This research is motivated by the need for 3D GIS data models that allow for 3D spatial query, analysis and visualization of the subunits and internal network structure of ‘micro-spatial environments’ (the 3D spatial structure within buildings). It explores a new way of representing the topological relationships among 3D geographical features such as buildings and their internal partitions or subunits. The 3D topological data model is called the combinatorial data model (CDM). It is a logical data model that simplifies and abstracts the complex topological relationships among 3D features through a hierarchical network structure called the node-relation structure (NRS). This logical network structure is abstracted by using the property of Poincaré duality. It is modelled and presented in the paper using graph-theoretic formalisms. The model was implemented with real data for evaluating its effectiveness for performing 3D spatial queries and visualization.

**Keywords:** 3D GIS; Topological data model; Poincaré duality; Combinatorial data model

1. Introduction

As the increasingly complex tasks in many geo-scientific and urban applications require the capability to analyse and visualize spatial features and their relationships in 3D space, three-dimensional geographical information systems (3D GIS) have become an important research area in the last decade or so (Houlding 1994, Pilouk 1996, Königer and Bartel 1998, Shioda 2001, Zlatanova et al. 2002, Coors 2003, Kwan and Lee 2004). Since conventional 2D GIS data models are inadequate for handling 3D geometry and performing 3D spatial analysis, the development of 3D GIS data models has attracted much interest in recent years (e.g. Wei et al. 1998, Ramos 2002, Tse and Gold 2003). The intention behind this interest is to improve the capability of GIS in handling 3D geometry, analysing 3D topological relations, performing 3D spatial queries, and visualizing the data.

Recently developed 3D GIS data models, however, largely treat geographical features such as buildings as indivisible entities without internal partitions or subunits (with the exception of Billen and Zlatanova 2003). Data models based on this conceptualization of 3D features pose several difficulties when applied in...
cadastral systems or emergency response. First, cadastral data (such as fire or land use code) may vary among the subunits or rooms within a building. Data models for 3D features need to be able to represent these attribute data at the subunit or substructure level. They cannot ignore the micro-spatial complexities and variations in land use or ownership within the structure. Second, to be able to perform 3D spatial queries like ‘Which rooms are above and below the rooms owned by company X?’ or to visualize the spatial relationships among the subunits within a building, cadastral information systems need to adequately represent the topological relationships among the subunits within a building (Lee 2001, 2004a,b, Lemmen and van Oosterom 2003). Third, effective emergency response to incidents within an urban structure requires effective routing not only on the urban transport network but also within the structure itself (Kwan 2003, Kwan and Lee 2005). Knowledge about the connectivity structure within a building (e.g. corridors) is essential for performing various network-based analyses that facilitate rescue operations (such as shortest path analysis). But existing 3D GIS data models lack this capability because they do not explicitly represent the network structure that determines the movement of people within a building.

This research is motivated by the need for 3D GIS data models that allow for 3D spatial query, analysis and visualization of the subunits and internal network structure of ‘micro-spatial environments’ (which means the 3D spatial structure within buildings). It explores a new way of representing the topological relationships among 3D geographical features such as buildings and their internal partitions or subunits. The 3D topological data model is called the combinatorial data model (CDM). It is a logical data model that simplifies and abstracts the complex topological relationships among 3D features through a hierarchical network structure called the node-relation structure (NRS). This logical network structure is abstracted by using the property of Poincaré duality. It is modelled and presented in this paper using graph-theoretic formalisms.

The rest of the paper is organized in the following manner. The next section (section 2) reviews recent research on 3D topological data models. Section 3 outlines the basic elements of the CDM, which include Poincaré duality, graph-theoretic formalisms and hierarchical network structure. Section 4 describes how these basic elements are used to derive the CDM for representing the topological relationships among 3D features in micro-spatial environments. Section 5 of the paper discusses an experimental implementation of the new 3D GIS data model and demonstrates how it can be used to perform spatial and thematic analysis and 3D visualization using real data on the campus area of the Minnesota State University at Mankato.

2. 3D topological data models

Topological data models explicitly represent the topological relationships among geographical features (the terms ‘feature’, ‘object’ and ‘spatial unit’ are used interchangeably in this paper). These relationships include connectivity, adjacency, inclusion and intersection (Egenhofer and Herring 1990, van Oosterom 1993, Zlantanova 2000). In the last decade or so, various topological models for representing 3D objects and their spatial relationships have been developed. The most relevant types of topological data models in the context of this research are feature-based 3D data models (e.g. Pigot 1992, Pigot and Hazelton 1992, Rikkers et al. 1994). These models are largely based on boundary representations or B-Rep (Raper 2000)—although there are feature-based 3D data models that used other
representational schema (e.g. object-oriented models developed by de la Losa and Cervell 1999 and Shi et al. 2003).

In boundary representation (B-Rep) models, a 3D object or feature is represented by a collection of faces that are glued together so that they form a complete, closing surface around the object (Mäntylä, 1988). Based on the fact that higher-dimension geometries are bounded by objects of lower dimensions, a B-Rep maintains an explicit ‘tree’ of boundaries: a solid is bounded by surfaces; a surface is bounded by edges; an edge is bounded by vertices (Corbett 1979, LaCourse 1995, Worboys 1995). A B-Rep therefore has a hierarchical data structure that characterizes 3D objects in terms of four primitives: point, edge, face and volume (Hoffmann 1989, Li 1994). Examples of topological data models based on B-Rep include the 3D formal data structure (FDS) developed by Molenaar (1990), the GOCAD system developed by Mallet (1990), the tetrahedral network (TEN) introduced by Pilouk (1996), the simplified spatial model (SSM) designed by Zlatanova (2000), and the urban data model (UDM) developed by Coors (2003). Besides these data models, topological relations among 3D objects in many 3D urban models, computer-aided design (CAD) and visualization systems are also handled by variants of the B-Rep model (e.g. Tempfli 1998, Holtier et al. 2000, Stoter and Zlatanova 2003, Stoter and van Oosterom 2002).

These B-Rep topological data models have limitations when they are used to represent 3D features or analyse their spatial relations in 3D micro-spatial environments. One of the difficulties is the required computational efficiency for maintaining the topological consistency of the model (van Oosterom et al. 2002). For instance, in most of these feature-based data models (e.g. Rikkers et al. 1994, Billen and Zlatanova 2003) topological relationships are handled by a geometric representation of the cells in a cell-complex and their local neighbourhoods. Local neighbourhood relations are defined in terms of their boundary and co-boundary cells. These 3D data models are inefficient for maintaining topological consistency because they require complex geometric computation that involves the geometric properties of the local neighbourhood topology and ordering of 3-cell (3D object) complexes. Even if the computational problem can be ameliorated, these 3D data models are still too complicated for representing topological relationships because the neighbourhood data for a 3-cell complex consists of a face and edge pair, while only half of the edge data is used for 2-cell complexes (Pigot 1992, 1995). Further, B-Rep topological data models use an enormous amount of data to represent complex 3D features such as the internal structure of a building. Data storage and handling may become an issue when using these data models.

In addition, since topological relations are handled in these B-Rep data models through a ‘tree’ of boundaries, and connectivity relationships among 3D features are not explicitly stored or readily available, these models are inadequate for applications that require network-based analysis. Additional means are often needed for improving the efficiency of 3D spatial analysis when using B-Rep data models—for example, three additional proximity tables for each 3D feature are added to describe the relationships of ‘around’, ‘below’, and ‘above’ in Holtier et al. (2000). However, network-based analyses that focus on the movement of people and the problem of spatial access within an urban structure (e.g. optimal route analysis) are still difficult to undertake even with these additional tables—since the connectivity relationships among 3D features still have to be derived from the ‘tree’ of boundaries (Lee 2004a). This becomes a major problem when dealing with
emergency response situations such as one in which paramedics need a quick solution in finding the fastest or shortest path to reach a particular room in a building with complex internal structure.

3. Three elements of the combinatorial data model

To address the limitations of current 3D feature-based topological data models for micro-spatial applications, a different approach for representing the topological relationships among 3D objects is adopted in this study. Its fundamental building block is a hierarchical network structure that simplifies, abstracts, and represents the subunits and their connectivity relations within a building. This network structure is called the node-relation structure (NRS). It is the basis of the 3D topological data model, called the combinatorial data model (CDM) developed in this study. This section describes the three basic elements involved in deriving the NRS and the CDM: (a) Poincaré duality; (b) graph-theoretical formalisms; and (c) a hierarchical network structure.

3.1 Poincaré duality

Poincaré duality is used in this study to derive topological relations among a set of 3D features or objects. Its point of departure is the dual graph, which is constructed by assigning a dual vertex to each polygon in the original graph and by joining a pair of dual vertices with a dual edge if the corresponding original polygons share an edge (which means that they are adjacent to each other). In a dual graph, 3-cells (3D objects such as a cube) in primal space are transformed to 0-cells in dual space, and 2-cells (a common polygon shared by two cubes) are transformed to 1-cells in dual space (Corbett 1985, Molenaar 1998). Using this property of the duality transformation, 3D objects in primal space can be transformed to nodes (or vertices) in dual space, and topological relationships among 3D objects can be transformed to links (or edges) between nodes in dual space. In these representational schema, nodes are abstractions of 3D objects in primal space, and links are abstractions of the topological relationships among 3D objects.

Figure 1 provides an example of the duality transformation in 3D space. Solids $s_1$ and $s_2$ in the primal are replaced by vertices $s_1'$ and $s_2'$ in the dual. Polygon $f_1$ shared by solids $s_1$ and $s_2$ is transformed to edge $f_1'$, which links two vertices $s_1'$ and $s_2'$ in the dual model and represents the topological relations between 3D objects $s_1$ and $s_2$. The dual graph abstracted from the 3D features or objects (e.g. rooms within a building) and their spatial relations is the NRS. Advantages of using Poincaré
duality include: (a) all topological properties are preserved under the duality transformation; (b) topological consistency in the 3D data model is effectively maintained; and (c) topological relations among 3D objects can be represented in dual space with sets of nodes and links. It greatly improves computational efficiency because it avoids the need to deal with 3D objects directly and thus the associated problem of complex geometric computation. It also helps resolve the difficulty associated with data storage.

3.2 Graph-theoretic formalisms

Topological relationships among 3D features or objects abstracted in the dual graph can be formalized using graph theory. A graph is formalized through specifications of three primal classes: vertex, edge and graph (Car and Frank, 1995; figure 2). A graph \( G=(V, E) \) consists of two sets: a finite set \( V \) of elements called vertices and a finite set \( E \) of elements called edges (Weiss 1994). Each edge is identified with a pair of vertices \( (v, w) \), where \( v, w \in V \). Graph \( G \) with vertex set \( V=\{v_1, v_2, \ldots, v_n\} \) and edge set \( E=\{e_1, e_2, \ldots, e_m\} \) can be described by means of matrices. One such matrix is the \( n \times n \) adjacency matrix \( A=[a_{ij}] \), where \( a_{ij}=1 \) if \((v_i, v_j) \in E\), and \( a_{ij}=0 \) if \((v_i, v_j) \notin E\). Another is the \( n \times m \) incidence matrix \( B=[b_{ij}] \), where \( b_{ij}=1 \) if \( v_i \) and \( e_j \) are incident, and \( b_{ij}=0 \) otherwise (Chartrand and Lesniak 1996). As these formalisms can be used to effectively represent topological relations (such as adjacency) and the NRS is a dual graph, formalization of the CDM is greatly facilitated using graph-theoretic notations.

3.3 Hierarchical network structure

Hierarchical network structure is often used to represent transportation networks, where high-level links (or edges) are the major highways connecting cities, while low-level links are the distributors or arterials that connect localities with access points to high-level routes (Mainguenaud 1995, Mainguenaud and Simatic 1992). Similarly, the connectivity relationships among the 3D objects in a building can be represented as a multi-level network. Figure 3 presents the multi-level connectivity relations in a hierarchical network. At the first level, connectivity relations are represented with three master_nodes and two edges, where a master_node represents an abstraction of the network on a particular floor and an edge describes the vertical connectivity between two floors (figure 3(a)). These nodes or edges are located at the stairways or elevators. Figure 3(b) shows the second-level network of a first-level master_node. This second-level network describes the connectivity relations on a particular floor and is represented by second-level edges and nodes. The second-level master_nodes

```java
class Vertex {
    Int Vertex_ID;
    ...
};

class Edge {
    Int Edge_ID;
    Vertex initial_vertex;
    Vertex end_vertex;
    ...
};

class Graph {
    Int Graph_ID;
    Vertex ArrayVertex = new Vertex[];
    Edge ArrayEdge = new Edge[];
    ...
};
```

Figure 2. The three primal classes of a graph.
are defined again at the third level, which describes the connectivity relations within a subunit of the building (figure 3(c)). Since connectivity relations are abstracted from the lower levels in one direction, a hierarchical network has a tree structure. The performance of spatial queries in 3D data models is greatly improved using this structure.

4. The combinatorial data model

This section describes how the CDM is derived based upon the three basic elements outlined above.

4.1 Defining the topological relations among 3D features

To define the topological relations among the geographical features or spatial units within a 3D micro-spatial environment such as a building, several assumptions about the nature of these spatial units are made. First, the spatial units in question are the residential/office units within a building. Second, these spatial units are represented as 3D spatial objects or features with flat top and bottom faces that are parallel to the \( x, y \)-plane (horizontal) and perpendicular to the \( z \)-axis (vertical). Third, the side faces of these spatial units are parallel to the \( z \)-axis. Fourth, face adjacency is considered as an adjacency relation between two 3D objects. In general, adjacency relationships can be determined by the results of combining two objects using an intersection operation. This means that the ordinary Boolean intersection of two 3-cells may produce a solid, a plane, a line, a point, or the null set. When the result is a plane, the topological relationship between two 3D objects is face adjacency.

Suppose the problem is to represent the topological relationships among the 3D units within a small building. The building has two storeys and each storey has four rooms, a hallway and a stairway (six 3D spatial units) as shown in figure 4. The 3D units are labelled from \( s_1 \) to \( s_{12} \). Spatial unit \( s_5 \) in the second floor has adjacency relationships with spatial units \( s_4 \) and \( s_6 \) on the same floor, as well as with spatial unit \( s_{11} \), which is on the first (different) floor. Adjacency relationships between a particular spatial unit and other units are the combination of adjacency relations in horizontal directions and adjacency relations in vertical directions.

Adjacency relationships can therefore be defined in two steps (figure 4). In the first step, adjacency relations among the 3D units in horizontal directions are derived from the topological relationships between the 2D polygons on a floor. The adjacency relations on floor \( i \) of the building can be described as graph \( Gh_i = (V(Gh_i), \)

![Figure 3. The multi-level connectivity relations in a hierarchical network.](image-url)
adjacency relations among the 3D units in vertical directions are defined by the layer-overlay function implemented in 2D GIS. The adjacency relationships between the floor \( j \) and floor \( j-1 \) of the building can be described as graph \( G_{vj} = (V(G_{vj}), E(G_{vj})) \), while \( j = 1 \) to \( n-1 \). By combining these two graphs, a graph that includes all topological relations in both horizontal and vertical directions—and hence all incidences in the NRS—is obtained. Figure 5 depicts the conceptual framework behind these procedures. The adjacency relationships among the 3D units within a 3D topological data model would be defined as:

\[ G = (V(G), E(G)) \]
building can therefore be described as follows.

For adjacency relationships, graph \( G = G_i \cup G_j \)
while, \( G = (V(G), E(G)); \ i = 1 \ to \ n; \ j = 1 \ to \ n - 1 \)

Graph \( G=(V(G), E(G)) \) represents all the adjacency relationships among the spatial units within the building in the example. It is a superclass of graph \( H=(V(H), E(H)) \), which represents connectivity relations because of \( V(H) \subseteq V(G) \) and \( E(H) \subseteq E(G) \). Graph \( H \) is therefore defined from graph \( G \) using the given feature attribute information for polygons and arcs in 2D. The outcome of these procedures is the adjacency and connectivity relationships among the 3D features (or spatial units) in the building.

### 4.2 Deriving the node-relation structure

Based on these definitions of topological relations in 3D space, the NRS can be derived through abstracting the sets of nodes and edges (unordered pairs of distinct nodes) from the 3D features or spatial units inside a building (figure 6). As shown in figure 6(b), one node set and two edge sets are defined in this example, which is formalized as graph \( G=(V(G), E(G)) \), where \( V(G)=N \) and \( E(G)=EA \), and graph \( H=(V(H), E(H)) \), where \( V(H)=N \) and \( E(H)=EC \). Graph \( G \) represents the adjacency relations among the 3D objects in the building, and graph \( H \) represents the connectivity relations among the 3D spatial units. Node set \( N=\{n_1, n_2, n_3, \ldots, n_{12}\} \) is an abstraction of the 3D features or spatial units in the building. One edge set represents the adjacency relationships, \( EA=\{ea_1, ea_2, \ldots, ea_n\} \), between the 3D units, and the other set represents the connectivity relations, \( EC=\{ec_1, ec_2, \ldots, ec_m\} \).

In the node set, the node \( n_1 \) in the NRS corresponds to the 3D unit \( s_1 \) of the building; node \( n_2 \) to \( s_2 \), node \( n_3 \) to \( s_3 \), and so on.

---

**Figure 6.** A building (a) and its node-relation structure (b).
In the EA set, the adjacency relations between spatial units $s_1$ and other spatial units are $ea_1=(n_1, n_2)$, $ea_2=(n_1, n_6)$, and $ea_3=(n_1, n_7)$, and the adjacency relations between object $s_2$ and other objects are $ea_4=(n_2, n_3)$ and $ea_5=(n_2, n_8)$. Because the NRS is defined as an undirected graph, $n_1$ is adjacent to $n_2$ and $n_2$ is adjacent to $n_1$, which is the edge $ea_1=(n_1, n_2)=(n_2, n_1)$. From this process, the set of edges can be defined ($n=22$). The NRS with node set $N=\{n_1, n_2, n_3, \ldots, n_{12}\}$ and adjacency relation edge set $EA=\{ea_1, ea_2, ea_3, \ldots, ea_{22}\}$ can be described by an adjacency matrix and an incidence matrix.

In the connectivity edge set ($EC$), the connectivity relations between unit $s_1$ and other units are $ec_1=(n_1, n_6)$ and $ec_2=(n_1, n_7)$, and the connectivity relations between object $s_6$ and other objects are $ec_3=(n_2, n_6)$, $ec_4=(n_3, n_6)$, $ec_5=(n_4, n_6)$, and $ec_6=(n_5, n_6)$. The set of edges can be defined ($m=11$) and is described with dark solid lines in figure 6(b). In the same manner, the NRS with node set $N=\{n_1, n_2, n_3, \ldots, n_{13}\}$ and the connectivity relation edge set $EC=\{ec_1, ec_2, ec_3, \ldots, ec_m\}$ can be described by an adjacency matrix and an incidence matrix.

To represent these topological relations using matrices, the adjacency matrix that represents adjacency relationships (matrix $A=[a_{ij}]$) can be combined with the adjacency matrix that represents the connectivity relationships (matrix $C=[c_{ij}]$) using a matrix addition operation (figure 7). The combined matrix (matrix $AM=[am_{ij}]$) describes both types of topological relationships between the nodes in dual space. In other words, matrix $AM=[am_{ij}]=A+C$ is the combined adjacency matrix of the NRS that represents the topological relationships between 3D spatial units or features (figure 7). Similarly, the two incidence matrices (matrix $B=[b_{ij}]$ and matrix $D=[d_{ij}]$) can be combined using a UNION Boolean operation. The combined incidence matrix (matrix $IM=[im_{ij}]$) describes all incidences of the NRS when the defined graphs are equivalence classes. However, graphs $G$ and $H$ are not equivalence classes because the collection of edge sets does not meet the required properties of equivalence classes. Their union is the domain and the intersection of the two distinct sets is an empty set. In other words, because the set of edges $E(H)$ representing the connectivity relations is a partition of the set of edges $E(G)$ representing the adjacency relations, the domain of the combined set of edges is equal to the domain of the set of edges $E(G)$.

\[
\begin{align*}
AM &= \left[\begin{array}{cccc}
am_{ij}
\end{array}\right] \\
AM &= \left[\begin{array}{cccc}
am_{ij}
\end{array}\right] = A + C \\
&= \left[\begin{array}{cccc}
a_{ij}
\end{array}\right] + \left[\begin{array}{cccc}
c_{ij}
\end{array}\right]
\end{align*}
\]

where,

\[
am_{ij} = \begin{cases} 
1 & \text{if } n_i n_j \in EA \\
2 & \text{if } n_i n_j \in (EA \cap EC) \\
0 & \text{if } n_i n_j \notin EA
\end{cases}
\]

\[
IM = \left[\begin{array}{cccc}
im_{ij}
\end{array}\right]
\]

where,

\[
im_{ij} = \begin{cases} 
1 & \text{if } n_i \text{ and } t_j \text{ are incidence} \\
0 & \text{otherwise}
\end{cases}
\]

(a) Adjacency matrix \hspace{2cm} (b) Incidence matrix

Figure 7. The combined adjacency and incidence matrices.
4.3 Deriving the hierarchical network structure of the NRS

To derive the hierarchical network structure of the NRS, the data model developed by Mainguenaud (1995) and Mainguenaud and Simatic (1992) for handling 2D multi-level networks—which is based on graph-theoretic formalisms and the object-oriented paradigm—is extended and applied to non-planar graphs in 3D space in this study. Based on this extended model, the hierarchical network structure of the NRS is derived by consolidating its sub-networks (or sub-graphs) to high-level nodes (figures 8 and 9). The basic components of the hierarchical network structure are node, edge and master_node. A master_node, which is an abstraction of a sub-network $G(S) = (V(S), E(S))$ and connect_edges, represents the connectivity relationships among the spatial units on a particular floor of the building. It is inherited from node, while a sub-network is inherited from network. The highest level of the network structure is graph $G(M) = (V(M), E(M))$ (as shown in figures 8(c) and 9). In order to connect a sub-network to different levels of abstractions, a master_node should include connect_edges, which is defined as follows:

For the sub-network $(N, E)$ of a master_node, 

$$
\text{connect_edges} = \left\{ \left( n_i, n_j \right) \mid n_i \notin N \land n_j \in N \right\} \cup \left\{ n_j \in N \land n_i \notin N \right\}
$$

As seen in the above definition, connect_edges represents the relationships between the node of one sub-network (master_node) and the node of other sub-networks at the lower level of the network. Therefore, the initial node of

![Figure 8. Connectivity relations in a node hierarchy.](image)

![Figure 9. Connectivity relations in a node hierarchy.](image)
connect_edges is not an element of the node set \( N \), and the end node of connect_edges is an element of the node set \( N \), or vice versa. To construct the network structure that connects the internal networks of many buildings, the road network is connected to the high-level master_nodes that represents the sub-networks of the buildings. For example, in the road map of the landmarks in a hypothetical small town (figure 10), each landmark is represented by a node at the highest level and the nodes are connected by the road network. Spatial queries at the macro-level (building-to-building queries) can be implemented in 2D space with a road network and master_nodes, while micro-level queries (feature-to-feature queries) can be implemented using the integrated NRS and road network.

5. Experimental implementation of the CDM

To evaluate the potential benefits of the 3D CDM described in the last section, an experimental implementation was conducted with real data (figure 11). The system has two components. The first component is a 3D NRS implementation module developed in the visual basic (VB) development environment (figure 11(b)). The second component is a 3D visualization module for visualizing buildings and geographical features in urban areas (such as roads and trees) in 3D (figure 11(a)). This component utilizes ERDAS Imagine 3D virtual extension module and ESRI ArcScene as the 3D viewers for displaying the urban features. The data set used is drawn from a comprehensive GIS database of Blue Earth County (Minnesota, USA), where the study site Minnesota State University (MSU) at Mankato is located. Building footprint data of the campus area was obtained from the Facility Management Department of MSU-Mankato.

To implement the CDM, the NRS of Trenton East Hall (one of the buildings on campus and referred to as TE) is extracted based on the procedures described in the last section. The NRS derived is then connected with the street network at the building’s entry points to represent the topological relationships among the

![Figure 10. Road map of the landmarks in a hypothetical small town.](image)
buildings in the locality. In the 3D NRS implementation module (figure 11(b)), each 3D object (room) is represented as a node and the topological relationships among the 3D objects are represented as edges—thin lines for adjacency relationships and thick lines for both adjacency and connectivity relationships. The NRS module has a viewing area for visualizing and exploring node-relation structures. It is referred to as the NRS viewer area in later discussion. The 3D model of MSU-Mankato campus (figure 11(a)) is based on the data model of ESRI ArcView 3D Shapefile. It is linked to a GIS database that includes the campus map and floor-by-floor information of the building. The model is developed with each node having a unique reference number (Node_ID) that is linked to a 3D polygon (PolygonZ_ID) defined in ArcView 3D Shapefile format. In this manner, the 3D representation of a room shown in the 3D visualization module has the same ID as its corresponding node in the dual graph, and the node set of the CDM can be joined with the attribute data of the 3D shapefiles for use in thematic or attribute queries. Three examples are provided below to illustrate the use of the CDM and NRS in queries of the attributes of 3D features and the adjacency and connectivity relations among the rooms within a building. Usefulness of the system in urban studies and planning applications is also discussed.

Example 1

Query of the attributes of 3D features. This example demonstrates how attribute queries and visualization of detailed land use patterns within a building can be performed with the implemented CDM and NRS. For the extraction of the attribute information about a particular 3D feature within a building, the user can visually choose a feature (e.g. a room within a building) in the NRS viewer area. A click with the mouse on a room runs a visual basic (VB) program, which then invokes the ‘query result’ window showing the attribute information of the room such as room number, room type, size of room and owner or renter information. As an illustration, this example shows the result of an attribute query based upon room type information (figure 12). In the NRS viewer area that displays the topological information among the 3D features in the building, the user sends a request by clicking the ‘display room types’ button. The result is returned and displayed in the NRS viewer area (figure 12(b)). Each node (room) is classified into eleven room
types such as classroom, faculty room, lab, main office and hallway. Each colour represents a different room type in the NRS viewer area. In the 3D visualization module, room type information is displayed to represent a 3D land use map of Trenton East Hall (figure 12(a)). In contrast to 2D land use maps, 3D land use maps can be constructed with floor-to-floor data of buildings in this manner and used to represent how urban space is used in micro-spatial environments. The NRS module and the 3D visualization module are effective for showing urban land use patterns using disaggregated information on individual 3D features.

As an important focus of urban planning is ensuring land use compatibility and environmental quality, the study of land use changes in urban areas has recently taken more spatial and behavioural attributes into account. Since most urban models treat geographical objects as 2D features, extending these models to 3D land use models will greatly enhance our ability to visualize spatial patterns and analyse the spatial relations among urban features in 3D, especially for applications such as 3D cadastres. For instance, the capability to perform attribute queries and visualization of land use patterns in 3D space as shown in this example will be useful for detecting the availability of floor space for a particular type of development in a building.

**Example 2**

**Query of adjacency relations.** This example demonstrates how spatial queries about the adjacency relations among the 3D objects within a building can be performed with the NRS and visualization modules. To perform an adjacency query, the user clicks a node in the NRS viewer area and invokes a VB program that opens a query result window showing a node-ID. The node-ID is associated with the room number. After selecting a node, the user clicks the ‘find adjacent objects’ button to send a request to the system, and the query results will then be displayed in the NRS viewer area. Figure 13(b) shows the result of a spatial query for all rooms that are adjacent to TE210. Based on the sub-graph (thick lines) that represents the query result, we can see that room TE210 (conference room) is adjacent to seven rooms, which are TE212 (auditorium), TE208 (computer lab), TE209 and TE211 (research labs), TE201 (hallway), TE110 and TE310 (classrooms). These rooms share a vertical or horizontal wall with TE210. Based on this topological information, the
same result is displayed in the 3D visualization module in figure 13(a). The 3D object representing TE210 is coloured in dark green, while the 3D features representing the rooms adjacent to TE210 are coloured in light green.

This example shows that the CDM implemented in the study can be used to find the neighbours of a particular feature or spatial unit in a building. An answer to the question ‘Which other 3D objects are located on top or under a particular 3D object?’ will provide information about its neighbours, the system can be very useful in environmentally oriented analyses such as noise or air pollution and emergency situations in micro-spatial environments. In addition, using information about adjacency relations, similar 3D spatial objects can be aggregated into 3D regions (clusters of similar 3D objects) with some thematic specifications about the types of the objects in the 3D region (Molenaar 1998). For instance, 3D residential units within a building can be aggregated into a 3D residential region, which can be represented by a connected sub-graph of the adjacency graph. This means that adjacency graphs for 3D features can be used as a tool for 3D spatial partition or generalization.

Example 3

Query of connectivity relations. This example shows how spatial queries about the connectivity relations among the 3D objects within a building can be performed with the implemented system. To perform a connectivity analysis, the user clicks on a node in the NRS viewer area and invokes a VB program that selects a from-node. The to-node is then selected by clicking on another node in the NRS viewer area. A VB program will open a query result window showing a node-ID. After selecting the from- and to-nodes, the user clicks the ‘find topological path’ button to send a request to display the query results in the NRS viewer area. Figure 14(b) shows a topological path between rooms TE321 and TE106 in Trenton East Hall. These two rooms are linked spatially through TE301 (hallway), TE304, TE204 and TE104 (east stairways) and TE101 (hallway). The sub-graph (thick line) represents the connectivity relationships between TE321 and TE106 in the NRS viewer area. The topological path is also displayed in the 3D visualization module (figure 14(a))—where 3D feature TE321 is coloured in dark green, 3D feature TE106 is in purple, and the connecting 3D features are in light green.
As illustrated in this example, the 3D NRS network shows connectivity relations and the functional structure of space within a building. Through revealing areas of high activity intensity (e.g. hallways in the horizontal direction and stairways or elevators in the vertical direction), the system provides information about the pattern of interaction between activity and space, which is often useful for applications such as the design of architectural spaces and emergency response operations (Seo 2003). For instance, urban or architectural spaces can be modelled and analysed with respect to particular types of human activities (e.g. pedestrian movement or traffic flow). Further, analysis and visualization of the topological paths between critical locations served by fire trucks, ambulances and other emergency vehicles are crucial for maintaining a safe urban environment. The CDM and NRS presented in this paper can therefore be useful in many urban applications.

6. Conclusion

This study develops a 3D topological data model for representing the adjacency and connectivity relations among 3D features in micro-spatial environments (such as the rooms in a building). The 3D data model is derived using Poincaré duality and theorized with graph-theoretic formalisms. The 3D topological data model is called the combinatorial data model (CDM). It simplifies and abstracts the topological relationships among 3D features through a hierarchical network structure called the node-relation structure (NRS). The NRS was implemented in a visual basic development environment and tested with data of the Minnesota State University Campus at Mankato. The system successfully performed spatial queries based on the attributes of the 3D features inside a building and analyses of the adjacency and connectivity relations among these 3D objects. The viewing function provided by its two modules also allows for effective visualization of these 3D features and the abstracted NRS.

The 3D CDM presented in this paper overcomes several limitations of current 3D GIS for micro-spatial applications and contributes to the advancement of this research area in important ways. First, it explicitly represents the internal partitions or subunits of buildings, while recent 3D GIS data models largely treat geographical features as indivisible entities without internal subunits. Second, it allows the performance of network-based analysis (e.g. connectivity analysis) by explicitly
representing topological relations with a hierarchical network structure, while existing 3D GIS data models lack this capability because they do not explicitly represent the network structure that determines the movement of people within a building. Third, it improves computational efficiency and eliminates the need to store massive amounts of data about the geometric properties of complex 3D objects through dealing with an abstracted NRS.

Two extensions of the CDM, however, are needed before it becomes widely applicable in micro-spatial environments. On one hand, the CDM presented in the paper represents adjacency and connectivity relations through a hierarchical network consisting of nodes and edges. It is therefore a purely logical data model by itself. In order to be able to perform 3D analyses that are based on the geometric properties of the topological relations among 3D objects (e.g. distance) such as shortest path analysis, the CDM needs to be complemented by and integrated with an additional data model that deals with the geometric representation of 3D features. Further, in order to maintain the consistency in data transition between the two data models, the full model requires a database design because a database approach brings advantages in security and data integrity as well as support for the management of model versions and query-based model decomposition.

Important progress in extending the CDM along this direction has been made recently by Lee (2004a,b). This work extends the CDM into a dual data model, which has a geometric component for handling the geometric properties of the topological relations among 3D objects, in addition to the logical component (the CDM). This geometric component is called the geometric network model (GNM) and was created by using a straight medial axis transformation algorithm (S-MAT) developed by Lee (2004a,b). It is linked with the combinatorial data model (the CDM) in the full dual data model and has been successfully applied in several areas. For example, it has been used to implement a modified Dijkstra’s algorithm on non-planar graph that searches for the optimal path on the 3D traffic network within a building (Lee 2004a). The application of the dual data model and the shortest path algorithm in emergency response in micro-spatial environments has been shown to result in considerable reduction in the time required to reach a disaster site inside a multi-storey building (Kwan and Lee 2005). Further, the model has been used to provide a framework for performing 3D indoor geo-coding that locates humans or particular 3D features within micro-spatial environments (Lee 2004b). These successful extensions and applications have forcefully proven that the CDM presented in this paper can provide a solid foundational framework for useful 3D GIS data models.

Extending the CDM in another direction is necessary because the data model represents 3D objects or features by abstracting them as nodes (or points) through an NRS. The data model does not implement any detailed representations of the geometric properties of 3D objects. While complex geometric computation is avoided by eliminating the need to deal with fully specified 3D objects, the data model cannot deal with topological relations that are defined in terms of the solid properties of 3D objects (e.g. the intersection of two 3D objects). Future research is therefore needed to enable the identification or query of all kinds of 3D topological relations among fully specified 3D objects. The CDM, however, is an indispensable and significant point of departure toward this development.

References


PIGOT, S., 1995, A topological model for a 3-dimensional spatial information system. PhD dissertation, University of Tasmania, Australia.


