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BIM-oriented indoor network model for indoor and outdoor combined route planning

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ABSTRACT

Emergency response and pedestrian route planning rely highly on indoor–outdoor geospatial data and a network model of the data; however, indoor geospatial data collection is time-consuming. Several studies have used the architecture, engineering, and construction (AEC) model to generate indoor network models. These models are subject to the input data types, and the attributes of interior building objects are usually incomplete; hence, the integration of building information modeling (BIM) and geographic information systems (GIS) can benefit indoor–outdoor integrated applications. To achieve data interoperability, an open BIM standard called Industry Foundation Classes (IFC) is maintained by buildingSMART. In this study, we propose a multi-purpose geometric network model (MGNM) based on BIM and explore the strategy of indoor and outdoor network connections. To achieve the goals, the IFC-to-MGNM conversion includes the following: (1) extraction of building information from IFC, (2) isolation of the MGNM information from the aforementioned building information, and (3) build up the topological relationships of MGNM into GIS Geodatabase. In addition, an entrance-to-street strategy is proposed to connect indoor networks, entrances, and outdoor networks for detailed route planning. The experimental results indicate that the MGNM could be generated from BIM automatically and applied to connect indoor and outdoor features for the multi-purpose application. Two use-case scenarios were developed to validate the proposed methods. Compared to actual distance, the relative error was improved by 5.1% and 65.5% in the horizontal and vertical routes, respectively, over the conventional indoor network model from 2D ground plan. In addition, the computational time taken by the proposed coarse-to-fine route planning method was 25% that of the traditional single-scale route planning method.

1. Introduction

Geographic information systems (GIS) integrate spatial information and spatial analysis for different applications [1]. For emergency response and pedestrian navigation, the integration of indoor and outdoor information is important for route planning. Such route planning requires detailed indoor information, usually obtained from the architecture, engineering, and construction (AEC) industry ground plans. As an emerging technology in the AEC domain, the building information model (BIM) is implemented over the entire building life cycle [2,3]. In addition, BIM improves route planning because it contains specific geometrical and semantic (attributes) information of building components and can be treated as an ideal source of spatial indoor information. Moreover, 3D BIM model and indoor graph network can be integrated to simulate a more realistic emergency situations using Virtual Reality technique [4]. Vanclooster and Maeyer [5] indicated that indoor data for route planning needs appropriate interior network edges, semantic information, and the ability to connect the indoor network with the outdoor network via building entrances, which can be achieved effectively with the integration of 3D GIS and BIM. The BIM in this study is focusing on 3D model (product view) but not the BIM process. Chen and Feng [6] demonstrated that the floor plan which contains detailed locations and dimensions of corridors and exit doors is an important spatial data to establish real-time emergency evacuation. Hence, the integration of BIM and GIS for emergency responses [7,8] is a priority in smart city applications.

The building information of an indoor environment is generally represented by a 2D floor plan, and indoor network modeling is required for indoor route planning. The existing indoor navigation models can be classified into four categories [9]: the geometric net-

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work model (GNM), the navigable space model, the subdivision method model, and the regular-grid model. The GNM [10] represents topological relationships among urban 3D objects; the navigable space model [11] describes the indoor and outdoor environments by using topology-connected surfaces, called walking spaces; the subdivision method [12–15] divides the interior space into individual cells to identify indoor "bottlenecks" and find the shortest and most natural path for specific situations (e.g., emergency escape); and the 3D regular-grid model [16] is a voxel-based model that considers path size to provide several indoor paths for users.

Due to its simple structure, the GNM has been widely used in indoor network analysis. For example, Meijers et al. [17] emphasized the concept of building internal partitions to derive the graph structure for semantic models, which is further processed to obtain a GNM. Karas et al. [18] improved the efficiency of the geometric model to GNM conversion. Becker et al. [19] extended the GNM to the multilayered space-event model. Boguslawski et al. [20] proposed a topological data structure called dual half-edge (DHE) to consider the connection between dual space and primal space. The DHE creates geometry (in primal space) and topology (in dual space) graphs automatically from CityGML. In other words, the DHE is a topological model based on CityGML. Currently, the GNM is not an industry standard but it is used for OGC IndoorGML. Although the above studies clearly define indoor entities for route planning, they are limited in terms of indoor data sources and the abstraction method. Most indoor GNM are generated from 2D floor plans because they are easily obtained, but the relationships among indoor spaces are too coarse for precise indoor applications. For example, some specific applications, such as emergency response, require accurate geometric distance information for decision making; hence, precise indoor information is needed.

Constructing a GNM is time consuming and complex; it involves digitizing by using either the GIS editor manually or generating from a floor plan and elevation drawings. To generate the GNM automatically, a detailed indoor model with semantic information is needed. Kim et al. [21] used the CityGML building model to generate indoor networks via the abstraction method. Different types of building elements (e.g. room, door, wall) are defined in CityGML, and this semantic information can be used to automatically generate nodes and edges of indoor networks. Chen and Huang [22] combined visibility graph (VG) and medial axis transform (MAT) algorithms to construct indoor geometry network from BIM-derived 2D floor plans, only the 2D geometric property was utilized in indoor model. Isikdag et al. [23] presented a BIM oriented modeling methodology to transform information from IFC into a BIM Oriented Indoor Data Model (BO-IDM) for facilitating indoor navigation. The BO-IDM is a schema similar to IFC and it represents the building with 18 indoor classes. They showed that IFC provides highly detailed semantic information for BO-IDM. In the GNM's application, Chen et al. [24] applied the GNM from BIM on fire-fighting simulations. It is a GNM-based and BIM information-supported framework, which focus on different fire stages, and ladder simulation in a 3D environment. BIM has detailed spatial information and well-defined building elements, yet automatically generating precise indoor networks from BIM has seldom been discussed.

In indoor–outdoor route planning, Whiting [25] focused on connections between indoor and outdoor features on a campus using complete definitions of both indoor and outdoor spaces. The approach used existing 2D floor plans, along with complete definitions of portal and space, to automatically generate the indoor tree-based structure network to store all entities for route planning. The advantage of spatial hierarchy structure is to improve the performance of route planning, but the number of building entities is the major problem with this approach. In addition, this approach links the building spaces but not the vector-based outdoor road network (i.e., connection to existing GIS roads). Mandloi and Thill [26] used a multi-model network that compared the cost between different indoor and outdoor networks. The inner building network is similar to the GNM, but the problem of actual geometric distance between floors still exists, and the entrances of the building need to be identified manually. Kwan and Lee [27] utilized node-relation structure (NRS) to represent the topological relations among 3D objects in multi-level structures. The node-relation structure connects objects (e.g. rooms and corridors) within building and between building entrances. Tao et al. [28] created a superclass by merging all indoor and outdoor network nodes, but the network size was huge and unsuitable for large areas. While many studies have directly connected the indoor and outdoor nodes relatively few have discussed the optimization of transfer arc between indoor and outdoor routes, hindering efforts to establish simultaneously route connectivity for indoor and outdoor environments.

Traditionally, establishing a 3D indoor network is a labor-intensive task, especially when the network nodes need additional semantic information. Furthermore, real-world objects change frequently and require updating to maintain data availability. For indoor environments, the traditional approach creates a GNM based on 2D computer-aided design (CAD) architecture model, limited by the non-object-oriented geometric representation and the lack of semantic information in 2D CAD data. Consequently, it produces an approximation of indoor entities that cannot meet the requirements of detailed indoor applications. With the maturity of BIM technology, an improved-GNM design is needed that corresponds to BIM and contains semantic information from BIM and across the building design-build-operate lifecycle.

Emergency response-related research focuses mostly on either the indoor environment [29] or the outdoor environment [30]. In practice, an emergency response operation is a combined indoor–outdoor process [27], but the combined route planning is challenging for several reasons.

(1) The need for indoor information: BIM provides indoor spatial information while GIS provides outdoor geospatial information and modular geospatial analysis. Because both the BIM and GIS represent the digital features of an urban environment, the combined indoor–outdoor emergency response requires information from these two domains. These indoor–outdoor models are designed for different domains, however, and cannot be directly integrated for specific purposes [31,32]. For example, BIM does not contain 3D indoor network for GIS analysis in indoor–outdoor combined route planning. A more in depth discussion of indoor mapping problems can be found in [33].
(2) The connection between indoor and outdoor networks: Indoor network data must be integrated with outdoor network data, but connection rules between the two types of data are not mutually developed, which makes shortest-route planning infeasible or inaccurate. Consequently, an effective and reasonable method to connect indoor and outdoor network is needed for indoor–outdoor combined route planning.
(3) The need for multi-scale indoor–outdoor route planning: Detailed indoor models increase the size of adjacent matrix in indoor networks and require more computational resources; consequently, route planning requires more computational time in processing large adjacent matrix. Therefore, the concept of multi-scale is needed to accelerate the performance of indoor–outdoor route planning.