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Research Article

Development of Data Fusion Method Based on Topological Relationships Using IndoorGML Core Module

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Geospatial datasets are currently constructed, managed, and utilized individually according to the spatial scale of the real world, such as the ground/surface/underground or indoor/outdoor, as well the particular purpose of the geospatial data used for location-based services. In addition, LBS applications use an optimal data model and data format according to their particular purpose, and thus, various datasets exist to represent the same spatial features. Such duplicated geospatial datasets and geographical feature-based GIS data cause serious problems in the financial area, compatibility issues among LBS systems, and data integration problems among the various geospatial datasets generated independently for different systems. We propose a geospatial data fusion model called the topological relation-based data fusion model (TRDFM) using topological relations among spatial objects in order to integrate different geospatial datasets and different data formats. The proposed model is a geospatial data fusion model implemented in a spatial information application and is used to directly provide spatial information-based services without data conversion or exchange of geometric data generated by different data models. The proposed method was developed based on an extension of the AnchorNode concept of IndoorGML. The topological relationships among spatial objects are defined and described based upon the basic concept of IndoorGML. This paper describes the concept of the proposed TRDFM and shows an experimental implementation of the proposed data fusion model using commercial 3D GIS software. Finally, the limitations of this study and areas of future research are summarized.

1. Introduction

Geoinformation has always been a challenge owing to a variety of data models, data formats, spatial resolutions, and methods of geometric and topological representations. In general, the real world is a huge feature connected by spaces made up of a combination of geographical objects. However, a geospatial dataset has been constructed, managed, and utilized individually according to the spatial scale of the real world, such as ground/surface/underground or indoor/outdoor, as well as the purpose of the geospatial data used for location-based services. In addition, LBS applications use an optimal data model and data format according to their particular purpose, and thus, various datasets exist to represent the same spatial features. Such duplicated geospatial datasets and geographical feature-based GIS data have caused serious problems in the financial area, compatibility issues among LBS systems, and problems with data integration among the various geospatial datasets generated independently for different systems. In other words, the spatial data representing the real world have fundamental problems in a variety of data formats, including spatial relationships among objects, data integration between 2D and 3D data, data compatibility among various types of spatial data, spatial resolution, and consistent representations in geometric and topological data [1].

To provide seamless LBSs between indoor and outdoor spaces, one of the most important requirements is to connect indoor with outdoor spaces. In general, although geographical features in an outdoor space have been represented as 2D objects, spatial entities in a micro built environment such as buildings have been represented as 3D objects in the building information model (BIM) or CityGML datasets. These 2D and 3D spatial data are generated based on various data models and formats according to the generation method applied. In this way, according to the purpose of the spatial information service, indoor spatial data and outdoor spatial data are constructed, managed, and utilized, where certain problems are caused with regard to the interoperability among spatial information systems, data compatibility, and utilization of data linkages [2].

In addition, the convergence or fusion of spatial data is required in integrating geospatial data generated based on geographical features individually. In other words, spatial data on transportation are constructed and used individually based on geographical features such as roads, railways, sidewalks, and subways. However, the need for linkage among individual traffic-related data has been revealed through the complex transportation system based on various types of transportation infrastructure. The system consists of various transportation subsystems such as passenger cars, buses, trains, and sidewalks. However, because most transportation services utilize multiple transport modes, it is difficult to independently utilize individual transportation systems. Therefore, research on interdependent and interactive multimodal transport systems is required. To provide such multimodal transport services, the fusion of various transportation data must first be studied [3]. This demand is related to urban facility management issues, as seen in the California power outages in early 2001. The California power outages have had a major impact on many urban-based service sectors such as oil, natural gas production in California, and water transport for crop irrigation, which has led to interest in the understanding and analysis of connectivity between major types of urban infrastructure, including water, sewer, electric and gas systems, among others, which are considered critical infrastructure [4, 5].

To solve these problems, research has been conducted to fuse geospatial data generated by various construction methods and data models [6]. As the developed methods for improving the interoperability and compatibility of data by combining spatial data with other data of different formats, there are three approaches: a data fusion method using geometric data conversion, a data fusion method based on visualization, and recently proposed geospatial data fusion methods based on topological relations of spatial objects.

The purpose of this study is to propose the development of a spatial data fusion model called topological relation-based data fusion model (TRDFM) using topological relations among spatial objects in order to utilize different geospatial datasets and different data formats. TRDFM is a data fusion model implemented in LBS applications and is used to directly provide spatial information-based services without a data conversion or exchange of geometric data generated by different data models. The proposed method was developed through an extension of the AnchorNode concept of IndoorGML adopted by the Open Geospatial Consortium (OGC) in 2015. The topology relations between objects are defined and described based on the basic concept of IndoorGML. In the following section, we describe the existing spatial data fusion methods. In the third section, we present the proposed TRDFM using topological relations between spatial objects based on IndoorGML. In the next section, an experiment on the data fusion method based on the proposed model is described, and the final section summarizes the limitations of this study and areas of further research.

2. Previous Studies

As mentioned in the previous section, existing spatial data representing the real world have limitations in implementing seamless LBS systems, such as various data formats, lacks of spatial relations among objects, and a lack of compatibility among geospatial data. To overcome these limitations, research on the convergence of spatial data has been carried out. The developed methods are classified into three groups: a data fusion method using a geometric data transformation, a data fusion method with a visualization aspect, and a data fusion method based on the topological relations of spatial entities. A review of previous studies is given to examine the direction and considerations of a more efficient approach to combining geospatial data.

The first spatial data fusion method is data fusion through a geometric data transformation [7] and can be grouped into two types. The first method in converting the data is in accordance with the format of the target data. The second method is to define one standardized format when there is a plurality of data to be combined and to convert the other data into a standardized format and combine them.

A data fusion method through a geometric data transformation is being actively studied for exchanging BIM data with the CityGML datasets [8, 9]. CityGML is an international standard data model adopted by OGC to represent urban spaces in 3D GIS, called a 3D city model. Industry Foundation Classes (IFC) is a representative standard data model of building information model (BIM) data. Research on converting datasets between two standards has been ongoing in the development of data fusion methods for the management and utilization of indoor spatial data [8]. BIM has more detailed information on buildings than CityGML. Therefore, research on converting BIM data into CityGML has been mainly conducted [9]. Data conversion from IFC to CityGML requires the transformation of attribute and geometric data. It is necessary to define the property data of the object to be converted from CityGML to IFC, and there is a need for an algorithm for simplifying the object data of the IFC geometry model based on rules for mapping between the two CityGML and IFC models [10]. In IFC and CityGML, the developed method has only been used to categorize the objects related to buildings and map the corresponding relations, defining the mapping rules that apply to each level of detail (LoD) of CityGML [7].

The data fusion method using a geometric data transformation requires analyzing how to map objects to objects of the target data, and mapping rules and geometric simplification algorithms should therefore be defined. As in the case of converting IFC to CityGML, there is a need to create additional objects because they are difficult to map perfectly owing to differences in the amounts of data.

Second, a data fusion method between spatial data based on visualization has been developed. This method visually represents different datasets in one application system.

Typically, V-World [11], which is implemented as an open space information platform, visually integrates various topographical 2D data, 3D building data, and 3D indoor space modeling data using digital elevation models (DEM) and orthographic images. Google Earth [12] also provides a 3D visualization system displaying 2D geospatial data through 3D topographical modeling and texturing. Currently, because of problems related to coordinate systems and scale issues, the linkage between 3D outdoor spatial data and indoor spatial data in a 3D visualization application cannot be expressed in a single viewer window or a smooth screen transition cannot be performed. To provide seamless navigation service or route guidance between indoor and outdoor spaces, a topological model expressing the spatial relations of indoor and outdoor spaces is needed. Therefore, a spatial data convergence method in terms of visualization has certain limitations in providing seamless indoor and outdoor services.

The third approach is a data fusion method based on topological relationships among spatial entities. This method merges data by connecting topological relationship data models of different datasets. The topological relation method (TRM) has been proposed using topological relationships between spatial objects to directly apply various geometric data generated by different data models for indoor spatial location services [2]. The ConnectEdge feature class defined in the 3D navigable data model (3D NDM), which abstracts the connectivity relationships of a building's internal structure, defines the connectivity relationships of spatial entities such as rooms and corridors, which are the movement paths of people [13]. Data fusion between IFC and CityGML, which are different data formats, was applied using topological representations through a node-link graph [14]. The same types of network-based topological representations utilizing node-link graphs are generated from the two geometry models by defining the topology data generation procedure and necessary attribute information for each geometry model. IndoorGML proposed an additional element for connecting indoor and outdoor spaces, which is presented as an anchor node concept. In all indoor spaces, there is an entrance for outdoor use, which is used as an anchor node to connect the indoor and outdoor areas [15]. Therefore, the TRM was developed not at the data level but at the application service level [16].

In this way, the developed methods for fusing spatial data are grouped into fused composite methods using a geometric data transformation, data fusion methods with a visualization aspect, and data fusion methods based on topological models. However, a data fusion method using a geometric data transformation requires the transformation of existing data, as well as corresponding relations of the mapping data, mapping rules, and simplification algorithms for various application services. A method based on visualization has difficulty in identifying the topological relationships among spatial entities represented in different datasets because the datasets are not merged into one geometric dataset with topological consistency even though they use the same coordinate system. The data fusion method based on topological models for connecting indoor and outdoor areas using AnchorNode proposed by IndoorGML was presented at the conceptual level, the model of which has limitations in implementing a practical integrated system to provide seamless LBSs in the real world. In this paper, we propose a generic spatial data fusion model by extending the concept of AnchorNode of IndoorGML. The proposed spatial data fusion model can be used to directly provide seamless LBSs from the urban scale (macro space) to the human scale (micro space) without converting or exchanging the geometric data of space-based spatial data and geographical feature-based spatial data.

3. Geospatial Data Fusion Model Based on IndoorGML Core Module

This section describes the IndoorGML core module used to develop a data fusion model based on IndoorGML. We also describe the proposed TRDFM, which extends the concept of an AnchorNode class defined in IndoorGML, and detail the procedure used for generating the proposed data fusion model.

3.1. IndoorGML Core Module. In this study, the proposed data fusion model is developed based on the basic concept of IndoorGML, which presents the topological relationships among the spatial entities in a graphical structure. IndoorGML was established as the OGC international standard and is an open data model for indoor navigation applications and XML-based formats to represent and exchange indoor spatial data for indoor navigation [15]. Because the IndoorGML core module is a topological data model used to represent spatial relationships among indoor spatial entities, the module does not provide a geometric representation of spatial entities but has interface classes associated with a space and spatial boundary feature classes defined in the exiting feature data models such as the CityGML and IFC models [17].

IndoorGML uses a node-relation structure (NRS) to express the connectivity and adjacency relationships among spatial objects. The NRS utilizes Poincaré duality to represent the topological relationships using dual graphs. Through a duality transformation, solid objects (3D) such as rooms within a building in a primal space are transformed into vertices (0D) in a dual space. The common surface (2D) shared by two solid objects is mapped to an edge (1D) linking two vertices in a dual space. Thus, the edges of a dual graph represent topological relationships among 3D objects in a primal space, such as doors, windows, or hatches, between rooms in a building. Similar to node-edge graphs, which use a dual graph to represent space-activity interactions [18], the NRS was developed to represent topological relationships such adjacency relationships as $G = (V(G), E(G))$ and connectivity relationships as $H = (V(H), E(H))$ among spatial entities in the real world. In IndoorGML utilizing a network model, the nodes represent rooms, staircases, elevators, doors, building exits, and hallways. The edges in IndoorGML represent the topological relationships among spatial entities, which indicate the paths of pedestrian movement between nodes within a building.

To analyze human activity using multimodal transportation systems in urban areas, the network-based topological model (called IndoorGML) needs to be integrated with a 2D network of the ground transportation system, such as a road network. In a road network represented by a node-edge graph, the nodes represent intersections of the roads, and the edges connected by two nodes represent road segments. To connect indoor and outdoor spaces, IndoorGML provides a concept for defining additional topology elements between indoor and outdoor spaces, called *anchor nodes*. The anchor node represents the entrance of a building as a special node in the topological graph as a mediator of an indoor and outdoor space connection. As shown in Figure 1, two-way access between nodes is possible when referring to an outdoor network through an anchor node, and the topological network of a building can be obtained from an external node when a vehicle enters the building. In addition, the geospatial data of an underground water pipe and ground water pipe, which are generated separately, can be connected through an anchor node. For smooth spatial connections, the anchor nodes have attributes such as node reference data of the external reference network and parameters for supporting coordinate system transformation of indoor and outdoor spaces [18].

3.2. Topological Relation-Based Data Fusion Model. As mentioned in the previous section, IndoorGML introduced an *anchor node* to connect indoor and outdoor spaces at the conceptual level, which means that the proposed data fusion method in IndoorGML has limitations in implementing a practical integrated system to provide seamless LBSs in an urban environment. In this paper, we propose the generic spatial data fusion model, TRDFM, by extending the concept of an anchor node of IndoorGML, as shown in Figure 2. The proposed spatial data fusion model can be used to directly provide seamless LBSs from the urban scale (macro space) to the human scale (micro space).

Figure 2 shows a UML diagram of the proposed TRDFM. The orange-colored classes in the UML are GML geometry objects, and the gray-colored classes represent the classes of the core module of IndoorGML. The pink-colored classes are those derived from the navigation module of IndoorGML used to determine the topology relations from the geometric data generated based on different geometric data models. The *NavigableBoundary* and *NonNavigableBoundary* feature classes represent the surfaces of 3D spatial entities such as rooms, which are the geometric representation elements of 3D surface-oriented data models. The *NavigableBoundary* and *NonNavigableBoundary* feature classes are mapped to the *Transition* feature, which is realized as an edge in the topological model. The *NavigableSpace* and *NonNavigableSpace* feature classes are associated with the spatial entities (*CellSpace* feature) and mapped to the *State* feature, which is realized as a node in IndoorGML. The blue-colored classes are feature classes defined to integrate datasets that represent spatial entities in different spaces such as the ground, surface, or underground.

To analyze human activity using multimodal transportation systems in urban areas, the building's network generated by IndoorGML needs to be integrated with a street network. The first step of the integration process is to define the connectivity relations between the building and ground streets. In other words, the connectivity relationships can be defined between the building network generated by IndoorGML and the street network representing road centerlines. The connectivity relations are represented by an edge, called *AnchorEdge* [19]. One node of *AnchorEdge* represents the entrance halls of the buildings, and the other node of *AnchorEdge* is on the street network, which is defined by the projection of the node onto the edge of the street network. The former node is called *AnchorNode* and represents an entrance hall of a building, whereas the latter is also *AnchorNode* representing the corresponding node of a street network generated in the manner described above. *AnchorEdge* is an edge that connects two *AnchorNodes*. *AnchorNode* has attributes such as absolute coordinates and variables for transforming the coordinate system and links the geometry data with the topology data. As shown in Figure 3, *AnchorNode* and *AnchorEdge* are defined as additional topology elements to connect between the building network and street networks in the proposed TRDFM.

AnchorNode and *AnchorEdge* are presented in the UML diagram of the proposed TRDFM, as shown in Figure 3. In Figure 4, the *State* class defined in the core module of IndoorGML represents a node in a dual graph of the geometric model of spatial entities in the real world. The spatial entities within a building can be associated with a room, corridor, door, or other elements. The *Transition* class in the UML diagram is an edge that represents the topological relationships among spatial entities. The *Transition* connects two *States* in the topological model of IndoorGML. The *State* class has two subclasses: *GeneralState* and *SpecialState*, indicated by an inheritance relationship in the UML object diagram. *GeneralState* is a node in the topological model of IndoorGML representing a space similar to a room in the real world, whereas *SpecialState* is a node introduced in the proposed TRDFM, called *AnchorNode*. The *Transition* class has two subclasses: *GeneralTransition* and *SpecialTransition*, indicated by an inheritance relationship in the UML object diagram. *GeneralTransition* is an edge in the topological model of IndoroGML representing the topological relationships among spatial entities, like rooms in the real world, and *SpecialTranstion* is an edge as described above, called *AnchorEdge*.

To formalize the topology-based data fusion model, TRDFM, including *SpecialState* and *SpecialTransition*, the schemas of the objects are shown in Tables 1 and 2. The primal classes of the TRDFM are *GeneralState*, *SpecialState*, *GeneralTransition*, and *SpecialTransition*, which are inherited from *State* and *Transition* classes defined in IndoorGML. A *State* consists of an identifier and position data in 3D (x-, y-, and z-coordinates), and *Transition* consists of an identifier and two *States*. Each *GeneralState* in the database has an identifier (Id), space type (Type), a space ID (RelatedSpaceId) represented by the corresponding space, and an edge ID (ConnectedEdgeId) of an edge connected to a node. *SpecialState* has additional attributes, as shown in Table 1, which are reference node data of the street network and conversion parameters used to support the coordinate system conversion

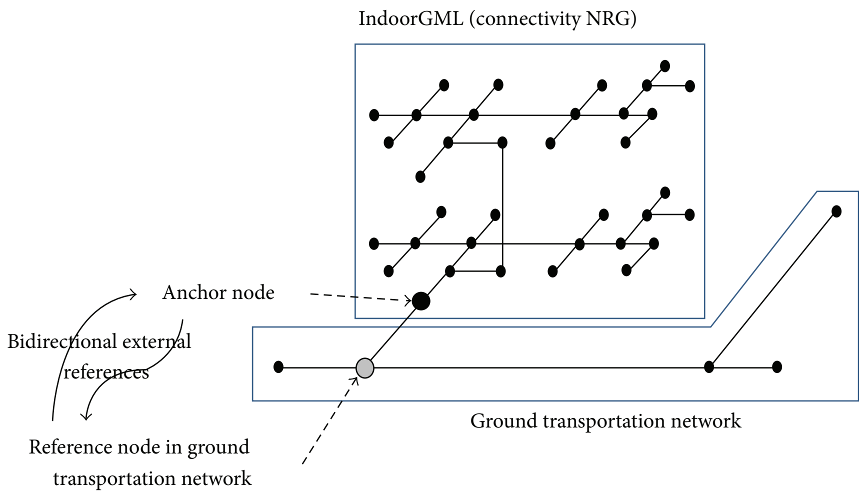


Figure 1: Anchor node connecting indoor and outdoor spatial networks (OGC [15]).

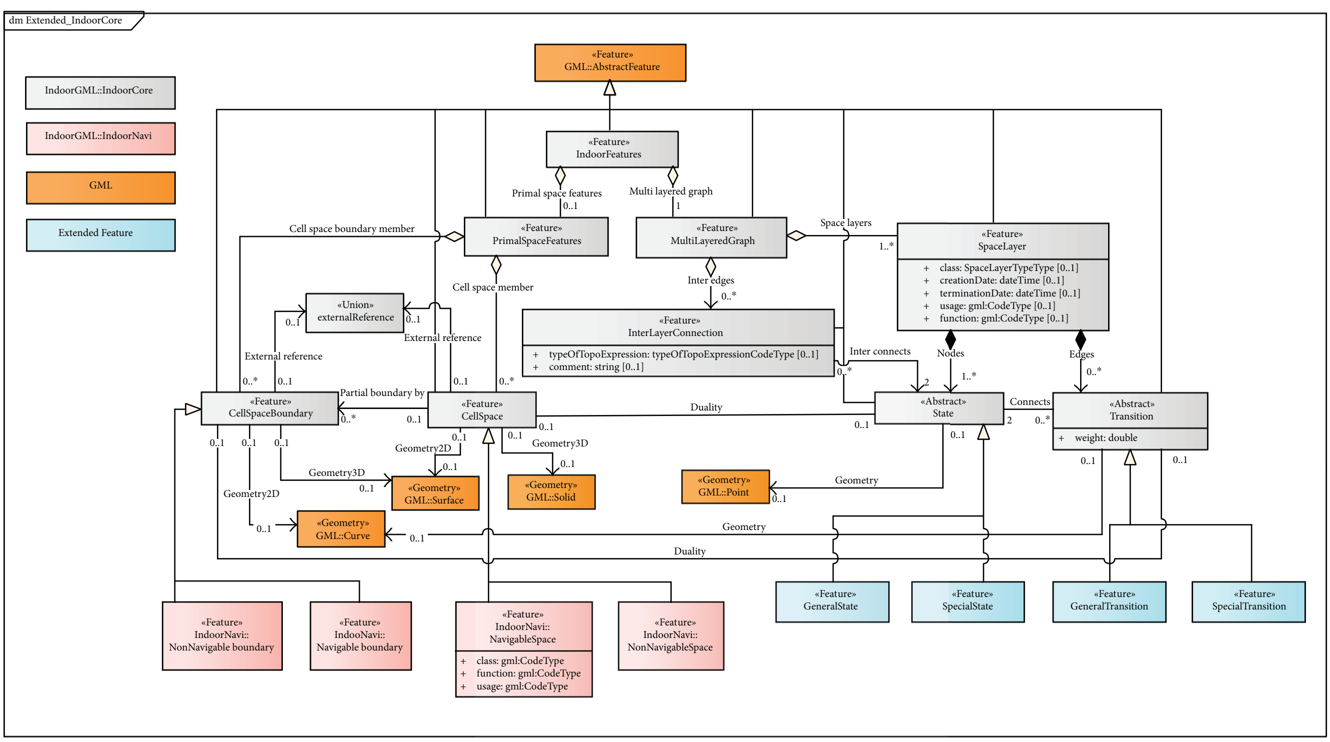


Figure 2: UML diagram of TRDFM based on IndoorGML core module.

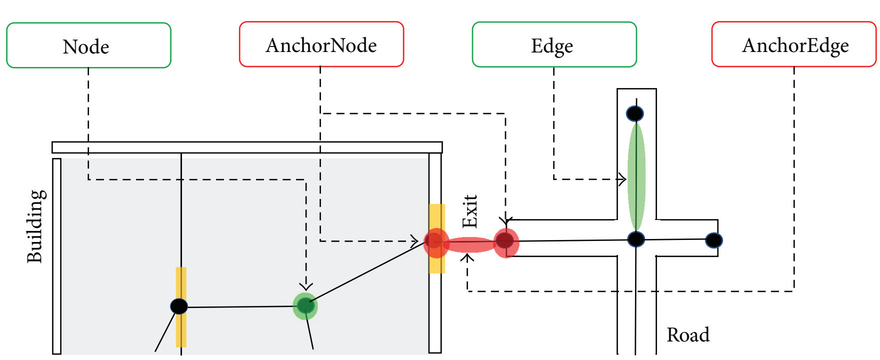


Figure 3: Spatial data fusion method based on topological relationships.

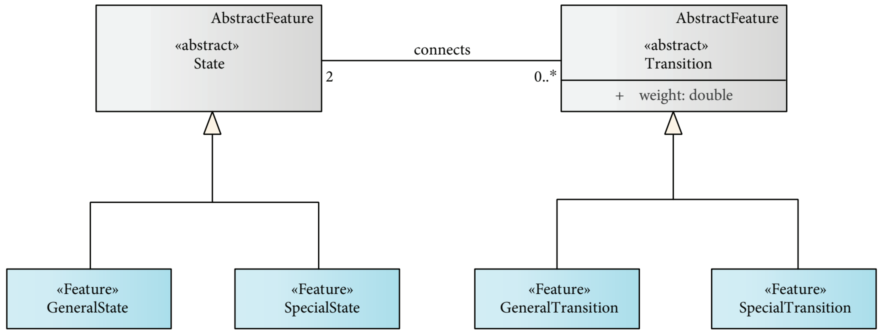


Figure 4: Topology data model: anchor portion.

Table 1: Required attribute information for *SpecialState* class.

Name	Type	M/O	Description
Id	String	M	Identifier
Type	NodeType	M	GeneralSpace/TransferSpace/AnchorSpace
RelatedSpaceId	String	M	Identifier of presented CellSpace or CellSpaceBoundary
ConnectedEdgeId	Set of edge	M	A set of edge to adjacent node
OriginPoint	Set of coordinates	O	Coordinates of node
RotationAngles	Set of value	O	CRS-converting parameter
RescalingFactor	Set of value	O	CRS-converting parameter
TranslationVector	Set of value	O	CRS-converting parameter

Table 2: Required attribute information for *SpecialTransition* class.

Name	Type	M/O	Description
Id	String	M	Identifier
L_Node	String	M	Identifier of left-side connected node
R_Node	String	M	Identifier of right-side connected node
Type	EdgeType	M	Connectivity/adjacency/anchor
RelatedSpaceId	String	M	Identifier of CellSpace or CellSpaceBoundary presented by connected node
LinkType	LinkType	O	Surface-ground/surface-underground/ground-underground
Activate	Boolean	O	Activate condition

and link the indoor spatial data, such as a building network, into outdoor spatial data, such as a street network. It consists of OriginPoint (x_0, y_0, and z_0), RotationAngles (α, β, γ, x, y, and z), RescalingFactor (s_x, s_y, and s_z), and TranslationVector (t_x, t_y, and t_z).

Each *GeneralTransition* in the database has an edge ID (Id), a left node connected to the edge (L_Node), a right node connected to the edge (R_Node), an edge type representing a topology relation, and a space ID (RelatedSpaceId). *SpecialTransition* has additional attributes, as shown in Table 2, which are LinkType and Activate_State data, in order to indicate the special type of connected network data, and thus, it can be utilized in various application services such as the opening and closing of entrances and exits.

3.3. Procedure Used to Generate Topological Relation-Based Data Fusion Model. Figure 5 illustrates the data that follow from the generation process of the proposed TRDFM. The input files are two GIS datasets including network datasets representing the centerlines of streets in an outdoor space and 3D solid GIS datasets representing a building and describing subunits within the building. Each solid representing a spatial unit has a label, which is a node abstracted from a solid in the TRDFM generated by the 3D Poincaré duality. All nodes representing spatial entities such as rooms, hallways, or entrances of a building are connected to each other based on their topological relations. The combined network graph is generated through the above processes as a logical node-relation graph (NRG) and geometric NRG [15]. The geometric NRG is the navigable data model of a building. The logical NRG is a pure graph representing the adjacency and connectivity relationships among the internal units of a building, and does not represent the geometric properties such as the distances among the units. However, the geometric NRG accurately represents their geometric properties so as to implement a network-based analysis, such as pathfinding.

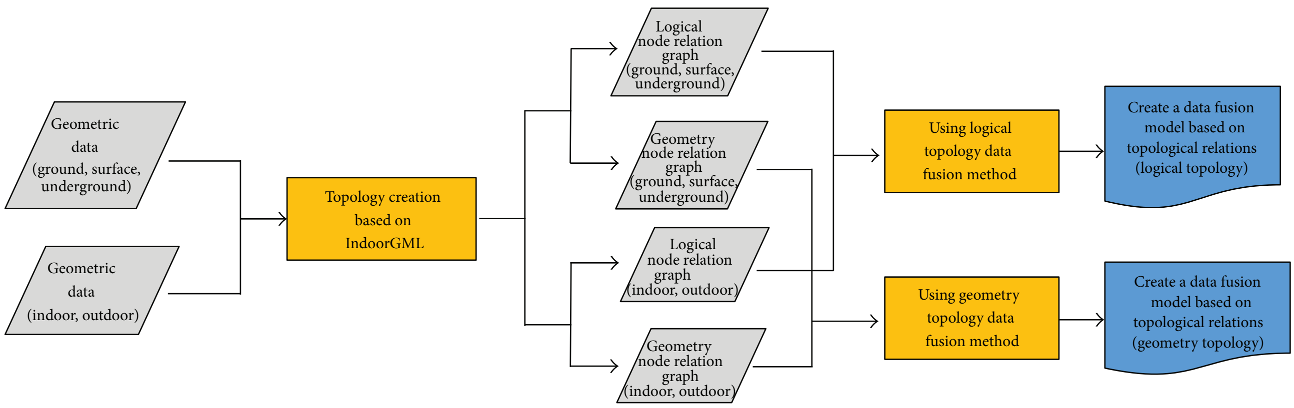


Figure 5: Flowchart of the proposed method.

As mentioned previously, geoinformation has always been a challenge because of the variety of data models, data formats, spatial resolutions, and methods of geometric representation. Despite the real world being a huge object, a geospatial dataset has been constructed, managed, and utilized individually according to the spatial scale of the real world, such as the ground/surface/underground or indoor/outdoor, as well as the purpose of LBS applications. In addition, the spatial dataset used for LBS applications is generated based on an optimal data model and data format according to their particular purpose. The 3D geometric modeling data formats for expressing an indoor space include 3D B-reps, CSG, IFC, and CityGML. These are largely divided into volume-oriented geometric modeling methods and surface-oriented geometric modeling methods. IFC is a representative volume-based data model. Therefore, the interior space geometry modeling of IFC is represented as a volumetric hexahedral geometry object. CityGML is representative surface-based geometric model. The geometry model of CityGML is a geometric element in a plane form, where each wall is represented, and each room is expressed as surrounded by the generated plane.

Figures 6 and 7 illustrate the method for generating topological data from 3D geometric data representing an indoor space generated by volume-oriented geometric models and surface-oriented geometric models. In the case of the geometric data of a surface-oriented data model, the spatial objects are divided into *NavigableBoundary* and *NavigableSpace* objects defined in IndoorGML. In the thin door model, a room is mapped to *NavigableSpace*, and a door is mapped to *NavigableBoundary*, which is mapped to the *State* object of the NRG represented by a node. A node of *NavigableBoundary* connects to the nearest *NavigableBoundary* node and connects to the adjacent *NavigableSpace* node. The edges represent the connectivity relationship of each door and the connectivity relationships of a door and a room. In the case of geometric data based on volume-oriented data models, which is called a thick door model, rooms are mapped to the *NavigableSpace* objects of the NRG realized by nodes in the TRDFM. In addition, doors are mapped to the *NavigableSpace* objects because the doors are represented as solid geometric objects in the geometric modeling data. Next, each of the nodes of *NavigableSpace* and the neighboring nodes are connected to the edge to show the connectivity relations of the spatial entities.

For road network data, as shown in Figure 8, the link generated along the centerline of the road corresponds to the *Transition* object, and the node generated at the road intersection point and the broken point corresponds to the *State* object and is utilized as the topological data.

The fusion of indoor spatial data and outdoor spatial data is achieved using *SpecialState* and *SpecialTransition* objects, as shown in Figure 9. *SpecialState* is represented as an *AnchorNode* object, and *SpecialTransition* is realized as an *AnchorEdge* object. *AnchorNode* is an anchor node located at the end of the road network that connects to the entrance of the building and represents the entrance of the building. *AnchorEdge* connecting the two *AnchorNodes* is integrated with the two datasets.

4. Experimental Implementation of the TRDFM

To evaluate the potential benefit of a topology-based data fusion model for developing a seamless service application through indoor and outdoor spaces, we conducted an experimental implementation of a system based on the TRDFM described in the last section. The dataset used for our implementation was drawn from a comprehensive GIS database of the National Geographic Information Institute in Korea, which is located in the study area of the University of Seoul. In this section, topological data were generated based on the TRDFM to integrate the building and street data. To investigate the convergence of different spatial datasets based on the generated NRGs, a shortest path search from an underground building space to a ground building space and a network analysis for a specific event occurrence scenario were carried out.

4.1. Experimental Spatial Datasets. The geometric datasets used in this study are shown in Figure 10. Figure 10(A) shows the 3D geometric data of 21C building (called building A) at the University of Seoul, Korea, generated from a building layer of the 1/5000 digital topographic map. Figure 10(B) shows the 3D geometric data of one of the underground buildings (called building B), also located at the University of Seoul (UoS), Korea. The 3D geometric data of 21C

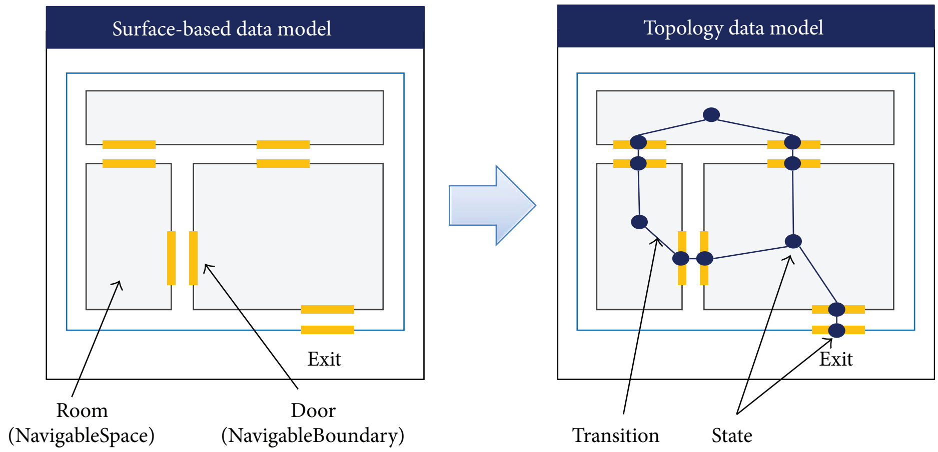


Figure 6: How to generate topology data using a surface-based data model.

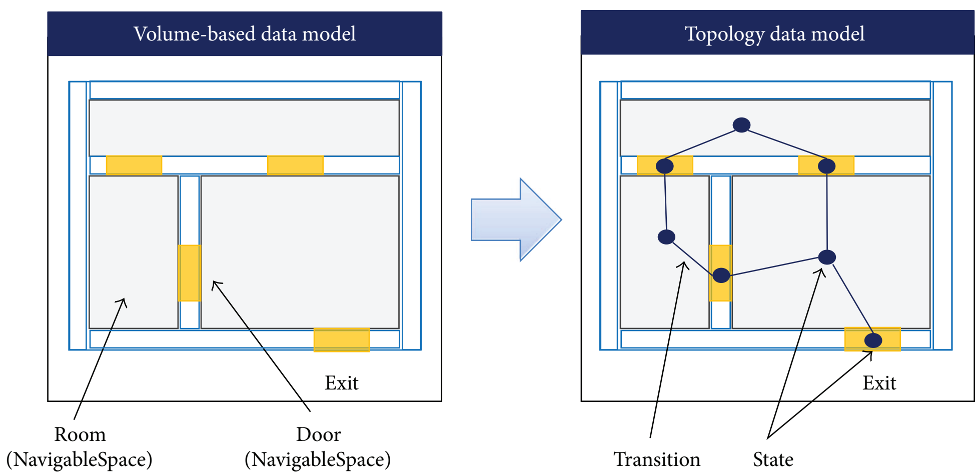


Figure 7: How to generate topology data using a volume-based data model.

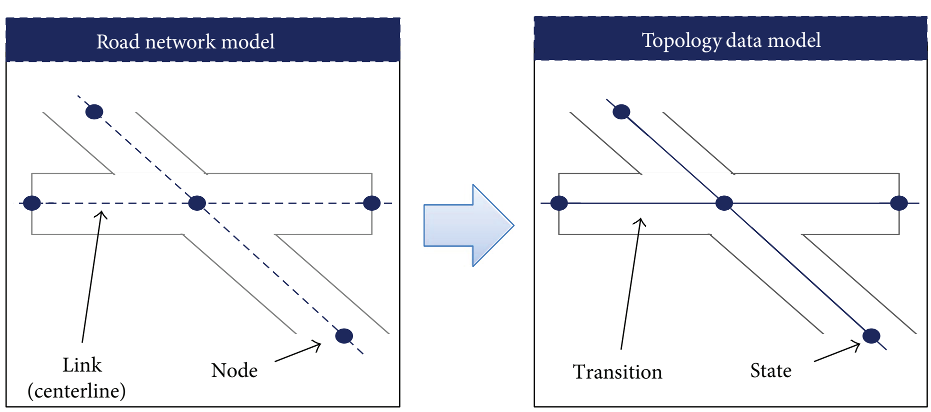


Figure 8: How to use topology data using the road network model.

building is formatted using the IFC geometric model, and the 3D geometry data of the underground building is generated in the CityGML data format.

The topological data of the study area were generated according to the procedure described in the previous section. In the case of 21C building, nodes in the topological data were constructed based on the thick door model, one of the volume-oriented data models used for each floor, from the first to the seventh, and the nodes were connected to construct an edge based on the connectivity relationships among the spatial entities. When the spatial relations of an indoor space are expressed using a node-edge structure, if the long

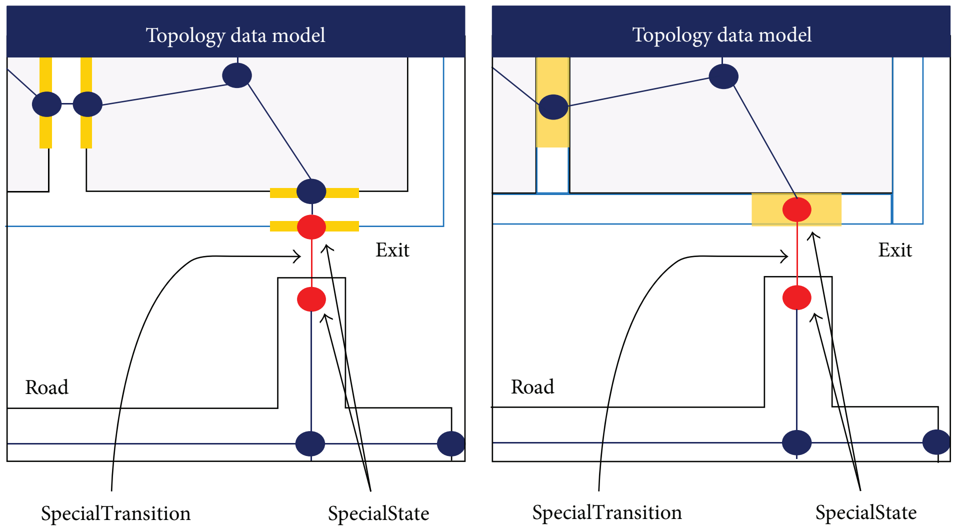
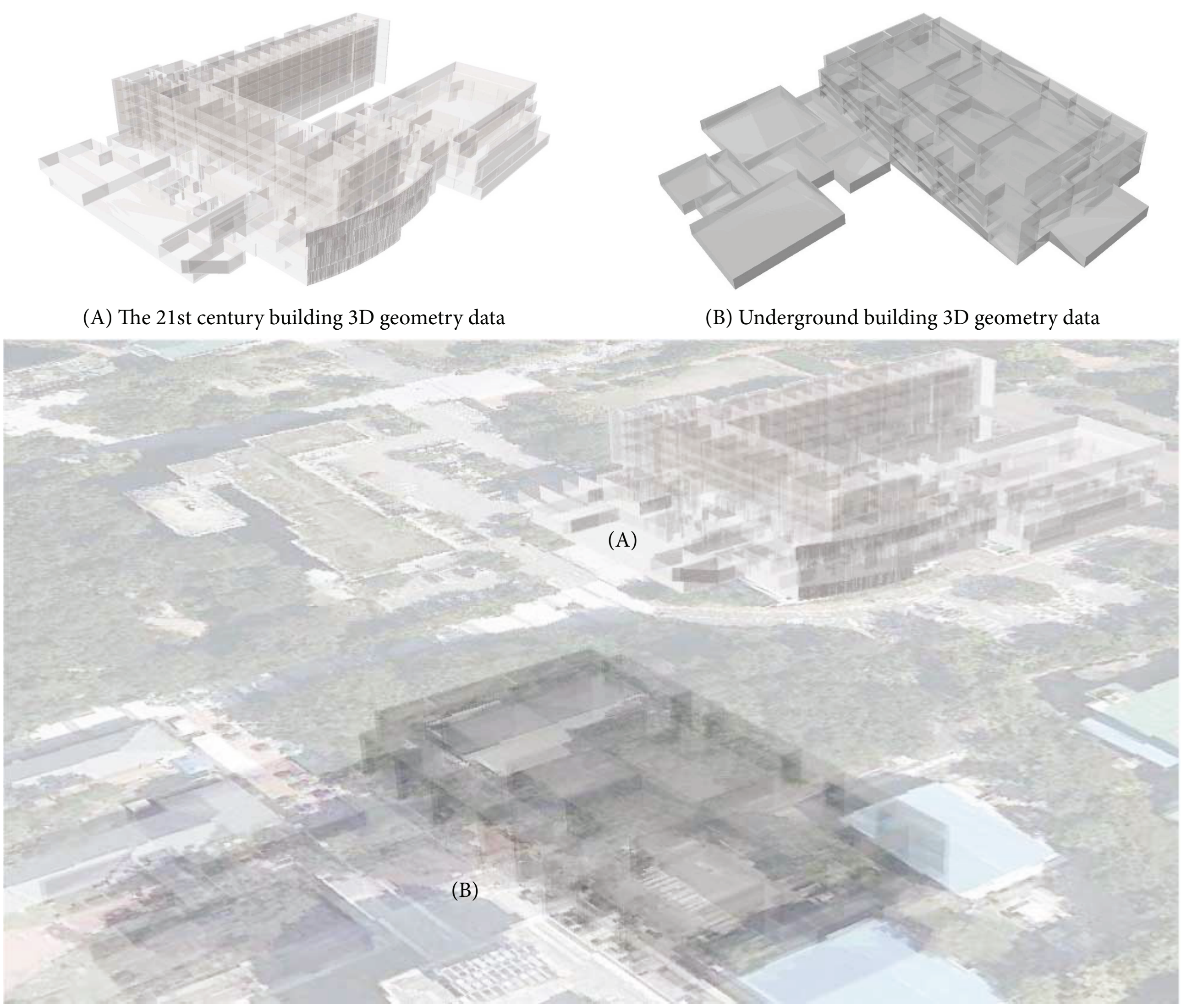


Figure 9: How to create *SpecialTransition* and *SpecialState*.



(A) The 21st century building 3D geometry data

(B) Underground building 3D geometry data

Figure 10: Geometric datasets of two buildings in the study area.

corridor space connected to the various rooms is expressed as a single node, the connection between rooms is defined through only one hallway node. In this case, the distance between the nodes is calculated incorrectly for network-based analyses. An effective spatial partitioning is needed to take into account the geometric aspects of the actual space and to derive more effective analysis results. In this study, we used a medial axis algorithm to generate effective topology data for the corridors. In the case of a long corridor, we used the medial axis algorithm to divide one space into several rooms, as shown in Figure 11. The medial axis was divided based on the door installed in each room and the built corridor nodes in front of the door. Figure 11(b) shows the results of the above process, called a geometric NRG in IndoorGML.

For the 3D vertical connectivity of each floor in the building, the nodes that have height information of each floor in the vertical movement space are constructed, and the edge connecting the constructed nodes representing a vertical movement space is constructed. The street network of the roads in the study area was constructed according to the method of topologic data generation based on the road network model. The topological data for the underground building are constructed based on the method described above, which are a logical NRG and a geometric NRG.

Figure 12 illustrates the combined network graph in a 2D viewer, which is integrated with the geometric NRG of buildings A and B, and the street network in the study area, using *AnchorEdges* and *AnchorNodes*. The combined network representing the connectivity relations among spatial entities can be used to provide seamless service applications through indoor and outdoor spaces. The experiment for network-based analysis will be described in the next section. In this experiment, nodes and edges are constructed with minimal attributes for connectivity analysis.

4.2. Connectivity Analysis Using TRDFM. In this study, we developed a demonstration program to visualize and analyze 3D network data by loading the generated topological data based on TRDFM. The demo program visualizes all of the loaded topological data in a 3D viewer, enables a data display through 3D rotation and movement, visualizes the results of the network analysis conducted by the user's selected node, and outputs the results. The topological data constructed for each layer are visualized in a 2D space, and the list of nodes and edges in the loaded topological data is provided and can be selected by the user. This allows users to conduct network analyses by selecting a specific space (node). The attribute data of the selected node or edge are also displayed.

Spatial data representing different spaces and data in different formats are expressed in the same topological model of the node-edge structure. All constructed topological network data are integrated through *AnchorEdge* objects. As a result, it is possible to analyze not only the network in each existing space but also the network connected to the other space. In this experiment, we implemented 3D spatial analyses by applying Dijkstra's algorithm to the combined 3D topological network data in the study area. A network analysis according to the shortest path search and the specific space event occurrence scenario was conducted to confirm the data fusion of different spatial datasets based on the topological relations among spatial entities.

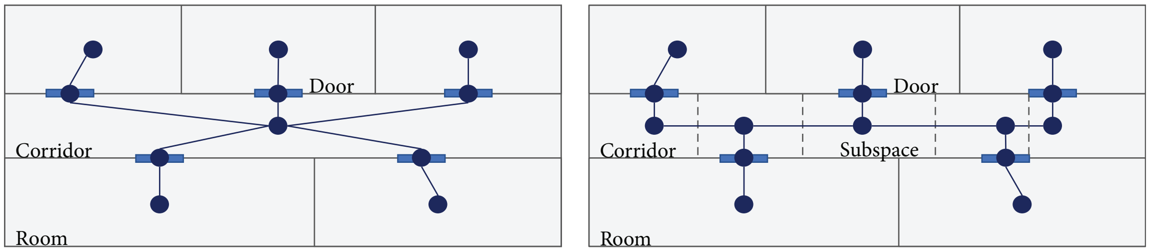
Dijkstra's algorithm is a shortest path search algorithm that finds the path that minimizes the sum of the costs from one node to another in a network [19]. This can be used to search for paths with the smallest cost (distance, etc.) from one specific space to another. According to the value of the edge having the cost data ranging from node to node, it is possible to search for a path based on the occurrence of an event such as the blocking or detouring of a specific space. The operation of the shortest path utilized by Dijkstra's algorithm is shown in Algorithm 1. The algorithm is implemented as follows: (1) find all edges connected to the starting node, (2) compare the connected edges and find the edge with the least cost, (3) make sure that the end node connected to the edge with the least cost has another path, and (4) compare the cost of the path and allocate the minimum cost. The algorithm searches for the shortest path by repeating the process until reaching the destination node.

In this experiment, the connection of the topological node is the connectivity relationship in a 3D continuous space. The shortest path search is performed by computing the minimum cost of the path of the 3D space using Dijkstra's algorithm based on the distance between nodes in the 3D space, that is, the distance property data of the edge, as described in Algorithm 1. The results of the shortest path search implemented in the network visualization and analysis program developed in this study are shown in Figure 13.

To verify the connectivity relationships of different spatial datasets based on the topological relations, we created the following setup: node 40021 (type, room) of the first basement floor of a virtual underground building is set as the start node and node 50043 (type, room) in 21C building as the destination node. As shown in Figure 13, node 40021 as the starting node is connected to the entry point of the underground building (building B), which is the anchor node 40053 (type = VerticalWay/anchor). It is connected to a node of the nearest road segment, which is anchor node 50076 (type = road/anchor). Next, it is also possible to use node 50082 (type = road/anchor) in the street network to connect to building A. The anchor node is connected to the final destination, node 50043, through the nodes on the first floor of the 21C building. The distance between the selected start and destination nodes is 138.2 m, and the minimum cost of the route is calculated. The derived shortest path is visualized in the 3D viewer of the demonstration program, as shown in Figure 13.

As a result of the shortest path search, the anchor node (40053) of building B and the anchor node (50076) of an underground building are connected to each other through an anchor edge (4005350076). The anchor node (50082) of the road and the anchor node (50045) indicating the entrance of 21C building (building A) were connected through the anchor edge (5004550082). Based on this result, the connectivity through the same topological models of different spatial data is confirmed.

The second network analysis in this experiment for data fusion based on the topological relations was conducted to



(a) Network from origin space (b) Network from subspace

Figure 11: Example of topology data construction through spatial division.

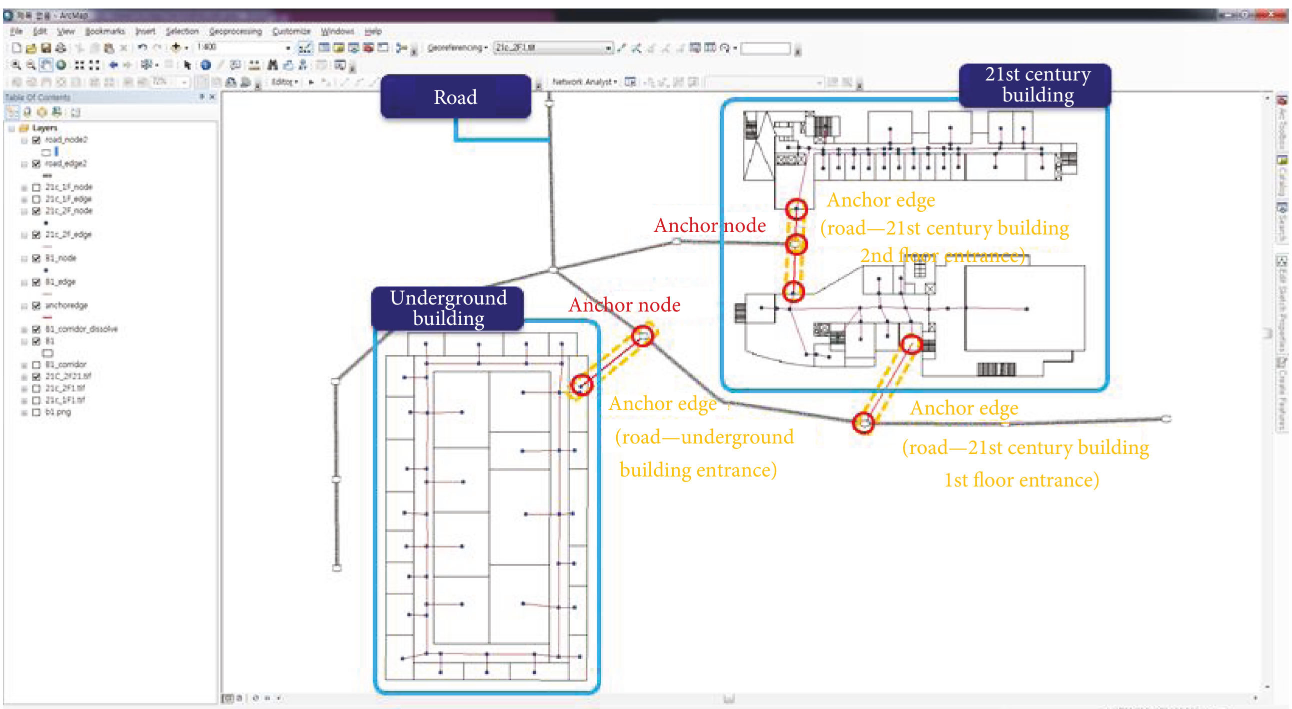


Figure 12: Topological data based on the TRDFM in the study area.

$(i \neq j \neq k \neq l)$

(a) Compare the costs of the edges connected to the start node(N_i)
(b) Add node(N_j) connected to the edge(E_i) with the least cost to the path
(c) The cost(C_i) of the edge(E_i) is allocated to the added node(N_j)
(d) Performs (a) operation starting from node(N_j)
(e) Add node(N_k) connected to the edge(E_j) with the least cost to the path
(f) The cost of the route (C_k=C_i+C_j) is allocated to the added node(N_k)
(g) Identify different paths between node(N_i) and node(N_k)
  ($g1$) Compared with the cost of another route(C_l) and the cost of allocated route(C_k)
  ($g2$) Reallocate the smaller cost to the node(N_k) with the minimum cost (C_k:=(C_l) *or* (C_k))
(h) Repeating (a) ~ (g) operations up to the destination node, calculating the minimum cost of the destination node

Algorithm 1: Dijkstra's algorithm operation.

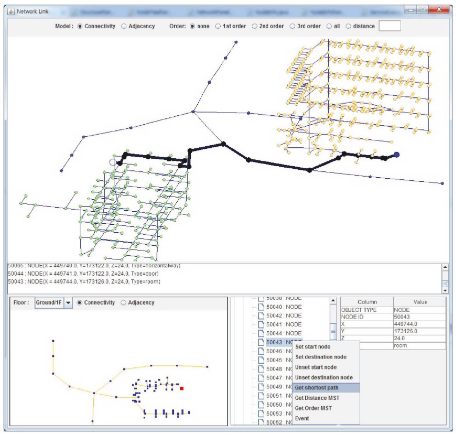


Figure 13: Shortest path search result screen.

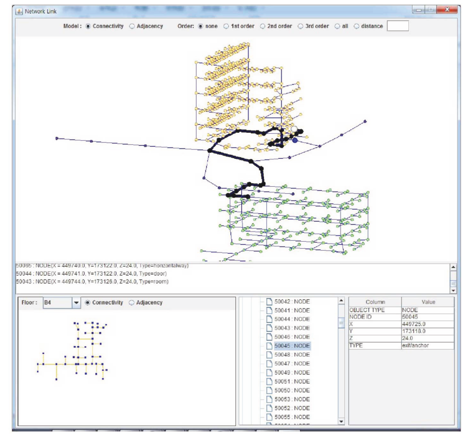


Figure 14: Shortest path search result screen showing event occurrence.

SetEvent (Graph, s)
in **_Graph G = (Node N, Edge E)_**
set node $n_s(x,y,z) \in N$
Out **distance of edge**
$d(n_i, n_j)$: *distance of edge* $(n_i, n_j) \in \boldsymbol{E}$
s, i, j : integer
Begin
Choose a Node $n_i \in \boldsymbol{N}$
FOR $j = 1$ to n
IF $(n_i, n_j) \in \boldsymbol{E}$ then
$d(n_i, n_j) < -\infty$
End
End

Pseudocode 1: Pseudocode for event generation algorithm.

determine the shortest path search according to the event occurrence within a specific area. A network analysis is used to search for the shortest path as determined based on the assumed scenario of the event, such as fire in a specific space, using Dijkstra's algorithm. With Dijkstra's algorithm, which calculates the minimum cost, the cost of all edges connected to the event space (node) at the time of the event occurrence is increased to the maximum value. The pseudocode of the event generation algorithm used to implement this is shown in Pseudocode 1.

As shown in Figure 14, the network analysis at the event occurrence has the following settings used to test the different spatial data connectivity implementations based on the topological relationships. The network analysis was conducted by generating an event at the entrance anchor node of 21C building where the ground building and road data are connected. The event scenario assumes that a fire occurred at the south entrance (node 50045) on the first floor of 21C building and that the second-floor doorway should be used (nodes 60076 and 60077). The search is for the shortest path from a specific room (node 40021) on the first basement floor of building B to a specific room (node 50043) on the first floor of building A.

As a result, the shortest path to the destination node 50043 was searched through the anchor node (60077), which is the entrance to the second floor of the western part of building A, without passing through the south entrance of the first floor. Likewise, the connectivity through the same topological relationships of different spatial data has been confirmed through an implementation of the network analysis, ranging from underground to the surface and to the ground. By setting the property values of the anchor edge connecting different spatial data, it is possible to utilize service applications such as a fire occurrence or opening/closing of the entrance/exit.

The result of the shortest path search using the network analysis based on the topology relation conducted in this experiment can be visualized along with the existing independent 3D geometric data, as shown in Figure 15. Independent from the geometric data, but based on the spatial relationships, different data can be fused to conduct such network analyses. Visualization is possible by displaying the results together with geometry datasets.

In this experiment, different geometric data are expressed in the same topological model according to the proposed convergence method. Through the experimental implementation, it is possible to provide a network analysis and application service linked to the existing independent data, and the analysis results can be visualized as geometric data to help the user's understanding.

5. Conclusion

Although the real world is a huge object, geospatial datasets have been constructed, managed, and utilized individually according to the spatial scale of the real world, such as the ground/surface/underground or indoor/outdoor, and the purpose of LBS applications. In addition, the spatial datasets used for LBS applications are generated based on an optimal data model and data format in terms of their particular purpose. Such duplicated geospatial datasets and geographical feature-based GIS data cause serious problems in terms of financial issues, compatibility among LBS systems, and data integration among various geospatial datasets independently

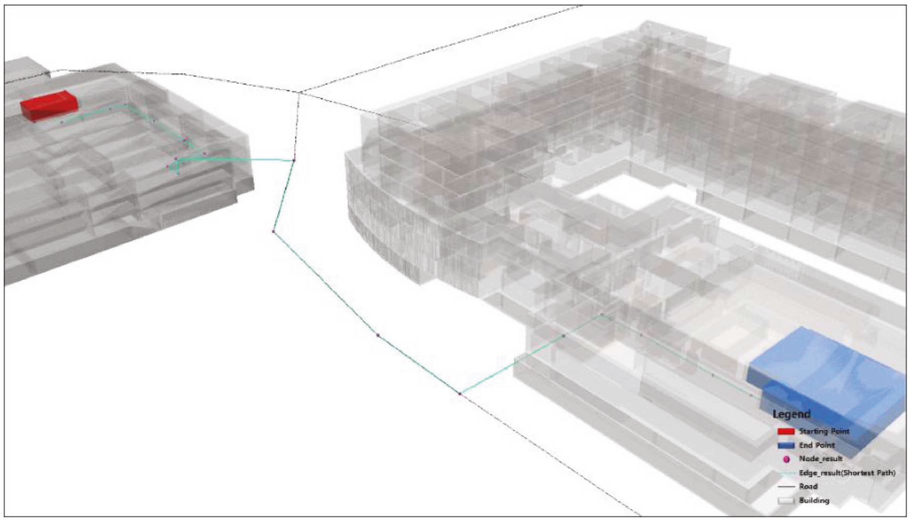


Figure 15: Visualization of geometry data and results of network analysis.

generated for different systems. These problems need to be addressed to better understand the interdependencies of major urban infrastructure that affect a wide range of modern urban societies and to analyze the flows and connectivity. To solve this problem, research has been conducted to fuse information generated using various methods and data models. This study proposed the development of a spatial data fusion model called the topological relation-based data fusion model (TRDFM) using topological relations among spatial objects in order to utilize different geospatial datasets and different data formats.

To realize the connectivity of different spatial data based on the topological relations using the proposed convergence method, we implemented a demo program to visualize topological datasets and conduct a 3D network analysis using Dijkstra's algorithm. In this manner, we implemented data connectivity based on topological relations. It is possible to query various 3D spatial data through connected network data through the fusion of different formatted geometric datasets based on topological relations. It is also possible to link indoor pedestrian navigation used in a car navigation system and indoor spaces in an outdoor space. In addition, a network analysis and application services are possible regardless of the scale of the space, such as route guidance from one subway station to another subway station, to ground transportation, or to the interior space of a building.

The proposed TRDFM contributes to the literature in significant ways because current geographical information systems still have huge problems in using differently formatted data in the same application. The most common method remains data fusion through a geometric data conversion. However, this study has several limitations that need to be addressed. First, efficient data utilization and various application services should be provided by expanding various 3D spatial query functions based on a topology-based data fusion. In addition, for the user's understanding and convenience, it will be necessary to improve the visualization functions so that the network analysis results based on the performed topological relations can be visualized along with the geometric data.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

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