it should be emphasized that with increased building complexity, the difference between the two graphs would also increase.

To reduce the need for additional manual input, we considered only IndoorGML core module. However, the model can be semantically enriched with IndoorGML Indoor Navigation module that provides information, useful for indoor navigation applications, by classifying the core module elements into navigable and non-navigable ones. If the local coordinates are used for modelling, the anchor space element can be used to establish a link between local and global coordinate reference systems and thus enable the integration of indoor-outdoor navigation.

The IndoorGML standard provides two different approaches for cell modelling, a "thin wall" model and a "thick wall" model. We have chosen the "thin wall" model, as it is closely aligned with floor plans in

Table 1
Comparison between JInedit solution and our proposed framework.

	JInedit	The proposed approach
Implementation software	standalone software	various possibilities
Floor heights	one for each floor	one for each room
Additional data inclusion	not possible	possible
Export to other formats	not possible	possible
Database integration	not possible	possible
Required user skills	low	high

the Slovenian Building Cadastre, which does not account for the thickness of walls. If construction plans are used instead, it would be better to use the "thick wall" model, as there, the walls are drawn with their actual thickness. One of the drawbacks of the "thin wall" model is that it does not allow creating the cells with the correct geometry while maintaining the correct outer shape of the building. These two concepts also raise open questions regarding modelling rules for 3D geometries in a 3D real property cadastre. If the 3D geometry provides the only reference to the physical structures of the building, which define the real extent of RRR in space, the correct geometry is not as important as in the case when 3D geometry defines the exact extent of RRR. The second option allows the reconstruction of the property unit geometry without the building structure (not yet built or demolished). An open (legal) question is also how the border between two property units is defined, the middle of the wall or on each side of the wall (Atazadeh et al., 2016).

The proposed framework has several features in common with JInedit software (Seo, 2017), which is an open source software that enables the creation of IndoorGML documents based on raster floor plans. While it uses the same input and provides practically the same output, there are several differences between our approach and Jlnedit software (Table 1):

- The JInedit is standalone software, while the process presented in this paper is a set of software independent operations that can be implemented using various spatially enabled software, which requires more skilled users.
- The proposed process enables more flexible height provision (each room can have its own floor and ceiling height) and hence better representation of a real-world situation.
- Only limited data can be acquired in Jlnedit, while the proposed process allows additional data, such as rights, restrictions and responsibilities, currently not supported by the IndoorGML standard to be captured and stored in the spatial database.
- The proposed process enables the export of 3D geometry in various 3D formats.
- The proposed process allows direct storage of geometry and attributes from the transformation phase into the database where routing capabilities can later be used.

6. Conclusions

The study aimed to create a framework for 3D indoor modelling of buildings from input raster floor plans to an IndoorGML compliant document. A detailed workflow for 3D indoor modelling has been provided, comprising a chain of processes starting from initial cadastral data in the form of a raster floor plan and ending with the OGC IndoorGML compliant document. We have tried to design the whole workflow in a generic way as much as possible, while also considering the particularities of Slovenian cadastral data. The IndoorGML standard is used for final outputs aiming to provide a model suitable for indoor navigation and location-based services. The data stored in the database enables fully automatic IndoorGML document generation on request while also taking advantage of all functionalities of a spatial database. The proposed approach is software independent and can be implemented with various spatially enabled software packages.

For the Slovenian case study, we identified key missing data in the current documentation of the Building Cadastre that is needed for 3D indoor modelling. To produce proper results, the need for vector floor plans has been identified, and additionally, floor height information and room-to-room connectivity are currently missing in the cadastral database. Although the paper does not focus on semantic enrichment of a 3D model, it should be stressed that additional data can be provided by linking the source data to land administration databases, which has great potential for semantic enrichment of IndoorGML models with information about rights restrictions and responsibilities, the value of the real estate, house number etc.

Although the framework is developed based on raster floor plans from Slovenian Building cadastre, it can be used for any similar data that represents 2D floor plans with some adjustments, especially regarding the manual input. A detailed description of all processes and the process diagram, together with the following remarks and considerations, can serve as a starting point to assess the data in national land administration systems worldwide, whether and to what degree the data can be used for 3D indoor modelling and what should be changed. Future research will be focused on the analysis of other data which is available by linking the source data to connected databases and their usability in the context of indoor navigation applications.

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