Development of a Building Topological Model for Indoor Navigation

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Abstract. Human high mobility is essential to the proper functioning of a modern world. For a fast and efficient ground transportation, a suitable and accessible positioning, route finding and navigation solutions are crucial. For outdoor traveling, mobile applications utilizing GNSS systems and navigation services based on road and pavement networks already provide a satisfying solutions. On contrary, an indoor environment is much more intricate. Localization with GNSS is impossible and there is no explicit traversable network inside the building as in outdoor routes. Multi-storey buildings, often with complicated room layouts and floor transitions, confined spaces and numerous areas restricted for visitors or impassable pathways for disabled people add another layers of complexity to this problem. This study covers the issue of creating a topological building model for indoor navigation. Necessities of such model are discussed and the fitting implementation, developed by ESRI, is detailed. The entire process, from data pre-processing to the model creation and visualization in ArcGIS Pro software, is delineated. A case study of development of such a model for a Geo-3EM building of Wroclaw University of Science and Technology (WUST) is conducted and the sample visualizations of a model and route finding are shown. Finally, the results are discussed and the future directions of research are presented.

1. Introduction

Mapping and modelling indoor spaces has become a rapidly growing industry. This has been possible due to popularisation of multiple concepts, e.g. Internet of Things (IoT), Simultaneous Localization and Mapping (SLAM), Building Information Modelling (BIM). Those technologies have made a digital representations of building interiors straightforward to create, easily manageable and essential for more advanced indoor solution. These can be employed in several sectors, such as civil engineering, business analytics, robotics or as an implementation of smart home, smart building or smart city concepts. Current trends and main research areas in this field were investigated in [1]. One suchlike concept is the indoor navigation, which concerns an issue of aiding the movement inside the building for humans (in particular people with disabilities or first-time visitors of a building [2]), enabling route planning for autonomous robots [3] or streamlining of the building evacuation in the emergency situations [4], [5].

A vital part of a well-functioning navigation system is the environment model. Numerous data models, standards and file formats, along with the different methodologies of their creation, have been tested for the implementation in an Indoor Positioning and Navigation System (IPNS). In [6] several building model formats, such as IFC, CityGML, IndoorGML and Indoor OpenStreetMap,
were described. Especially IndoorGML, actively developed by the Open Geospatial Consortium (OGC), is a promising standard for the indoor navigation, since it has the potential to include both the information about high-level building structure and individual object localization (i. e. through Flexible Space Subdivision (FSS)) [7, 8]. However, such a data model often lacks the information essential for the navigation, e. g. topology, path traversability or room entrance permissions. To solve this problem, a proper data structure is needed. Geometric Network Models [9] is often used, though more sophisticated structures, like dual-half edge [10], have been also successfully applied.

The data required to create an IPNS model (floor plans, CAD drawings, BIM models) are not always present and need to be acquired. Moreover, the subsequential process of a model development can be arduous. Therefore, automatization of this procedure is an appealing field of research. Article [11] proposes The algorithm of automatic 3D indoor network creation, which aims to eliminate routes unnatural for humans to follow, as opposed to traditional approaches, based on the medial axis transformation [12]. The procedure of semi-automatic processing of vectorized floor plans for the navigational model creation is shown in [13]. In [14], a convolutional neural networks is used to extract the necessary information and create an indoor data model directly from the floor plan rasters. A procedure of automatic development of an 3D indoor navigation network with a low-accuracy data, based on surveying benchmarks, is proposed in [15]. Another source data type was utilized in [16], where point clouds were utilized to automatically create an 3D navigational building model. Obstacle-aware indoor navigation, based on the point cloud data acquired with the laser scanner, was investigated in [17]. The multitude of varying approaches to the problem of building modeling for indoor navigation has been the motivation to investigate an implementations of such a model, proposed by one of the leading GIS solution providers - ESRI, which tackles this issue through the implementation of their own data model, included in the ArcGIS Indoors software.

The paper is organized as follows. Section 2 describes the requirements of an indoor environment numerical model for successful navigation and shows ESRI’s implementation of such a model. Section 3 outlines the data processing workflow in the ArcGIS Indoors. Section 4 contains results of a case study of developing a model for navigation inside a Geo-3EM building, located on a Wroclaw University of Science and Technology (WUST) campus. Section 5 presents conclusions from the research and outlines future work directions.

2. Data Model for Indoor Navigation
The topological model of a building with a strictly defined structure is the first stage in the process of creating an indoor navigation and positioning system. This model can be created based on the information contained in floor plans, which can be provided in shapefiles, CAD or BIM models. In the process of creating a building model, additional information, such as relationships between floors and characteristics of source layers, must also be defined. The model must be associated with a topological network to move inside the building, so each element of the model should have information about the connection with other elements [18]. Nowadays, few solutions are available for building models for IPNS purposes. IndoorGML is a standard for the indoor spatial data model promoted by OGC. The main concept of IndoorGML is the organization of indoor space as a collection of cells, where the cell is defined as the smallest structural unit of internal space. Each cell has a semantic representation to enable classification and determination of connections between cells. In addition to the semantic representation they also have a geometric representation. Geometric representation is not the main focus of IndoorGML (it was previously defined by ISO 19107, CityGML and IFC) [19]. Basic concepts of IndoorGML were discussed in [7].

The ArcGIS Indoors Information Model (AIIM) is used to manage the GIS data that defines interior spaces. It is also used to convert building data from CAD or other sources to the ArcGIS
Indoors geodatabase layers. This model has a hierarchical structure and stores data in a specific order. The widest feature class includes Sites and specifies a collection that includes one or a complex of buildings. Each object in the dataset is called a Facility and is a single building. The floors within one facility are called Levels and Units are understood as rooms bounded by walls located within one floor. Walls, doors and windows that further define and describe Units are listed as Details. Zones are areas that may contain blind areas excluded from mobility networks as opposed to the PoI (Points of Interest) layer, which contains points, people and things to which the route is mapped. Events is a layer that is also placed at a specific time, so it is possible to navigate to the current event. Based on the structure of the objects contained in AIIM, a topological network of connections between individual Units is generated. Sites defines the area within which connections between individual buildings of the complex are possible. The boundaries of the facility area define the space within which there may be connections between Levels. Units are rooms limited and defined by the Walls. The Doors are used to specify connections between individual PoI, which are generated based on the Units layer. Units defined as staircases or elevators allow to move between Levels. Zones identify areas that may be excluded from the movement network [20]. Described hierarchy of ArcGIS Indoors feature classes is presented below in the Table 1.

**Table 1. Hierarchy of ArcGIS Indoors feature classes**

| ArcGIS Indoors feature class | Description | Geometry Type |
|-----------------------------|-------------|---------------|
| Sites                       | Multiple facilities | polygon       |
| Facilities                  | Buildings in the data set. | polygon       |
| Levels                      | Separate floors within one building. | polygon       |
| Units                       | The rooms contained within one floor delimited by walls. | polygon       |
| Details                     | Objects define the units the transitions between them. | polygon, line |
| Zones                       | Define zones where movement is restricted - blind areas. | polygon       |
| Points Of Interest          | Places or items to which the route will be determined | polygon       |
| Events                      | Current event specified in place and time | point         |

3. AIIM Development and Usage in ArcGIS Pro
Most data processing tasks are high-level processes, but most of them are automated in the ArcGIS Indoor. The tools for this purpose are included in a separate toolbox named Indoors Tools. Order of tasks is presented in the diagram below (Figure 1). The first step in AIIM development, that enables the management of the indoor GIS information in ArcGIS Pro is to create a geodatabase, compliant with the AIIM schema.

**Figure 1.** Simplified processing diagram in ArcGIS Indoors Toolbox

The input data on the basis of which the topological model of the building is created can come from various sources and formats. Commonly, data and information in the form of floor plans is available in the form of vector data, such as AutoCAD .dwg or MicroStation .dgn files.
It is also possible to export the necessary information from the BIM model and use it to prepare floor plans as CAD files. If data is available for example as a floor plans in images form they must be first georeferenced and next manually digitized. To use the ArcGIS Indoors automated processing tools, floor plans must be stored in separate files. Moreover, the data contained in floor plans must be properly organized. Elements such as: windows, walls, doors, stairs, elevators and other details should be on separate layers and can be represented as lines or closed objects. Import and further processing is possible both on the basis of lines and polygons.

The next step is to load the prepared floor plans data to the previously created AIIM. In ArcGIS Indoor this is handled with the Import floor plans To Indoors Geodatabase tool. This process also requires defining import settings in the configuration spreadsheet. It is used to map floor plans layers to the adequate Indoors layers and attribute fields. The import settings Excel file should contain information on the imported layers and individual floors, for example names, addresses, ID numbers of subsequent floors or their heights. After running this process, user evaluation is needed to eliminate possible errors.

POIs, as previously described, are places, people, things, building elements that constitute the content of the map interesting for the user - elements that we want to able to navigate to. These are points that are embedded in the same coordinate system as a given building and are defined by the three coordinates x, y and z. The most basic group of POI, which is obtained indirectly as a result of importing CAD layers to Indoor layers, is called Places and Things. They are generally centroids of polygons identified as Units in AIIM. Calculation of centroids based on polygon data and loading them to the POI feature class is possible using the Feature to Point, Feature To 3D By Attribute and Append tools. From the level of the attribute table, individual descriptions and names of POIs can be defined.

The final step in AIIM development is generation of a navigational network. Creating a network of connections consists of several stages. The Generate preliminary pathways tool allows to generate a regular lattice that is placed on each floor, excluding places with walls or other prohibiting movement elements. The density of this mesh should be adjusted to be smaller than the narrowest doorway.

The Generate Indoor Pathways tool allows generating a regular preliminary network (lattice) that is superimposed on each floor, excluding places with walls or other constraints. At this stage, the connections are defined within the floors, but not between the floors. The Generate Floor Transitions tool is used to define connections between floors within a building. The output of this process are vertical 3D lines representing features like elevators, stairs or escalators. Originally also stairs are represented as 3D vertical lines, so their geometry must be manually corrected after the automated processing to achieve realistic route length and 3D display. The final network dataset is created by thinning an existing preliminary connection network. The thinned network only stores optimal connections between selected routable locations (e.g.: POIs, events). At the end, the whole network should be manually inspected by the operator to ensure that all units are connected to it and that its topology is correct. This process can be eased with the use of pre-made scripts, provided with ArcGIS Indoors for the verification process.

When the final navigational network is completed and verified, the model is ready for performing the network analysis. ArcGIS software includes Network Analyst toolbox, which is streamlined to use such a model for carrying out analysis such as optimal route finding between several locations or identifying the closest facility of a selected type. Those analyses can be performed online as a service by the end user, if the ArcGIS Indoor model is properly hosted online. Other available analyses include solving location-allocation problem or determining the service area of a facility may be useful for the building administration, since they could use it for optimizing resource allocation in the building. All abovementioned tools in the ArcGIS Network Analyst toolbox are based on the Dijkstra’s algorithms for finding the shortest route [21], while the location-allocation problem solver also employs more advanced algorithms like.
Hillsman editing and metaheuristics [22]. Exhaustive description of algorithms used in the Network Analyst can be found in [23].

4. Case Study: Geo-3EM Building, WUST Campus

Workflow described above has been tested through development of a model for indoor navigation for Geo-3EM building, located on the WUST campus. BIM model created by Kazana in [24] (Figure 2) in Autodesk Revit has been utilized as a source dataset. Elements such as walls, windows, doors, floors, rooms (named units in AIIM) and room labels have been exported to CAD file, separately for each floor. Then, extracted features were examined in Autodesk AutoCAD. Topology of selected objects were adjusted and floor outline line features have been digitized. Since selected features from the BIM model, such as windows, can be used for enriching the final visualization, although they are not useful in the process of creating a pathway network, those details were deleted from the CAD drawings. Example content of such a file can be seen in the Figure 3.

**Figure 2.** Revit BIM model of Geo-3EM [24]  

**Figure 3.** CAD floorplan of ground level of Geo-3EM

Subsequently, next processing steps, described in Section 3 were carried out in ArcGIS Pro software with ArcGIS Indoors Python environment and Toolbox installed. Firstly, the file geodatabase has been created and transformed into an empty ArcGIS Indoors geodatabase, containing prototype feature classes, representing AIIM components and the network datasets. Afterwards, the AIIM was populated with objects imported from CAD files for each floor. The initial network mesh (Figure 4) and vertical transitions have been generated. The consecutive part of manual correction of the network topology was significantly tedious, as many mesh elements have been mistakenly separated from the main network due to the narrow openings in the walls or doors. Those rooms had to be manually connected to the lattice. Network generated inside the staircases was adjusted, since only parts of them can be covered by the planar lattice, while the rest should be present only in the vertical transitions layer. The preliminary transition feature class also needed rectification, since only straight vertical lines have been generated with the tool and the natural geometry of stairways has not been preserved. Moreover, transitions were not topologically consistent with the planar pathways and their endpoints had to be snapped to the previously adjusted network. Results of manual editing of floor transition features is depicted in the Figure 5.
After the revision of preliminary networks, POI features have been created from unit centroids. Objects redundant for the navigation of a casual user, such as storage rooms, were excluded from this operation. In the next step, the preliminary network, transition and POI feature classes were used to create the final, 3D pathway network (Figure 6). Thereafter, the standard ArcGIS Geoprocessing tools included in the Network Analyst (e. g. route planning, service area analysis) can be utilized and shared as an online service.

With the 3D network created and route planning enabled, several types of visualizing the resulting model have been tested. Default icon set included in the ArcGIS Indoors, intended for mobile device map application, have been used to mark POI locations. The map is displayed for each floor separately (omitting the geometry of transitions). Switching between different floors is done through range properties of the map layers. Two-dimensional map (Figure 7), which can be incorporated both in the mobile application or in a web portal with ease, offers the best clarity of the map, though the lack of third dimension may negatively affect users' perception of distances. Furthermore, 3D display of the route could help the user create a cognitive map of the path in their mind, which should facilitate efficient and natural navigation inside the building.
Two different approaches to designing a 3D display of the model were examined. First, a simple addition of transition layer and height information to the floor maps (Figure 8), and an integration of a BIM with the aforementioned feature classes (Figure 9). The former directly addresses the issue of visualizing the route in 3D space, adding height information to the point, line and polygon layers, while the latter combines them with more sophisticated shapes and objects. Their detailedness depends on the Level of Model Detail (LoD) which refers to the complexity of a 3D geometrical model representation. With an accurate, high LoD model, the user experience can be improved further, as it should allow one to effortlessly recognize distinctive features of their surroundings (often called landmarks). It may be important for seamless use of the web application, as it is intended to use rather as a route planner before the movement. Therefore, any information helping the user to create the mental map and remember the pathway is vital. As a downside, discussed 3D visualizations are not yet suited for the mobile applications, though the landmark recognition would not be as essential for the mobile user, as the online navigation and positioning with the mobile device would work by means of an integrated IPS and indoor navigation solutions.

Figure 8. 3D floor plan visualization with marked POI and the navigational network
Finally, route planning with the constructed 3D network has been tested: an example lab, located on the second floor was chosen as the starting point and the quickest route to an emergency exit was calculated in two scenarios: normal navigation, without any restrictions and with elevators turned off. Second case aims to simulate the evacuation route in an emergency scenario, e. g. the fire hazard. The results are shown in Figures 10, where the shortest route is presented, and 11, where the elevators have been excluded from the pathway network. The network analysis quickly and correctly found optimal routes.

The building model for indoor navigation, created with the ArcGIS Indoors, proved to be an effective solution. Integration with an existing GIS software is undisputed advantage of the tested implementation, since it greatly eases the data manipulation and management and allows experienced GIS professionals to leverage the benefits of using indoor navigation. Nonetheless, the first stage of the model development: importing selected geometrical building features from CAD files or BIM models still requires the presence of those high-level data models. The ESRI indoor modeling approach currently does not directly tackle this issue, to which few solutions were discussed in Section 1.
5. Conclusions
In this paper, the procedure of development of a building navigational model from the BIM model in the ArcGIS Indoors environment has been examined and applied to the example building, located on a WUST campus site. AIIM model, the main data model in the ArcGIS Indoors, has been thoroughly described and employed in a case study. The whole process proved to be intuitive and highly automated with the toolbox provided in the software, but some user involvement was still necessary. Depending on the quality of the BIM data, it may be necessary to adjust the attributes and geometry when the data is loaded into ArcGIS Indoor. Sometimes it is also required to manually modify the created network due to the detail of staircases. These elements could be considered as possible improvements by the developers of ArcGIS Indoor to minimize user involvement in developing the network through allowing greater flexibility of the import tools. Nevertheless, the fact worth emphasizing is the versatility of the solution, since it can be adjusted to use different source data formats.

Experimental route planning, performed with the resulting network, produced correct results and is suitable for navigating users in an indoor environment. Developed maps for navigation are clear and simple, which is highly desired for such an application, especially in the context of possible navigation with a mobile device. Besides the simplicity of use, an interesting feature implemented in AIIM is the spatiotemporal aspect of the data. Event layer allows to store and share information about meetings or incidents happening at the given time in a certain place. This could facilitate for e. g. booking spaces and tracking accidents or people location density in real-time, which could be helpful especially during the current pandemic. However, the development process of the AIIM building model, especially its network, contains several simplifications, which mostly generalize the model. While for aiding human movement in the building it can be a desirable outcome, for purposes like autonomous robot navigation it may result in sub-optimal route planning.

While the navigation is an important part of the IPNS capabilities, the greatest utility comes from pairing it with a positioning service and making the service available from the mobile device. In the future, this areas will be further researched and such a system will be developed for the test site at the WUST campus.

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