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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.

To address the above issues, this study proposes an algorithm to automatically generate an improved, 3D indoor network model from BIM called the **multi-purposed geometric network model (MGNM)** using an Industry Foundation Classes (IFC)-to-MGNM strategy. MGNM refines geometry and attributes information of traditional GNM. For example, the nodes of GNM are space and stairs, while nodes of MGNM contain various other elements, such as rooms, doors, windows, and landings from BIM. Furthermore, the edges (links) of GNM contain only space–corridor, corridor–stair, and stair–stair information, while the edges of MGNM are more flexible to meet the need of different applications, containing space–door, space–window, door–corridor, corridor–stair, and stair–landing information. The MGNM network is more complete and flexible than the traditional GNM network (Fig. 1), and because it is designed to connect indoor BIM data and outdoor GIS data, it could become a value-added product from existing BIM, especially for emergency responses.

This study proposes a strategy, the entrance-to-street strategy, to automatically connect indoor and outdoor networks based on a transfer arc, that connects indoor entrances and outdoor routes. The entrances of indoor network can be connected to different outdoor vertices, and the entrance-to-street strategy optimizes the transfer arc based on perpendicular and shorter path conditions, thus combining indoor and outdoor networks for route planning. Additionally, a coarse-to-fine approach is also proposed to support the indoor–outdoor combined route planning to improve the computational efficiency, consider different scales (city-scale and building-scale), and reduce computational time.

The GIS model is represented by geometric primitives (i.e., points, lines, and polygons), while BIM consists of high-level building entities (e.g., columns, walls, spaces, windows, doors, pipes) [34]. The BIM in this study is focusing on 3D model (product view) but not the BIM process. The interoperability of BIM and GIS must extract the semantic information between the high-level entities and geometric primitives [35]. Due to the lack of spatial functionality in BIM [36], this study transformed the BIM-extracted semantic information into GIS topological relationships among geometrical primitives by automatically extracting the indoor MGNM from BIM via geometric and semantic information (see Section 3.2) while obtaining the outdoor route from GIS outdoor road networks. The building entrance nodes were chosen to suitably connect the indoor and outdoor information. In addition to demonstrating the effectiveness of combined indoor–outdoor route planning, the proposed method provides a valuable reference to address spatial problems involving scenarios such as indoor–outdoor emergency response, path finding, and location-based services (LBS). The aim of this research was to automatically generate an indoor network model from BIM and combine it with outdoor GIS road network for coarse-to-fine route planning. The major processes were IFC-to-MGNM conversion, entrance-to-street connection, and coarse-to-fine route planning. In addition, the validation of proposed method included (1) comparison of MGNM and traditional GNM results, (2) performance of coarse-to-fine route planning, and (3) demonstration of emergency response and pedestrian route planning applications.

2. Experimental data

The BIM indoor data in this work are from Engineering Building 2 (EB2) at the campus of National Chiao Tung University (NCTU) (Fig. 2), a four-story building modeled based on 2D drawings and field surveys in the Autodesk Revit® 2014 environment. This BIM model is transformed into an IFC 2×3 open standard format. Three outdoor datasets were used for combined indoor–outdoor route planning—the outdoor road network, CityGML LOD1 prismatic building model [37], and facility point data around campus—in which the LOD1 block model contains only building boundaries and estimated building heights from number of floor. The outdoor road network and facility point data were downloaded from OpenStreetMap (i.e. www.openstreetmap.org) (Table 1).

3. Generation of the multi-purpose geometric network model (MGNM)

For the framework of IFC-to-MGNM, we first define the proposed MGNM, the node of which contains attributes of building elements (e.g. door, window, room, corridor, stair, landing). The edge (also called transition) of MGNM is a 3D path precisely extracted from BIM. Second, we introduce the conversion from IFC to MGNM. The major work includes the extraction of node and the generation of edge.

3.1. Definition of MGNM

The proposed MGNM is an indoor geometric network model that improves the geometry and attribute information of GNM [10]. The BIM/IFC semantic information are extracted simultaneously with the geometric information and attached to topological primitives (i.e., node and edge) A summary of the component elements of MGNM (Table 2) shows that each MGNM element can be referred to corresponding IFC classes. Defining a navigable indoor space is necessary for indoor spatial information [38]. The relationships among all constructive elements are derived by different approaches: *IfcRelSpaceBoundary* class for horizontal components; and geometric estimation for vertical components.

Space represents the interior area of a building, which may be surrounded by walls (such as offices, classrooms, and washrooms) or be an implicit functional area [17,25]. A space is seen as the base unit of indoor navigation. **Portal** refers to the physical connections between building elements and can be classified into horizontal portal (e.g., door), vertical portal (e.g., stair), and emergency portal (e.g., window). **Route** is the edge (or path) between nodes. Hori-

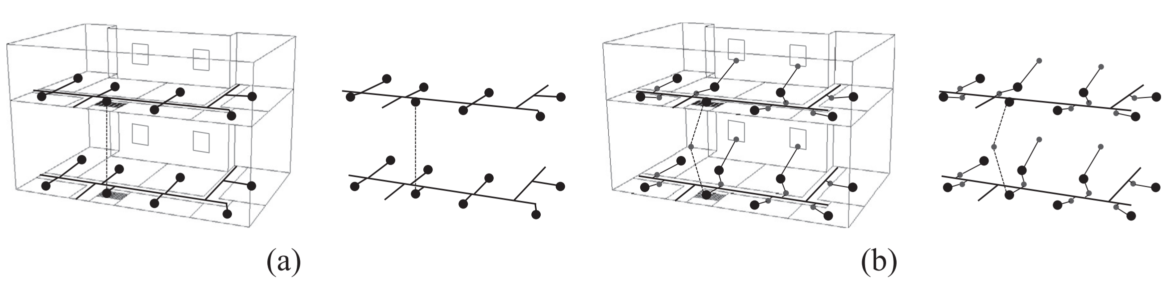

Fig. 1. Comparison of GNM and proposed MGNM: (a) GNM and (b) MGNM.

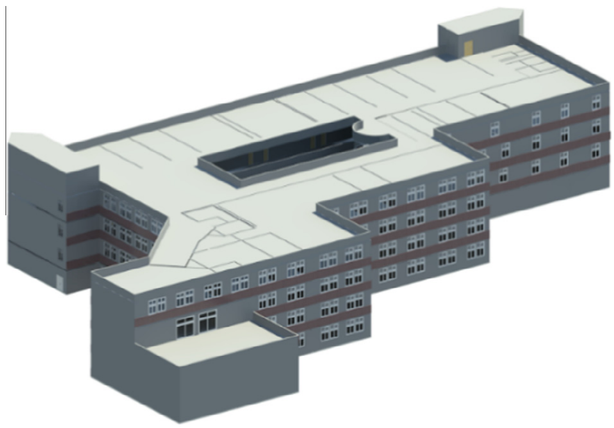

Fig. 2. BIM of engineering building 2.

zontal route refers to the edge between horizontal nodes, vertical route to the edge between different stories, and emergency route to the edge between a space and its window(s). The IFC has no direct corresponding class to provide information about vertical links, so the vertical route (i.e. stair) is generated by geometric estimation. The vertical route is generated from stair and landing areas. There is no direct connection between stair and landing from IFC. Therefore, we have to design a geometric estimation to connect the stair and landing areas. The geometric estimation is to determine the connectivity of stair and landing areas based on 3D distance. Staring from the lowest stair area, the landing area near to the lowest stair area is selected based on 3D distance. Then, we connect the lowest stair and corresponding landing area. We sequentially connect all the stair and landing areas by geometric estimation.

An example of MGNM for two rooms (Fig. 3a) shows the corresponding MGNM elements (Fig. 3b). The building objects are mapped to the nodes, and semantic information is attached to these nodes; edge(s) are inserted between node pairs when a spatial relationship exists. A 3D building in BIM can be converted automatically to a MGNM for network analysis (e.g., shortest-path analysis). Structures of MGNM include nodes, edges, semantic information, and topology (Fig. 4).

3.2. Derivation from IFC to MGNM

The proposed scheme to automatically construct an indoor network model from BIM includes three major steps. Step 1 extracts the essential building information from a BIM/IFC file and constitutes building element tables for the next step. Step 2 uses these building element tables to calculate the required MGNM information, including corridor footprints, space footprints, and opening element centroids. Next, the footprints of corridors and spaces can be converted to the medial axis and centroids, respectively. In Step 3, an MGNM is constructed using three elements (i.e., corridor footprints, space footprints, and centroids of opening elements) to generate six types of edges with topological relationships; these nodes can be assigned to the semantic information (see node attributes in Fig. 3b). Finally, the MGNM is converted to a feature class in the ArcGIS Geodatabase. Because MGNM elements are extracted directly from the IFC building objects (i.e., object-based abstraction), the entire process is called IFC-to-MGNM conversion.

3.2.1. Extraction of building information from IFC

After mapping the MGNM elements and the corresponding IFC classes (Table 2), the IFC entities can be retrieved and extracted for further processing. The needed building elements information classes (Fig. 5) are extracted from IFC "product" and "relationship." "Product" refers to a physical or conceptual object that occurs in space, and "relationship" describes the connections among building elements [39]. The IFC elements use a relative coordinate system rather than a mapping coordinate system; therefore, the coordinates of IFC elements from the relative coordinate system (points refer to *IfcSite*) (Table 3) must be converted to the mapping coordinate system, a process implemented by the transformation matrix from *IfcLocalPlacement* and *IfcAxis2Placement3D.*

Table 1
Summary of materials.

Scale	Data name	Data type	Usage
Indoor	BIM	IFC	Generate the indoor network MGNM (by IFC-to-MGNM) and the muitipatch geometry
Indoor/ outdoor	Entrance point	Feature class (point, from MGNM)	Entrance-to-street strategy and route planning
Outdoor	Facility point	Feature class (point)	Provides the fire station and hospital information in Hsinchu city
	Outdoor road	Feature class (polyline)	Route planning
	LOD1 building model	Feature class (3D polygon)	Route planning visualization and entrance-to-street strategy

Table 2
Corresponding between MGNM elements and IFC classes.

MGNM elements	Meanings	Element name	IFC classes
Node	Space	*Room*	*IfcSpace/ifcRoom*
	Space	*Washroom*	*IfcSpace/ifcRoom*
	Vertical portal/space	*Stair area*	*IfcSpace/ifcStair*
	Vertical portal/space	*Landing area*	*IfcSpace*
	Horizontal portal	*Door*	*IfcOpeningElement/ IfcRelAssociatesMaterial*
	Emergency portal	*Window*	*IfcOpeningElement/ IfcRelAssociatesMaterial*
Edge	Horizontal route	*Corridor*	*IfcSpace*
	Horizontal route	*Room-to-Door*	*IfcRelSpaceBoundary*
	Horizontal route	*Door-to-Corridor*	*IfcRelSpaceBoundary*
	Vertical route	*Stair*	*ifcStair*
	Emergency route	*Room-to-Window*	*IfcRelSpaceBoundary*
	Emergency route	*Corridor-to-Window*	*IfcRelSpaceBoundary*

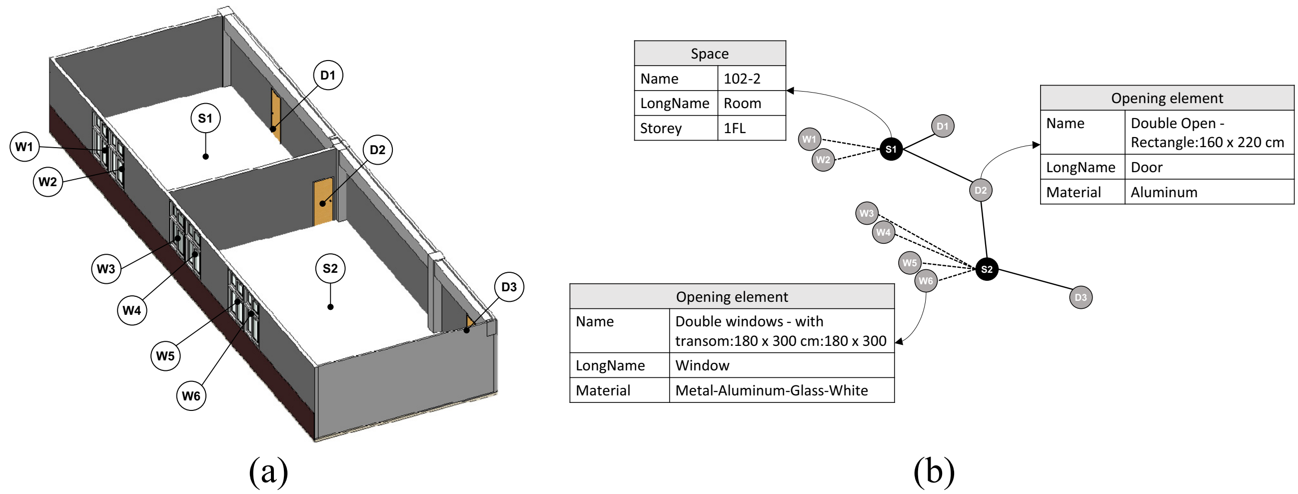

Fig. 3. Building elements and its corresponding MGNM elements: (a) two rooms in BIM and (b) nodes (with attribute) and edges of MGNM extracted from rooms.

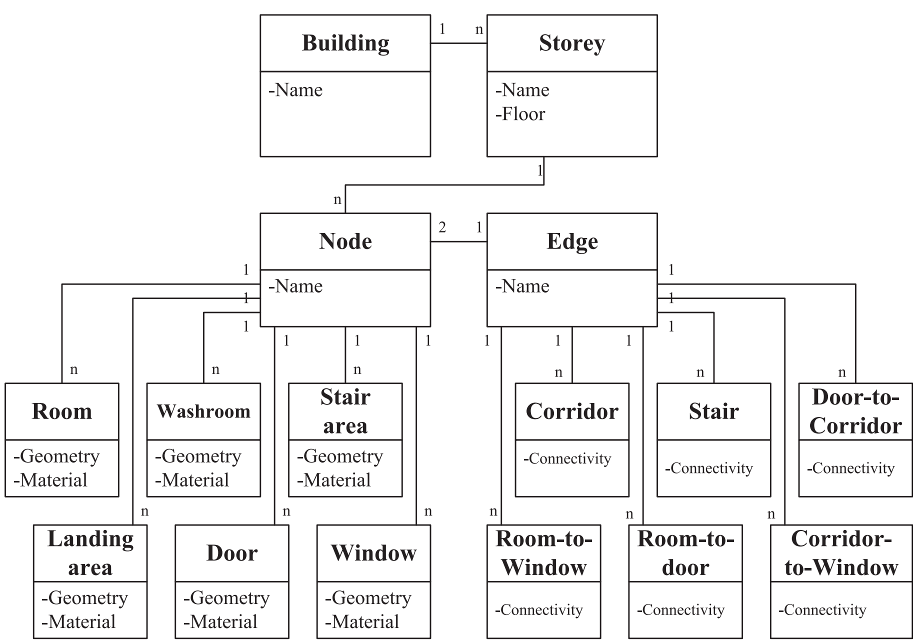

Fig. 4. UML of MGNM.

3.2.2. Calculate required information for MGNM

The indoor network contains two major components: nodes and edges. This stage automatically extracts the nodes (i.e., centroids of spaces and opening elements) and edges (i.e., horizontal, vertical and emergency routes) from IFC to comprise geometric (i.e. 3D coordinates) and sematic properties (i.e. attributes). All extracted notes and edges are then combined into MGNM. Semantic information, including element names, types of nodes and edges, categories of nodes and edges, and descriptions is also attached to each MGNM element (Table 4). The details of nodes and edges extraction are described below.

3.2.2.1. Nodes. The nodes of MGNM are extracted from the centroids of rooms, washrooms, stair areas, landing areas, doors, and windows (Fig. 5). The nodes of doors and windows are calculated in *ifcOpeningElement*, while the other nodes are calculated in *ifcSpace*. Notice that, some of the BIM model does not contain *ifcSpace*, in this case, we can use *ifcRoom* rather than *ifcSpace*. Centroids of *ifcSpace*, calculated from coordinates of space boundaries, and *ifcOpeningElement* represent the location of door and window. All spaces are abstracted to the nodes, except the corridor space. Because the corridor is a building element connected to other spaces (e.g. from corridor to rooms), the footprint of corridor space is abstracted to horizontal route or edge (see Section 3.2.2.2). The centroids of doors and windows can be calculated from *IfcOpeningElement*, separated by the *IfcRelFillsElement*. In this study, the heights of nodes for opening elements are snapped to the minimum elevation of *ifcOpeningElement*. For example, nodes of doors are dropped to the floor and nodes of windows are dropped to the lowest elevation of windows.

3.2.2.2. Edges. The edges of MGNM include horizontal and vertical edges. The horizontal edges connect corridors, rooms, washrooms, doors, and windows, while the vertical edges use stairs to connect floors. The horizontal routes include five different types: corridor, room-to-door, room-to-window, door-to-corridor, and

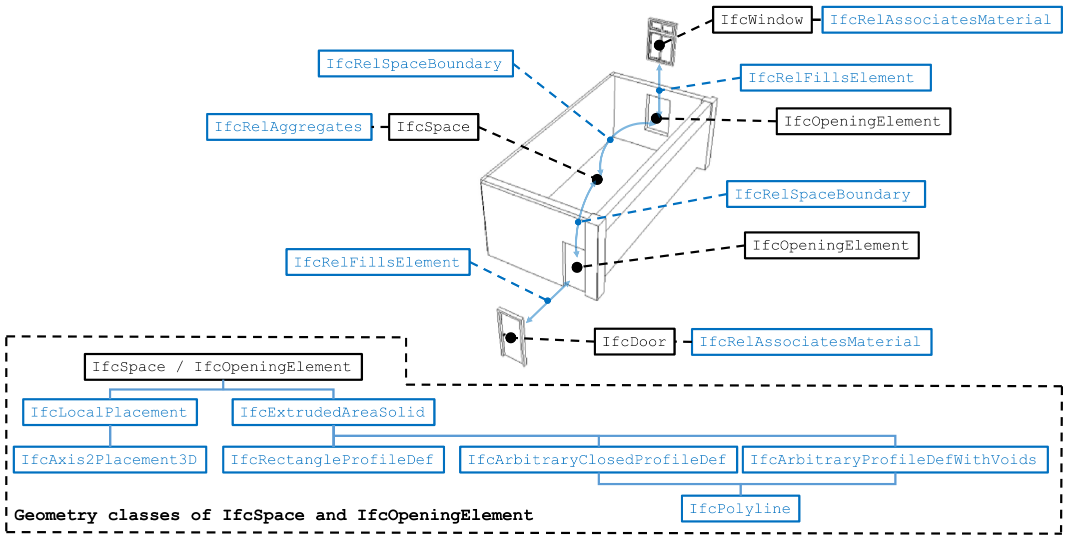

Fig. 5. Relationship among space, opening elements, and its building elements.

Table 3
Selected IFC classes.

IFC type	IFC class	Role/sub-type	IFC sub-class
Product	*IfcSpace* *IfcOpeningElement*	Representation	*IfcExtrudedAreaSolid* *IfcRectangleProfileDef* *IfcArbitraryClosedProfileDef* *IfcArbitraryProfileDefWithVoids* *IfcPolyline*
		Object placement	*IfcAxis2Placement3D* *IfcLocalPlacement*
Relationship	*IfcRelationship*	Association Connection	*IfcRelAssociatesMaterial* *IfcRelFillsElement* *IfcRelSpaceBoundary*
		Decomposition	*IfcRelAggregates*

Table 4
Summary of MGNM element detection methods.

MGNM elements	Types	Categories	Descriptions
Node	*Room* *Washroom* *Stair area* *Landing area*	Space Space Vertical-portal/space Vertical-portal/space	Calculated from space boundaries
	Door *Window*	Horizontal-portal Emergency-portal	Calculated from the opening element
Edge	*Room-to-door* *Room-to-window* *Corridor-to-window*	Horizontal-route Emergency-route Emergency-route	Obtained from the topological relationship in IFC
	Door-to-corridor *Stair* *Corridor*	Horizontal-route Vertical-route Horizontal-route	Obtained from the topological relationship in IFC with geometric regularization Obtained from stair Calculated from corridor boundaries

corridor-to-window. The room-to-window and corridor-to-window routes are designed for emergency response while the others are used in indoor route planning. The vertical route only considers the stair between floors. Notices that, the elevators and escalators can be extracted from BIM and can be also considered in an indoor network. Considering the emergency cases usually do not use the elevators and escalators due to the problem of power supply, this study did not include elevators and escalators in the proposed indoor network.

Corridor: The most challenging work in this stage is to automatically extract the route from the boundaries of corridor. The horizontal route from corridor is constructed by the medial axis, which is calculated from the corridor footprints. In this study, the Medial Axis Transform (MAT) method [40–42] was modified to calculate the corridor paths, using corridor boundaries as input data and corridor paths as output data. The extended-MAT method is proposed to generate the path from corridor. The idea is to connect the midpoints of inner triangles to form an initial path. Then,

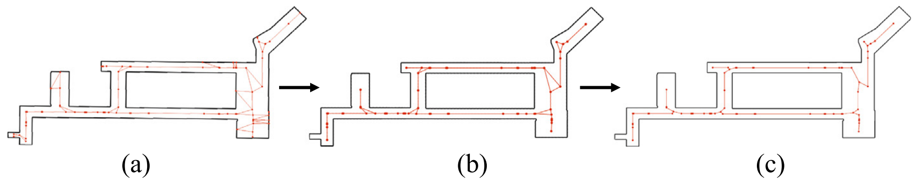

Fig. 6. Corridor path optimization: (a) connected midpoints of triangle's edges, (b) results of removing unnecessary nodes, and (c) results of inner triangle removal.

to simplify and replace the unnecessary nodes to form a final path. We connected the midpoints of the inner triangle's edges to generate the skeleton of corridor (red lines in Fig. 6a). The corridor boundary may have some small cavities (such as columns) or irregular shapes, so the boundary is prone to produce some narrow triangles, which leads to the appearance of extra lines. We addressed this issue by removing the unnecessary nodes by the corridor boundary buffer to maintain the corridor's symmetry and topological structure (Fig. 6b). After the first optimization, some inner triangles remained (red triangles in Fig. 6b), which may cause unreasonable route loops. To remove the unreasonable loops, we detected these inner triangles and replaced the triangle by it center (Fig. 6c). The pseudo codes for horizontal-route extraction are as follows:

Procedure *MAT-based corridor path optimization*
This procedure calculates the medial axis from corridor footprints based on CDT.
Pre *footprintEdge must be initialized*
Post *nodes and edges of medial axis printed*
Return *medialAxis contains the number of node*
1 loop (the number of corridor)
Step1: connected midpoints of triangle's edges (See Fig. 6a)
1 *read corridor footprint and forms the footprintEdge (outer polygon and inner polygon)*
2 *create the Delaunay triangles from footprintEdge*
3 *remove the Delaunay triangles inside inner polygon*
4 *connect midpoints of the triangle's edges to generate the skeleton of corridor*

Step2: remove the unnecessary nodes (See Fig. 6b)
1 *define a buffer size bufSize*
2 *remove the redundant points very close to footprintEdge by bufSize*

Step3: inner triangle removal (See Fig. 6c)
1 *detects the inner triangles and determines their centers*
2 *delete the edges of triangles*
3 *link these centers to correspond triangle nodes*

2 end loop

Door-to-corridor: The topological relationship (i.e., connectivity) between doors and corresponding corridors can been extracted from the *IfcRelSpaceBoundary*. In this step, we extracted these doors for all opening element nodes and projected them onto the Corridor route perpendicularly. If the perpendicular point from node to corridor does not exist, then it will link to the nearest point on the Corridor route. Note that the elevation of route is dependent on the *z*-coordinates of the corridor and the doors (Fig. 7a).

Room-to-door: The topological relationship (connectivity) between rooms and the corresponding doors were also recorded in the attributes of *IfcRelSpaceBoundary*. Because both room and door areas are opening elements, this step connects the room nodes and corresponding door nodes based on the connectivity in IFC (Fig. 7b).

Room-to-window: This room-to-window is an emergency route inserted between a room node and a window node when the connectivity relationship exists. The corresponding windows and rooms can be found and connected to each other from space's nodes and opening element's nodes using the *IfcRelSpaceBoundary* (Fig. 7c).

Corridor-to-window: This corridor-to-window is a special emergency route between a corridor and a window (Fig. 7d), similar to door-to-corridor, room-to-door, and room-to-window. The connectivity information is also stored in the *IfcRelSpaceBoundary*.

Stair: This vertical route plays an important role in connecting the different stories in a building. Because the BIM provides detailed building information, it can improve the connectivity of indoor network in the vertical direction. The stair areas are linked sequentially to form a complete vertical route. To connect the vertical and horizontal routes, we connected the vertices from corridors to nearest stairs' vertices (Fig. 7e).

3.2.3. Construction of MGNM

The MGNM contain both geometric and sematic information from IFC. The geometric information includes the 3D coordinates of nodes and edges; the semantic information includes the material of each opening element from the *IfcRelAssociatesMaterial* and its attribute (i.e., Name and LongName) from *IfcSpace*. We obtain the materials of doors and windows indirectly from *IfcOpeningElement*. They are originally recorded in *IfcDoor* and *IfcWindow*. The *IfcRelFillsElement* is used to connect the corresponding *IfcDoor/IfcWindow* from *IfcOpeningElement*. Then, the materials can be obtained from *IfcRelAssociatesMaterial* of *IfcDoor/IfcWindow*. Finally, the nodes, edges, and semantic information of MGNM were connected and converted into a GeoDatabase (e.g., the 3D Shapefile and feature class) for GIS analysis (Fig. 8).

4. Indoor and outdoor combined route planning

4.1. Entrance-to-street strategy

The entrance-to-street strategy integrates indoor and outdoor networks for route planning. We generated a transfer arc, an arc from building entrance to street, to automatically connect the indoor and outdoor networks to link the indoor MGNM from BIM and the outdoor road network from GIS to use in the geospatial analysis. The building entrance information is stored in the MGNM's nodes from IFC while the outdoor street is extracted from OpenStreetMap. The major concern for entrance-to-street is to find the shortest transfer arc between building entrance and roads, which cannot be overlapped with other buildings. To fulfill this requirement, the input data in this stage contain indoor MGNM, road network, and additional CityGML LOD1 buildings. The role of LOD1 building boundaries is to avoid overlap between transfer arc and building.

With the entrance-to-street strategy, all MGNM entrances can be extracted, projected to outdoor road networks, and used for forming transfer arcs. In the simplest case, roads surround the buildings, with no obstruct objects between, with some exceptions,

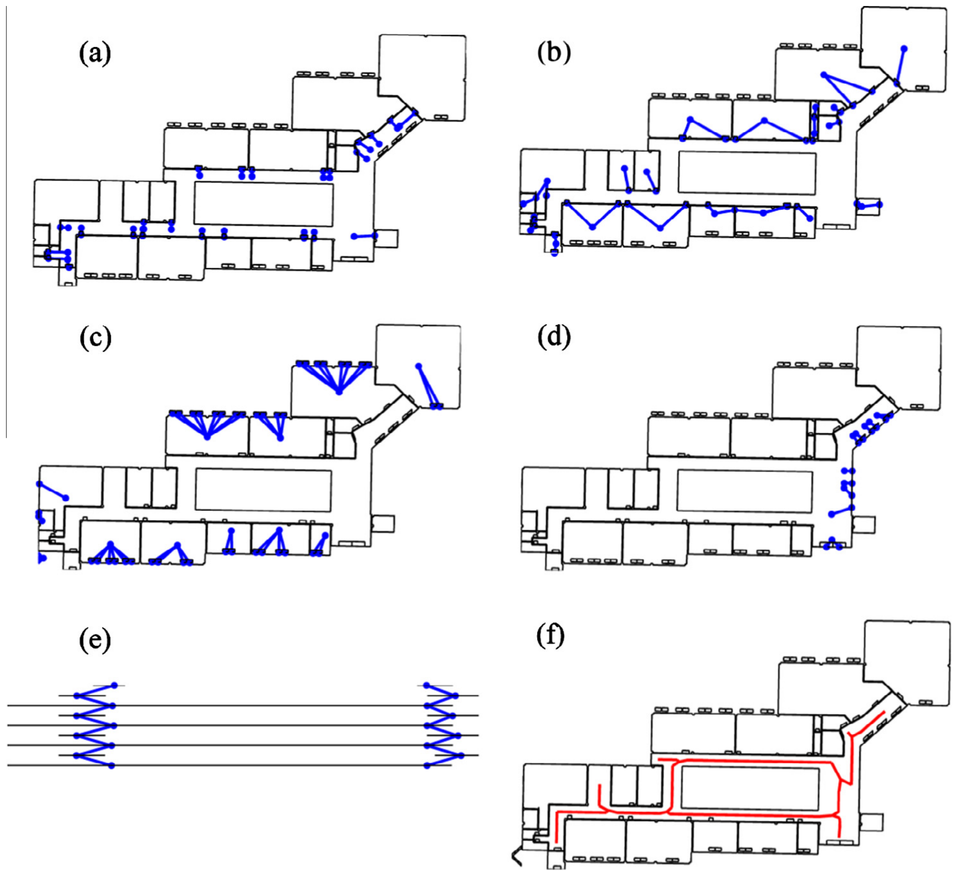

Fig. 7. Edges of MGNM: (a) door-to-corridor, (b) room-to-door, (c) room-to-window, (d) corridor-to-window, (e) stair, and (f) corridor.

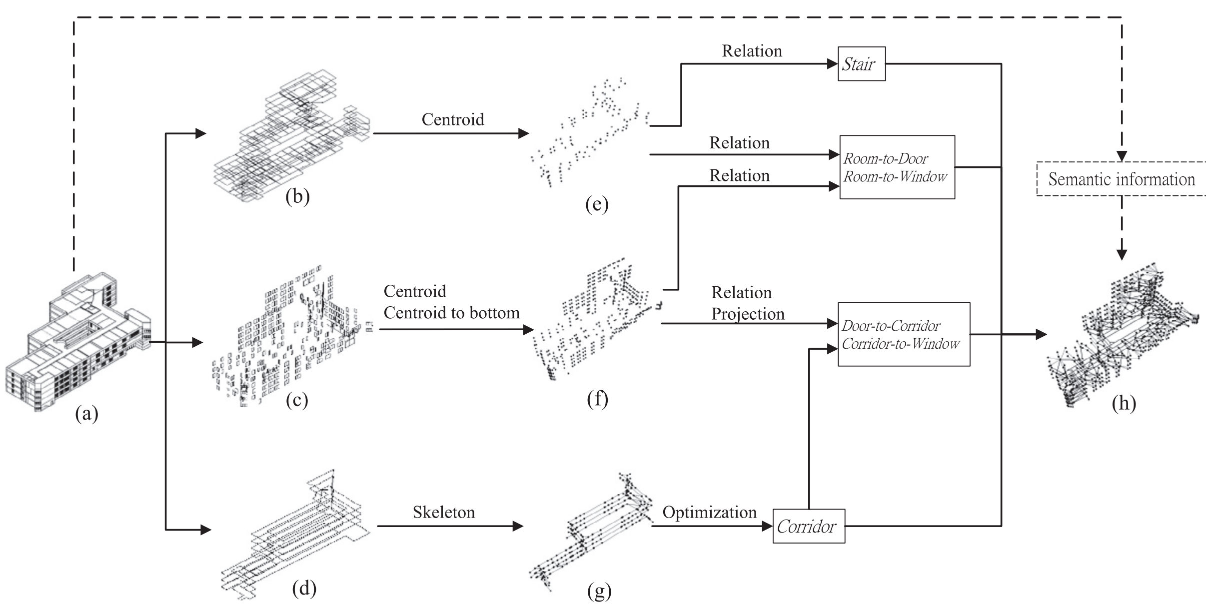

Fig. 8. IFC-to-MGNM conversion workflow diagram: (a) BIM/IFC model, (b) space footprints, (c) opening elements, (d) corridor footprints, (e) space nodes, (f) opening element centroids, (g) medial axis of corridor, and (h) MGNM.

such as complex buildings. For instance, if the transfer arcs of buildings in areas with high building density cannot be projected to the road directly, which often occurs in urban areas, the boundaries of the CityGML LOD1 building model can be used to obtain all building regions and avoid the intersection of transfer arcs and building regions. The building boundaries can be also extracted from BIM (e.g., *ifcWall*). Because not all buildings are created and stored as detailed BIM, we used the building boundaries from CityGML LOD1 rather than BIM.

The aim of the entrance-to-street connection strategy is to automatically find a transfer arc [43] that does not intersect with the building or other buildings, such as a transfer arc generation for entrance nodes (Fig. 9). The first step projects all MGNM entrances nodes to the edges of the outdoor road network. If the node cannot be projected onto the edge of the road network perpendicularly, then it connects to the nearest node on the road edge, as in the case of transfer arcs without occlusion (Type I in Fig. 9a). If a candidate arc intersects with the boundaries of the LOD1 building model, this entrance is occluded by a building object, and we split the building boundaries to generate a new transfer arc along the building façade (Type II in Fig. 9b). The candidate transfer arcs can be superimposed with the boundaries of the LOD1 building models. Finally, all the entrances of buildings are connected to outdoor roads via transfer arcs.

4.2. Coarse-to-fine route planning

Once the MGNM is converted to the GeoDatabase in the GIS system, both the outdoor and indoor networks can jointly establish connectivity between the outdoor and indoor features. These topological relationships are stored in the 3D network dataset and used to determine the cost of each edge, which in this study was simply the length of that edge. The length of the edge is usually considered to find the shortest path in route planning. If the traffic condition is available, it is possible to consider the traffic condition in outdoor route planning. However, this study only considers the length of the edge in route planning.

Given that the combined indoor and outdoor route planning in this study was based on Dijkstra's algorithm [44], a network graph was represented by an adjacency matrix that stores the adjacencies between node pairs. The shortest path was calculated using the costs in the adjacency matrix, which means that both the indoor and outdoor nodes were stored in a 2D $n \times n$ array, which we called single-scale route planning. Although this method has clear advantages, it must search the entire dataset to find optimal results, a time-consuming process.

To improve the computational efficiency, a coarse-to-fine approach was proposed to support the indoor and outdoor combined route planning for different scales (city-scale and building-scale) and reduce the computational time. This approach stores the indoor network (i.e., MGNM) and outdoor network (i.e., roads, transfer arcs, LOD1 building nodes, and entrances from MGNM) in different adjacency matrices. The goal of the coarse-to-fine approach is to separate the city-scale from the building-scale in the adjacency matrix. A city-scale building is represented by the center point of the LOD1 building model, while a similar building is represented by MNGM in the building scale to determine outdoor paths from the LOD1 building point in the city scale. We then calculated the detailed indoor paths from the MGNM in the building scale. Because the adjacency matrix is separated into different scales, the coarse-to-fine approach makes the indoor and outdoor route planning more effective (Fig. 10).

5. Results and discussion

The indoor and outdoor combined route planning was tested in two use-case scenarios: case 1, an emergency response scenario; and case 2, pedestrian route planning. The results of IFC-to-MGNM, entrance-to-street, and coarse-to-fine processes for these two cases are further discussed in Sections 5.1 and 5.2, with verification results in Sections 5.3 and 5.4.

The prototype of IFC-to-MGNM conversion for transferring information from BIM/IFC into MGNM was implemented in three steps. Step 1 was implemented in the xBIM (eXtensible Building Information Modeling) toolkit to extract the corresponding IFC classes/relations and list them in the building element tables. Step 2 was implemented in the Matlab environment and followed the relationships among the tables to calculate the topological primitives. Step 3 converted the MGNM topological primitives into the Geodatabase in ERSI ArcGIS software, a process based on Pyshp (Python Shapefile Library). All nodes, edges, and attributes were converted into the GIS environment (Fig. 11). This proposed scheme can be applied to other BIM to generate indoor networks. The total computational time was 63 sec using a personal computer with 2.93 GHz CPU and 8 GB RAM.

The MGNM is generated automatically from IFC via IFC-to-MGNM conversion and determines the number of MGNM elements (Table 5). Because the building has two stairways, the model has 10 stair area nodes, 8 landing area nodes, and 16 stair routes. There are 307 total window nodes (Table 5); however, the sum of room-to-window edges and corridor-to-window edges is 310 because the linkages could be one-to-one and one-to-more, such as when a window belongs to both a room and a corridor or when a room has one or more doors. Moreover, some of the rooms are inside other rooms, and not all doors are directly connected to the corridor.

5.1. Case 1 – Emergency response

Case 1 describes a simple emergency scenario. When a fire breaks out and someone is trapped in the innermost room of building, firefighters need to know the shortest path to the room, the

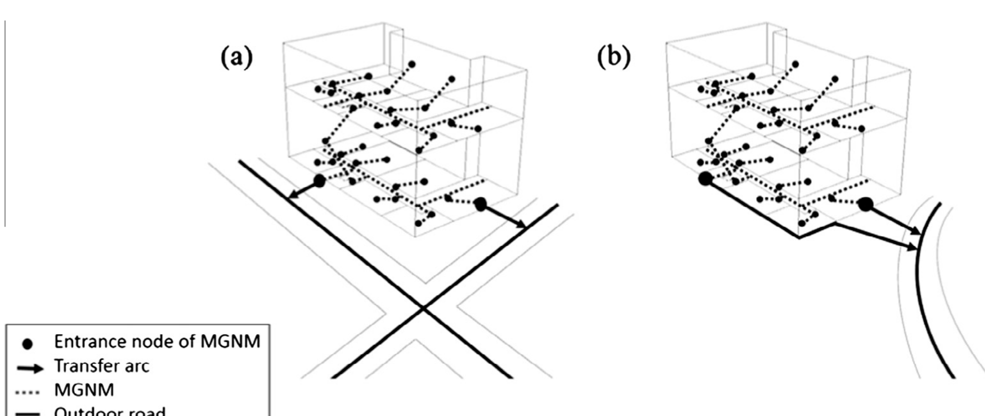

Fig. 9. Examples of Type I and II transfer arcs: (a) all transfer arcs are Type I and (b) one entrance cannot directly be projected to outdoor roads, and it forms a Type II transfer arc.

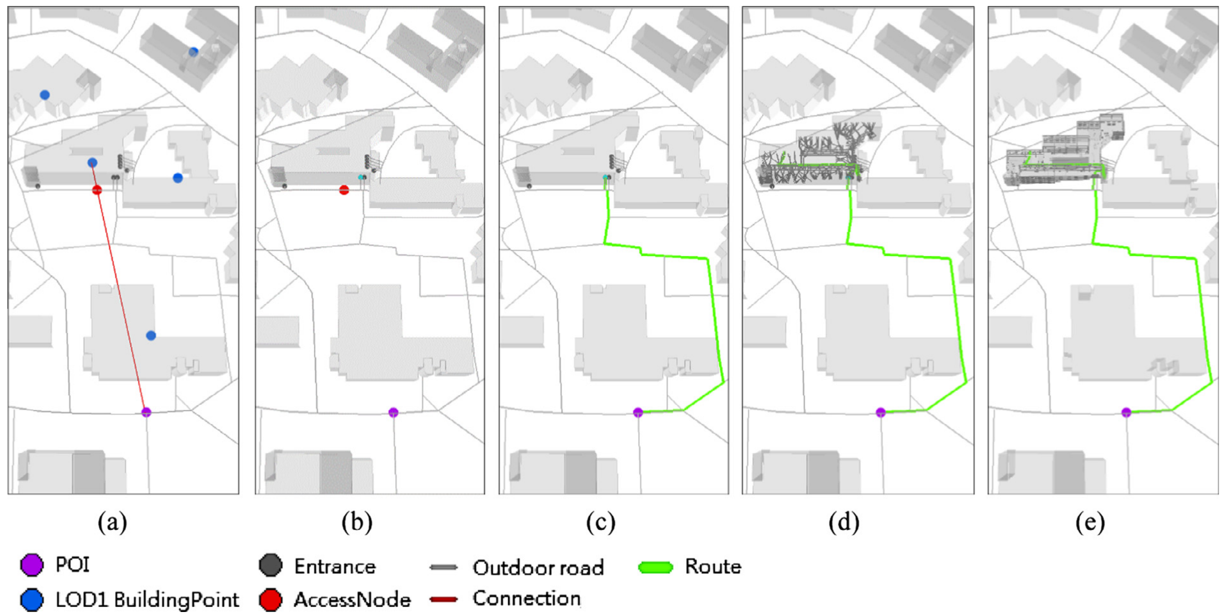

Fig. 10. Coarse-to-fine route planning. (a) Each LOD1 building generates its central point; the connection can be generated using the "building point" and the outdoor POI (place-of-interest), and the "access node" can be identified. (b) The nearest entrance can be selected using the "access node." (c) The shortest outdoor path between a POI and an entrance is calculated. (d) The shortest indoor path between an entrance and an indoor room is calculated based on the MGNM. (e) A combined route and use of the fine geometry model (i.e., multipatch) to replace the LOD1 model are shown.

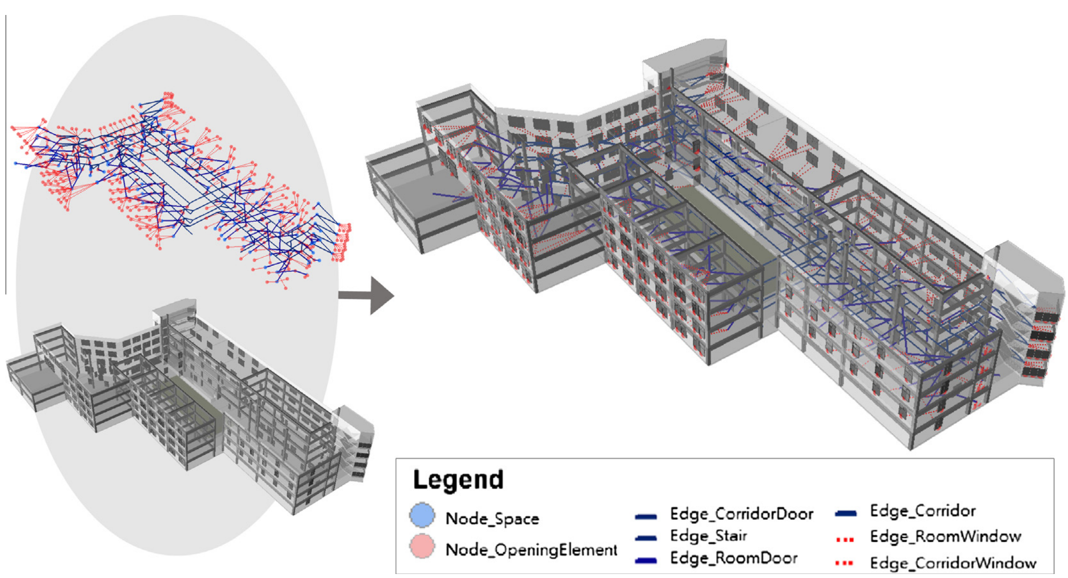

Fig. 11. 3D model and MGNM.

length of fire hose required, and all door and window information along this path, which requires combined indoor–outdoor analysis. The operation is divided into four parts: (1) define the indoor destination; (2) calculate the shortest path from the fire station to the indoor destination; (3) obtain information about opening elements; and (4) determine the optimum location for parking the fire engine.

The first stage defines the indoor destination. Here, we analyzed which is the innermost room in the building (i.e., the room farthest from the nearest exit) and applied the indoor closest entrance analysis. All paths from rooms to the nearest exit are shown in Fig. 12a. Then, we used different colors to visualize the length of path for every room in Fig. 12b. As the rooms on the ground floor are near to the exit of the building, therefore, they show a shorter path than the rooms on other floors. So, we can easily determine the innermost room, the room that has the longest path to the exit, by comparing the length of paths from all rooms. In our example (Fig. 12) all paths from the rooms to the nearest exit in the building are shown, indicating the innermost room is 416, with a total moving length of 80.30 m; therefore, in this simulation, we defined room 416 as the destination.

The second stage identifies the shortest path from the fire station to this room by performing shortest path analysis as a 3D scene simulation (Fig. 13). In our example, the firefighters would enter EB2 from entrance 8 (Fig. 13a), take the path through stair (Fig. 13b), and traverse the building (Fig. 13d). The total length of this path is 1452.12 m (contains indoor path 80.31 m and outdoor path 1371.81 m). In this stage, the height and attribute of each

Table 5
Number of MGNM elements.

MGNM elements	Meaning	Element name	IFC classes	Quantity
Node	Space	*Room*	*IfcSpace/IfcRoom*	95
	Space	*Washroom*	*IfcSpace/IfcRoom*	17
	Vertical portal/space	*Stair area*	*IfcSpace/IfcStair*	10
	Vertical portal/space	*Landing area*	*IfcSpace*	8
	Horizontal portal	*Door*	*IfcOpeningElement/IfcRelAssociatesMaterial*	142
	Emergency portal	*Window*	*IfcOpeningElement/IfcRelAssociatesMaterial*	307
Edge	Horizontal route	*Corridor*	*IfcSpace*	327
	Horizontal route	*Room-to-door*	*IfcRelSpaceBoundary*	156
	Horizontal route	*Door-to-corridor*	*IfcRelSpaceBoundary*	129
	Vertical route	*Stair*	*IfcStair*	16
	Emergency route	*Room-to-window*	*IfcRelSpaceBoundary*	251
	Emergency route	*Corridor-to-window*	*IfcRelSpaceBoundary*	59

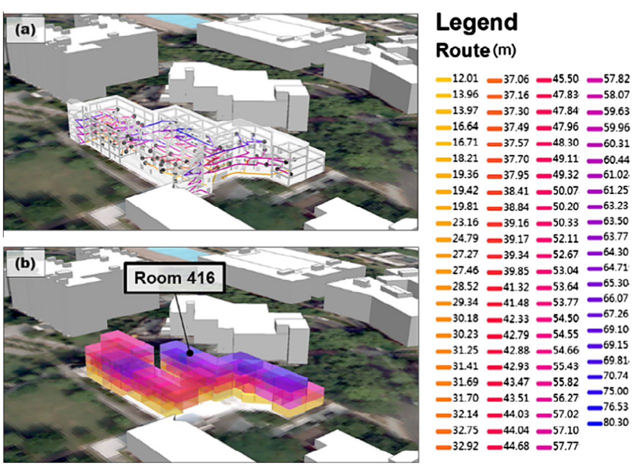

Fig. 12. Closest room analysis for determining distance from each room to nearest entrance in 3D scene: (a) route for each room; (b) visualization of distance from each room (IfcSpace type = room).

window can be obtained from MGNM (Fig. 13e), including dimension, material, story, and name. This stage demonstrates the benefit of using BIM to generate an indoor network model, which not only provides the coordinates but also the attributes of building elements.

The third stage obtains information about all opening elements along the path. In our example, there are three doors to this path. Additionally, using the MGNM emergency route *Room-to-window*, room 416's window location and material can be easily identified (Fig. 13c). Node room 416 has two adjacency *Room-to-window* routes, which means that this room has two windows, and the window node shows that these are double windows with transoms and are composed of aluminum and glass.

The fourth stage selects the location for parking so the fireman can use the rescue ladder to reach victims. Window locations (Fig. 13e) can also help determine the best location for parking the fire engine and even help firefighters locate and break the windows for rescue missions.

5.2. Case 2 – Pedestrian route planning

Case 2 is pedestrian route planning for indoor and outdoor multi-stop application. This scenario involves a student at the North Gate who first wants to find the washroom, then meet classmates in Room 413 of building EB2 and, finally, go to the Composite Sports Building (Fig. 14c). For the first stage, the nearest facility analysis helps find the nearest washroom. Using the attribute of MGNM nodes, 17 washrooms are found in building EB2; hence, the route planning result is as follows: go to the washroom near entrance 7 on the first floor; then go through the east side stairs to Room 413; finally, go out of EB2 using the west stairs down to entrance 1 (Fig. 14). Case 2 indicates that a building in MGNM can be part of route planning, and detailed entrance information provides flexible route planning results. The planned route for case 2 contains three hybrid routes.

5.3. Verification of network analysis results

The verification is a two-part process: (1) compare indoor route planning results (indoor distance and time) between traditional GNM and proposed MGNM and (2) compare distance among GNM, MGNM, and actual distance, measured using a 30 m tape. The distances measured for our two cases (Table 6) can be converted into traversal time based on the average adult walking speed (e.g., 5 km/h). In case 1, the traversal times of MGNM and GNM are 111.63 sec and 66.93 sec, respectively, and the difference is 24.4 sec; in case 2, the traversal times of MGNM and GNM are 237.16 sec and 150.75 sec, respectively, and the difference is 86.41 sec. To compare MGNM, GNM, and the reference distance, the relative error of GNM is larger than 32%, while the relative error of MGNM is less than 6%, indicating that the MGNM from BIM is more reliable than traditional GNM.

The visualizations of indoor GNM and MGNM in cases 1 and 2 (Figs. 15 and 16, respectively) show that the main improvement of MGNM is the vertical connection. Furthermore, the ability to traverse the interior rooms through appropriate doors is another distinct improvement. Our summary shows that the differences between MGNM and GNM lie in both in the horizontal and the vertical components (Table 7), indicating that the vertical error is larger than the horizontal error.

The above case studies suggest that in terms of either the vertical or horizontal distance, the MGNM route from BIM is closer to the true distance. In case 2, the relative error of MGNM's vertical part is larger than that in case 1 because case 2 used both staircases of building, which led to cumulative error. In contrast, case 2 indicates the length of the stair on the east side is 37.14 m and the stair on the west side is 32.31 m. However, in GNM, the lengths of these two stairs are the same; this further indicates that MGNM more accurately reflects the building's staircase geometry. In the case study analysis, the MGNM with the entrance-to-street strategy generates more meticulous applications to combined indoor and outdoor route planning; for example, the first operation of case 1 can be used to determine the escape sling configuration of a building.

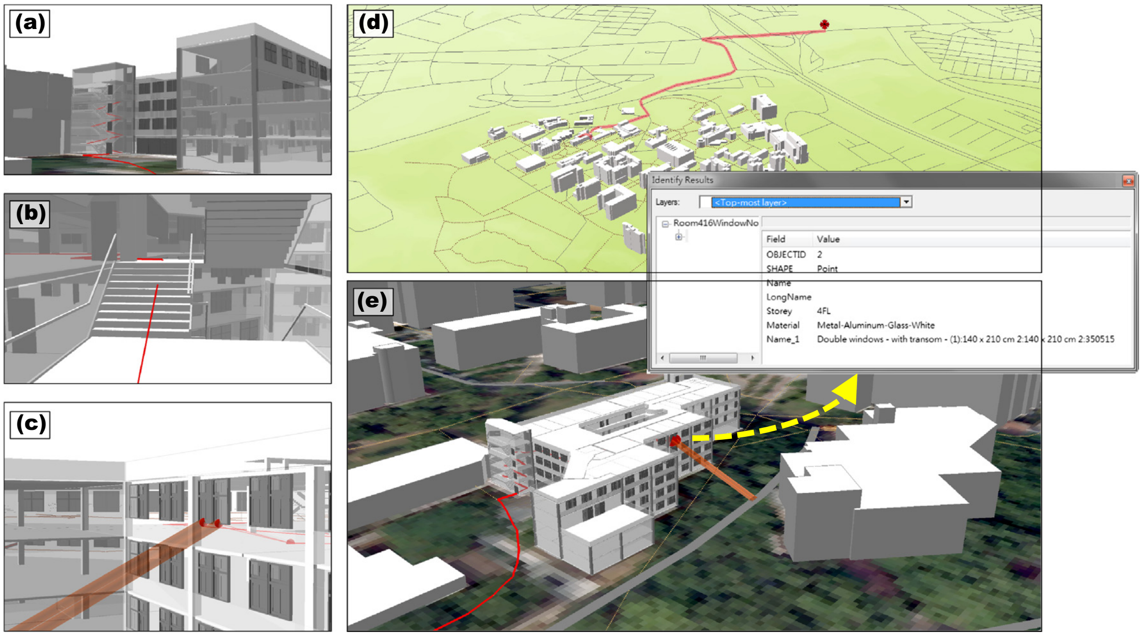

Fig. 13. Shortest path analysis from fire station to room 416 in 3D scene: (a) suggested entrance point, (b) suggested path inside building, (c) rescue ladder and windows of room 416, (d) bird's-eye view of entire scene, (e) location of windows and suggested location for parking fire engine.

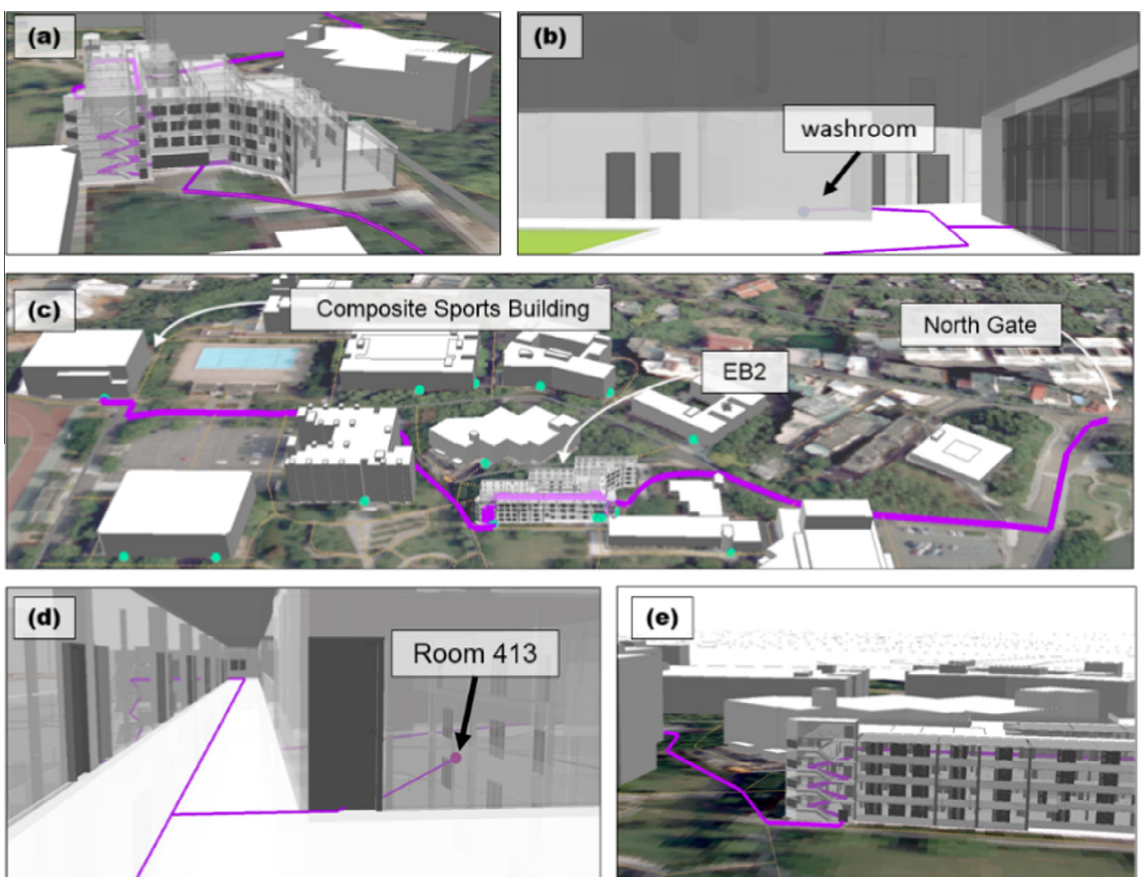

Fig. 14. Shortest path analysis for case 2 in 3D display: (a) route from North Gate step into EB2; (b) location of washroom and route through nearest entrance to this washroom; (c) entire route of case 2, where each building has corresponding entrances (green points); (d) route to enter room 413, and then from room 413 to the Composite Sports Building; (e) route for leaving EB2 through entrance1. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 6
Verification of network analysis results.

Case	MGNM		GNM		Reference distances (m)
	Distance (m)	Relative error (%)	Distance (m)	Relative error (%)	
1	80.31	5.4	47.05	44.6	84.96
2	172.30	5.6	123.73	32.2	182.56

Table 7
Verification of network analysis results in horizontal and vertical parts.

Case		MGNM		GNM		Reference distances (m)
		Distance (m)	Relative error (%)	Distance (m)	Relative error (%)	
1	Horizontal	43.17	2.4	39.31	6.7	42.15
	Vertical	37.14	13.3	7.74	81.9	42.82
2	Horizontal	102.86	7.4	108.45	13.3	95.74
	Vertical	69.44	20.0	15.28	82.4	86.82

5.4. Efficiency of indoor and outdoor combined route planning

The indoor and outdoor combined route planning cases indicated that the indoor routes are shorter than the outdoor routes, but the indoor routes contain more nodes than the outdoor routes (Table 8). This means that the high-density indoor entities in the indoor network (i.e., MGNM) led to the rapid expansion of the adjacency matrix; the size of adjacency matrix is increasing, as is the computational time, which increases the time to compute the shortest path. The coarse-to-fine approach could be an effective way for route planning. The sizes of the indoor and outdoor adjacency matrices are 4082×4082 and 5016×5016, respectively, with differing computation times between single-scale and multi-scale cases (Table 9). The coarse-to-fine approach clearly reduces the computational effort in route planning.

The complexity of Dijkstra's shortest path algorithm using adjacency matrix is $O(E\log V)$. The V and E are the number of vertices and number of edges, respectively. The coarse-to-fine strategy reduces the complexity by dividing the indoor and outdoor networks into different scales. For example, the V_1 and V_2 are the number of vertices of building, and road network; the E_1 and E_2 are the number of edges of building and road network. In a single scale, all the vertices and edges from all buildings are merged together as $O((E_1 + E_2)\log(V_1 + V_2))$. In coarse-to-fine strategy, the theoretical time complexity for the divided point sets will be reduced to $O(E_1 \log(V_1)) + O(E_2 \log(V_2))$.

Because the computational time is related to the number of transition points, the differing number of transition points are used to compare these two approaches. The single-scale computation time is 22.94 sec when the number of transition points is two, but 3.57 sec (indoor) and 5.38 sec (outdoor) with the coarse-to-fine approach (Fig. 17). For each additional transition point, the computation time increases as the number of transition points increases in single-scale computations. The coarse-to-fine approach is more efficient than the single-scale approach because it uses the LOD1 building model to obtain the corresponding indoor matrix. Moreover, the computational ratio between the coarse-to-fine and the single-scale approaches is about 1:4 (48.18:204.30), meaning that coarse-to-fine approach needs only 25% of the route planning computational time required by the single-scale approach.

Table 8
Route length and pass through nodes in two cases.

Case		Indoor (m)	Outdoor (m)
Case1	Route length (m)	80.31	1371.81
	Number of nodes	76	60
Case2	Route length (m)	170.62	598.81
	Number of nodes	260	50

Table 9
Comparison of different approaches in two cases.

Case	Method	Computation time (sec)
Case1	Single scale	22.94
	Coarse-to-fine	8.55
Case2	Single scale	67.79
	Coarse-to-fine	21.88

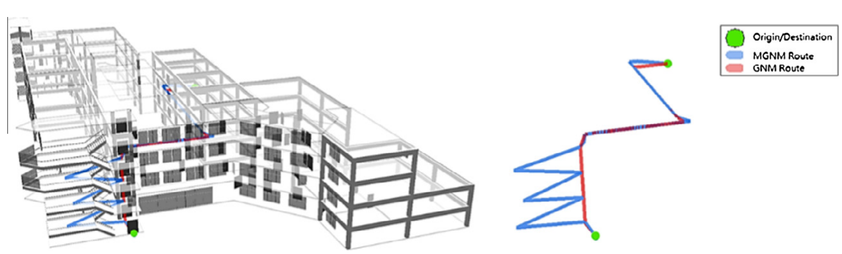

Fig. 15. Comparison of indoor route between GNM and MGNM in case 1.

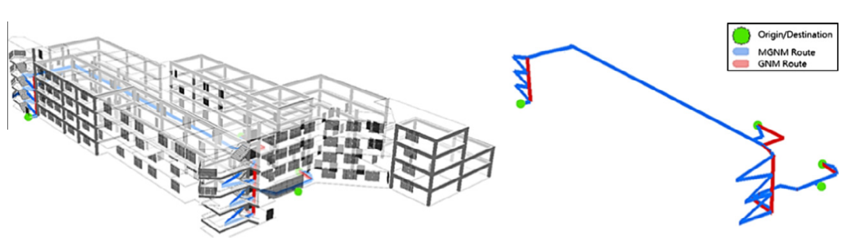

Fig. 16. Comparison of indoor route between GNM and MGNM in case 2.

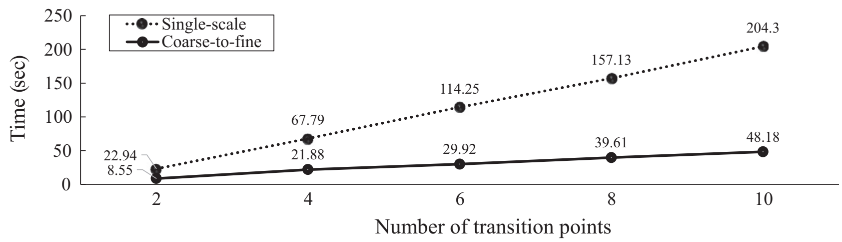

Fig. 17. Computational times with different numbers of transition points.

6. Conclusions and future works

This study proposed an indoor network model from BIM for various indoor–outdoor route planning applications (e.g., emergency response and pedestrian route planning). A framework of IFC-to-MGNM was developed to validate the proposed scheme and indicate its feasibility and effectiveness. The advantage of this method is that it effectively reuses existing BIM data and also extends the BIM to GIS analysis. The indoor network model can be treated as the value-added product of BIM for spatial analysis. We used detailed building elements from BIM to automatically generate the indoor MGNM, which not only improved the efficient but also improved details when compared to the existing indoor network model, the GNM. In the application stage, the MGNM was converted to Geodatabase in GIS software; therefore, the GIS analysis function can be easily adopted for indoor and outdoor application. The proposed coarse-to-fine approach is a countermeasure to improve the computational time for complex indoor and outdoor networks.

The major contributions of this study are: (1) to establish a BIM/IFC to MGNM framework by mapping the relationship between IFC and indoor network, and presenting a method and guidelines to automatically derive the indoor network from IFC; (2) to combine the indoor and outdoor networks through a proposed scheme to connect the entrance of buildings and streets via transfer arcs; and (3) to establish a coarse-to-fine route planning process that considers both city and building scales to accelerate the performance of route planning. The proposed method enables automated indoor network generation from BIM model. This study utilized the geometric and semantic information from BIM models to generate detailed indoor network automatically. The proposed indoor network considered all the opening elements (i.e. doors and windows) to construct a detailed indoor network model. It can improve spatial analysis function for BIM as well as improve the capability of emergency evacuation for indoor environment.

The proposed scheme integrates indoor information from BIM with outdoor information from GIS, subsequently improving the integration between the AEC and geospatial domains. Furthermore, indoor and outdoor route planning analysis can effectively provide a specific route for emergency response and pedestrian route planning, highlighting the rich geometric and semantic information advantage of BIM. The conclusions are summarized as follows:

(1) Using the BIM/IFC format as the indoor data source, a multipurpose indoor network data model can be generated automatically. Geometry and attributes can be generated simultaneously and become a part of the 3D GIS dataset, which improves the efficiency of the indoor network generation.
(2) IFC-to-MGNM conversion automatically generates an interior network based on building elements, which means that the network can adjust itself to changes in digital building models. Particularly, the BIM approach is inherent throughout the building life cycle, and any change to any part of the building is coordinated in all other parts. The length of MGNM was improved in horizontal and vertical components. The accuracy of the average length of the two application cases was improved by 5.1% in horizontal direction and 65.5% in vertical direction.
(3) The entrance-to-street strategy uses multiple sources of GIS data, including OpenStreetMap data for strengthening road information of the area surrounding the building (especially footpaths), and CityGML LOD1 building for visualization and assistance in determining entrance barriers. The entrance-to-street strategy can determine surroundings and select countermeasures accordingly (i.e., vertical projection connection or along building facades).
(4) In the indoor network, rooms, doors, and connection parts are abstracted as nodes, and these detailed entities may result in a huge adjacency matrix. By using the coarse-to-fine approach, the computational time required for route planning can be reduced.

In this study, the proposed MGNM was converted to Feature Class in Geodatabase to directly link the MGNM and GIS analysis function. To consider the development of OGC indoorGML for data interoperability, however, future work should extend the MGNM to OGC IndoorGML as well as continue to improve MGNM included the conversion of IFC-to-MGNM for to indoor utility networks.

Acknowledgment

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References

[1] V.K. Bansal, M. Pal, Potential of geographic information systems in building cost estimation and visualization, Autom. Constr. 16 (2007) 311–322.
[2] R. Volk, J. Stengel, F. Schultmann, Building Information Modeling (BIM) for existing buildings – literature review and future needs, Autom. Constr. 38 (2014) 109–127.
[3] T. Cerovsek, A review and outlook for a 'Building Information Model' (BIM): a multi-standpoint framework for technological development, Adv. Eng. Inform. 25 (2011) 224–244.
[4] U. Rüppel, P. Abolghasemzadeh, K.M. Stuebbe, BIM-based immersive indoor graph networks for emergency situations in buildings, in: Proceedings of the International Conference on Computing in Civil Engineering and Building Engineering, 2010, pp. 65–72.
[5] A. Vanclooster, P. De Maeyer, Combining indoor and outdoor navigation: the current approach of route planners, in: Advances in Location-Based Services, Lect. Notes Geoinform. Cartogr., 2012, pp. 283–303.
[6] P.H. Chen, F. Feng, A fast flow control algorithm for real-time emergency evacuation in large indoor areas, Fire Saf. J. 44 (2009) 732–740.
[7] A.Y. Chen, F. Peña-Mora, Y. Ouyang, A collaborative GIS framework to support equipment distribution for civil engineering disaster response operations, Autom. Constr. 20 (2011) 637–648.
[8] U. Isikdag, J. Underwood, G. Aouad, An investigation into the applicability of building information models in geospatial environment in support of site selection and fire response management processes, Adv. Eng. Inform. 22 (2008) 504–519.
[9] L. Liu, S. Zlatanova, Towards a 3D network model for indoor navigation, Urban Regional Data Manage.: UDMS Ann. (2011) 79–94.

[10] J. Lee, A spatial access-oriented implementation of a 3-D GIS topological data model for urban entities, Geoinformatica 8 (2004) 237–264.
[11] A. Slingsby, J. Raper, Navigable space in 3D city models for pedestrians, in: Advances in 3D Geoinformation Systems, Springer, 2008, pp. 49–64.
[12] F. Lamarche, S. Donikian, Crowd of virtual humans: a new approach for real time navigation in complex and structured environments, Computer Graphics Forum, vol. 23(3), Wiley Online Library, 2004, pp. 509–518.
[13] B. Lorenz, H.J. Ohlbach, E.P. Stoffel, A hybrid spatial model for representing indoor environments, in: J.D. Carswell, T. Tezuka (Eds.), Web and Wireless Geographical Information Systems, Proceedings, Springer-Verlag, Berlin, 2006, pp. 102–112.
[14] E.-P. Stoffel, B. Lorenz, H.J. Ohlbach, Towards a semantic spatial model for pedestrian indoor navigation, in: J.-L. Hainaut et al. (Eds.), Advances in Conceptual Modeling-Foundations and Applications, Springer, 2007, pp. 328–337.
[15] L. Liu, S. Zlatanova, A "door-to-door" path-finding approach for indoor navigation, in: Proceedings Gi4DM 2011: GeoInformation for Disaster ManagementAntalya, Turkey, 2011.
[16] W. Yuan, M. Schneider, Supporting 3D route planning in indoor space based on the LEGO representation, in: Proceedings of the 2nd ACM SIGSPATIAL International Workshop on Indoor Spatial Awareness, ACM, 2010, pp. 16–23.
[17] M. Meijers, S. Zlatanova, N. Pfeifer, 3D geo-information indoors: structuring for evacuation, in: Proceedings of Next Generation 3D City modelsBonn, Germany, 2005.
[18] I.R. Karas, F. Batuk, A.E. Akay, I. Baz, Automatically extracting 3D models and network analysis for indoors, in: Innovations in 3D Geo Information Systems, Lect. Notes Geoinform. Cartogr., 2006, pp. 395–404.
[19] T. Becker, C. Nagel, T.H. Kolbe, A multilayered space-event model for navigation in indoor spaces, in: 3D Geo-Information Sciences, Springer, 2009.
[20] P. Boguslawski, C.M. Gold, H. Ledoux, Modelling and analysing 3D buildings with a primal/dual data structure, ISPRS J. Photogramm. Rem. Sens. 66 (2011) 188–197.
[21] J.S. Kim, S.J. Yoo, K.J. Li, Integrating IndoorGML and CityGML for indoor space, in: 13th International Symposium, W2GIS 2014, Seou, 2014, pp. 184–196.
[22] A.Y. Chen, T. Huang, Toward BIM-enabled decision making for in-building response missions, IEEE Trans. Intell. Transp. Syst. 16 (2015) 2765–2773.
[23] U. Isikdag, S. Zlatanova, J. Underwood, A BIM-oriented model for supporting indoor navigation requirements, Comput. Environ. Urban Syst. 41 (2013) 112–123.
[24] L.C. Chen, C.H. Wu, T.S. Shen, C.C. Chou, The application of geometric network models and building information models in geospatial environments for fire-fighting simulations, Comput. Environ. Urban Syst. 45 (2014) 1–12.
[25] E.J. Whiting, Geometric, Topological & Semantic Analysis of Multi-Building Floor Plan Data, Engineering Science, University of Toronto, 2006.
[26] D. Mandloi, J. Thill, Object-Oriented Data Modeling of an Indoor/Outdoor Urban Transportation Network and Route Planning Analysis, Springer ScienceþBusiness Media, 2010.
[27] M.P. Kwan, J. Lee, Emergency response after 9/11: the potential of real-time 3D GIS for quick emergency response in micro-spatial environments, Comput. Environ. Urban Syst. 29 (2005) 93–113.
[28] M. Tao, T. Gallagher, B. Li, A.G. Dempster, C. Rizos, Indoor/outdoor on campus navigation system: and implementation at the university of New South Wales, in: International Conference on Indoor Positioning and Indoor NavigationSydney, Australia, 2012.
[29] N. Li, B. Becerik-Gerber, B. Krishnamachari, L. Soibelman, A BIM centered indoor localization algorithm to support building fire emergency response operations, Autom. Constr. 42 (2014) 78–89.
[30] M.Y. Cheng, G.L. Chang, Automating utility route design and planning through GIS, Autom. Constr. 10 (2001) 507–516.
[31] V. Singh, N. Gu, X. Wang, A theoretical framework of a BIM-based multi-disciplinary collaboration platform, Autom. Constr. 20 (2011) 134–144.
[32] J. Irizarry, E.P. Karan, F. Jalaei, Integrating BIM and GIS to improve the visual monitoring of construction supply chain management, Autom. Constr. 31 (2013) 241–254.
[33] S. Zlatanova, G. Sithole, M. Nakagawa, Q. Zhu, Problems in indoor mapping and modelling, Int. Arch. Photogramm. Rem. Sens. Spatial Inform. Sci. XL-4/W4 (2013) 63–68.
[34] N. Gu, K. London, Understanding and facilitating BIM adoption in the AEC industry, Autom. Constr. 19 (2010) 988–999.
[35] M. El-Mekawy, A. Östman, I. Hijazi, A unified building model for 3D urban GIS, J. Geo-Inform. 1 (2012) 120–145.
[36] S. Daum, A. Borrmann, Processing of topological BIM queries using boundary representation based methods, Adv. Eng. Inform. 28 (2014) 272–286.
[37] T.H. Kolbe, Representing and exchanging 3D city models with CityGML, in: 3D Geo-Information Sciences, 2009, pp. 15–31.
[38] C. Nagel, T. Becker, R. Kaden, K. Li, J. Lee, T.H. Kolbe, Requirements and space-event modeling for indoor navigation, OpenGIS Discussion paper, Open Geospatial Consortium, 2010.
[39] buildingSMART, IFC2x Edition 3 Technical Corrigendum 1, 2007.
[40] H. Blum, A transformation for extracting new descriptors of shape, Models for the perception of speech and visual form, 19, 1967, pp. 362–380.
[41] L. Prasad, Morphological analysis of shapes, CNLS Newslett. 139 (1997) 1997–2007.
[42] S. Taneja, B. Akinci, J.H. Garrett, L. Soibelman, B. East, Transforming an IFC-based building layout information into a geometric topology network for indoor navigation assistance, Proceedings of the 2011 ASCE International Workshop on Computing in Civil Engineering, vol. 1, 2011, pp. 315–322.
[43] J. Lee, S. Zlatanova, A 3D data model and topological analyses for emergency response in urban areas, in: J. Li, S. Zlatanova (Eds.), Geospatial Information Technology for Emergency Response, Taylar and Francis, London, 2008, pp. 143–168.
[44] E.W. Dijkstra, A note on two problems in connexion with graphs, Numer. Math. 1 (1959) 269–271.