EXPERIMENTING TIN DATA STRUCTURE FOR REPRESENTING PLANE SURFACE AND SUBSURFACE SPATIAL OBJECTS - PRELIMINARY WORK

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ABSTRACT:

Understanding and analyzing complex spatial objects involves the integration of surface, terrain, and subsurface data into 3D spatial models. However, describing and efficiently analyzing the connections between these data model is particularly challenging. This study aims to generate TIN data structure that enable the 3D representation of surface terrain subsurface integration. Furthermore, to ensure accurate representation within a unified 3D model, spatial relationships between the TIN data model could be obtained. Consequently, three – dimensional Triangular Irregular Networks (3D TIN) mesh of spatial objects representations and indexing structures were created. The integration of spatial objects, encompassing surface, terrain, and subsurface elements, is realized through a unified model. This synergy is achieved by combining the distinct 2D and 3D topology structures of each component. The resulting comprehensive model captures the intricate relationships and interactions within the spatial environment. This study provides additional insight into the representation and analysis of surface, terrain, and subsurface management in 3D spatial models. Hence, better decision making, resource management, underground utility installations, and evaluation of spatial objects will be made possible in our future work.

1. INTRODUCTION

The integration of spatial objects involves combining various spatial data models to create a unified representation of surface and subsurface objects, enhancing visualization, organization, and management in various disciplines like engineering and planning (Apeh & Rahman, 2023; Djunarsjah & Handayani, 2021). Traditional 2D representations of urban environments have proven inadequate in representing the complexity of the real world. In recent years, the development of extensive 3D spatial models that accurately depict the integration between surface, terrain, and subsurface objects has become imperative due to the growing intricacy of urban environments and infrastructure progress (Fadli et al., 2018). Chen & Schneider (2009) suggested that in 3D modeling, the presence of data structures is of paramount importance as they assume a vital role in the representation of the geometry and topology of objects within a three-dimensional space. These structures serve the purpose of both storing and arranging the data that delineates the configuration, dimensions, and placement of objects within a 3D model. In addition, data structures serve the purpose of representing the connections among objects within a three-dimensional model. There exist various classifications of spatial data structures that are employed in the representation of three-dimensional models. Among the frequently utilized data structures are regular grid, k – dimensional (k-d Tree), octrees, Binary Space Partitioning BSP, Boundary representation (B-rep) and Constructive Solid Geometry (CSG) etc.

This study utilizes Triangulated Irregular Networks (TIN), a data structure, with potential applications in urban development and sustainability. TINs have been utilized in various applications, including the creation of authentic cities, the investigation of inhabited structures, and the examination of urban surroundings (Xiao et al., 2023).
It explores methodology, results, and applications, and references related works on data structure. The next section describes related works that investigated data structure. Section 3 outlines the data utilized in this experiment, Section 4 describes the experiments, and Section 5 discusses the paper's conclusion.

2. RELATED WORKS

In the ever-changing fields of geoinformatics, geospatial science, and planning, the progression of 3D spatial data modeling is a crucial and extensively examined area. This domain encompasses the complex creation of spatial data structures and, importantly, the skillful merging of both surface and subsurface data. The portrayal of spatial information in 3D has become increasingly essential for a multitude of applications, including environmental management, and infrastructure development.

2.1 3D Spatial Data Structure

3D space is required for analysis and visualization. Furthermore, the three-dimensional spatial data model is a representation of spatial characteristics that represent the attributes of objects in three dimensions (Li et al., 2019). Data model and data structure are the basic contents of spatial data organization (Yanbing et al., 2015). 3D spatial data models establish the way spatial objects are depicted within a three-dimensional space. This depiction encompasses the geometric characteristics of entities (such as coordinates, shapes, etc.) as

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well as the accompanying attributes that communicate non-spatial data.

Additionally, 3D city models must represent both 3D objects and terrain in a single coherent model, yet there are still numerous challenges to be resolved (Yan et al., 2019). One of the most common of these challenges is the data structure for the 3D spatial data model. An underlying data structure is necessary for a 3D spatial data model to efficiently organize and display the three-dimensional data. Choosing the right data structure is essential for handling the relationships and complexity of the spatial data.

Spatial data structures are crucial for spatial organization and database generation. They form the core of 3D models, regardless of application area. A well-designed data structure is essential for effectively managing and handling a wide range of diverse data types. It plays a pivotal role in ensuring the utmost integrity of information, as well as facilitating seamless and highly efficient access to this invaluable data. Several researchers including Abdul-Rahman & Drummond. (2000), Che et al. (2009), Duncan et al. (2012), Y. Wang (2006), and Penninga, (2005), employed diverse data structures in their 3D models for various practical scenarios.

These models offer seamless integrated data structures for urban surface and subsurface objects, geometric and topological 3D object-oriented models, and surface and terrain integration.
There exist various categories of data structures employed in the representation of three-dimensional models, with each possessing its own unique characteristics. For example, regular grid is a simple data structure that divides the available space into a regular grid of cells. It is the most parallelizable and provides constant time access, but it requires quadratic or cubic (2D, 3D) space, k – dimensional (k-d Tree) is a binary tree data structure used to organize points in a k-dimensional space. It is compact and simple, but has non-constant accessing time, octrees is a tree data structure with exactly eight children for each internal node. It is used to partition a three-dimensional space into eight octants by recursively subdividing it. It is small and basic, yet it has a variable access time, 3D Formal Data Structure (3D FDS) is a data structure that represents 3D spatial data types like points, lines, surfaces, and volumes. It is used in a database setting to handle both general and complex 3D spatial objects (Chen & Schneider., 2009).

Several researchers proposed different data structure for different purposes. For instance, Jaljolie et al (2018) put forward profound insights centred around data structure and functionalities required to establish and execute an efficient and dynamic three-dimensional land management system in Israel, Chen & Fang (2019) proposed R O-tree data structure whose objective is to enhance the efficiency of spatial indexing in the transmission, parsing, and real-time visualization of large-scale 3D scenes in the Web domain, Boguslawski et al. (2022) presented a proposal for a mechanism that enables the seamless loading of 3D spatial models. These models were implemented using the dual half-edge (DHE) data structure and were stored in a database. Furthermore, Stanchev & Paraskevov. (2023) introduced a mesh data structure and a walking-on-mesh approach. These techniques were aimed at achieving efficient polygon traversal and integration into the 2.5D mesh. From the foregoing, data structures, such as voxel grids, octrees, or other mesh-based structures, are used depending on the specific needs of the 3D spatial model.

This study is experimenting with the TIN data structure. This choice may not be unconnected with its flexibility and adaptability to irregularly shaped surfaces and enable for accurate depiction of terrains and other complex 3D geometries, efficiency in storage compared to normal grids or other volumetric representations, TINs require less memory for storage, particularly when the surface is uneven and has different degrees of detail, TINs can be easily combined with other types of spatial data to provide a comprehensive representation of a 3D environment that may contain buildings, terrain, and subsurface objects and also TINs data structure are particularly suited to visualisation applications. The triangulated structure facilitates the rendering and display of 3D surfaces using software tools, assisting in the interpretation of spatial data. TIN data structure is being used to demonstrate how it can manage integration within spatial objects of the surface and subsurface.

2.2 Surface and Subsurface Integration

Surface and subsurface spatial elements must be seamlessly integrated into the data model. This entails representing the intricacies of diverse objects' spatial relationships in 3D. The data integration requires a well-designed data structure that accommodates the distinctive characteristics of both. To integrate real-world modeling, spatial objects must be modeled appropriately and in line with specified data models. (Duncan & Rahman, 2013) proposed a geometric, topological 3D object-oriented approach for integrating surface and subsurface spatial data objects. Yan et al. (2019) developed a method for merging 3D objects and terrain in digital twin 3D modeling. Chen et al. (2018) proposed strategies for merging aboveground and subsurface 3D spatial elements in a virtual globe environment. Wang et al. (2023) proposed multidisciplinary spatial earth data representation techniques. Al Kalbani & Abdul Rahman. (2019) presented a theoretical framework with the intention of incorporating both surface and subsurface 3D geospatial objects data structure into the Oman Spatial Data Infrastructure (SDI), utilizing the established CityGML standards (Figure 1). It is their contention that addressing the challenges within the data structure will ultimately lead to a more comprehensive perspective and introduce opportunities within the sphere of 3D SDI.

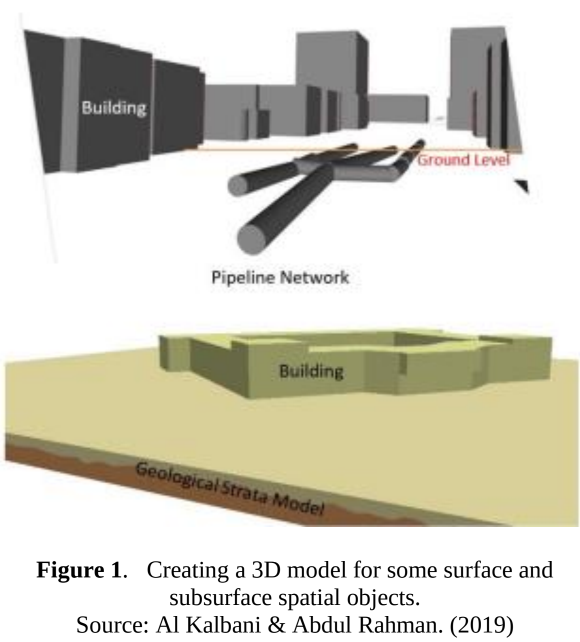

Figure 1. Creating a 3D model for some surface and subsurface spatial objects.
Source: Al Kalbani & Abdul Rahman. (2019)

As put forward by Kaden & Kolbe (2012), a prerequisite for achieving integration among these datasets is the necessity to consider the structural, geometrical, and semantic disparities that exist between the various sources of data. Thus, in 3D integration, geometrically distinct representations should be smoothly blended, with the terrain surface being the mutual interface for both surface and subsurface objects.

The ongoing experiment (of this paper) is focused on the establishment of a unified 3D spatial data model for surface (building), terrain, and subsurface (basement compartment of the building) through the incorporation of both 2D and 3D Triangulated Irregular Network (TIN) data structure basically in visualization while the respective topologies of each will be constructed in the advancement of this experiment. The primary objective of this is the development of a prototype that enables the effective management and visualization of 2D and 3D spatial objects. The integration of 2D and 3D TIN data structures will facilitate the creation of a singular 3D model, thereby enabling its utilization for spatial analysis purposes. This prototype will provide users with the capability to efficiently handle and visually perceive 2D and 3D spatial objects within a singular context.

3. DATA SOURCE

For our experiments, the following datasets were used:

Building Footprints of UTM Campus: The data on the footprint of the building was stored in the Geographic JavaScript Object Notation (GeoJSON). The building footprints (Figure 2) serves as one of the datasets for our experiment. The central library of UTM, which is a 5-story building, acts as a pivotal element in producing the 3D model examined in this study. By utilizing the distinct height data, a comprehensive three-dimensional depiction of the central library is generated. This 3D model forms the basis of the entire spatial data structure, facilitating the integration of the building's characteristics with other spatial elements like terrain and subsurface objects. The generation of the 3D model based on the building footprints is highlighted further in subsequent section.

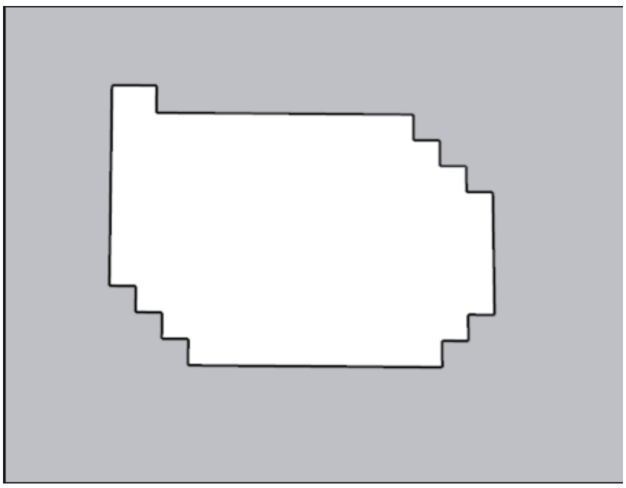

Figure 2. Building Footprint of UTM library Building

Terrain Elevation Data: This dataset captures the elevation information for the designated area of interest. Terrain data is of utmost importance in the integration of spatial data, especially in cases where triangulation and 3D modeling are utilized. The effectiveness and significance of triangulation, often aided by technologies such as the Triangulated Irregular Network (TIN), are greatly enhanced when based on real terrain attributes. Utilizing this terrain elevation data, a terrain surface was generated as illustrated in Figure 3. The TIN model is a representation of the terrain using a network of interconnected triangles. Each vertex of a triangle corresponds to a distinct data point, and the edges establish the relationships between these points. This method of triangulation permits a thorough and precise depiction of the terrain, effectively capturing the interplay between the terrain and other structures.

Figure 3. Relating terrain data to a building footprint of the library.

Subsurface Object Data: Like the building footprints, the subsurface object data followed a comparable procedure. Extrusion based on approximate height information was applied to create three-dimensional representations of subsurface features, completing the spatial representation of surface and subsurface objects. Figure 4 illustrates the simulated basement compartment of the building (representing the Subsurface object). Real world object of the subsurface in the near future work may extend to water pipe connection underneath the building and they are more complex. The incorporation of subsurface three-dimensional entities with a Triangulated Irregular Network (TIN) and the subsurface is of utmost importance in the development of an all-encompassing spatial framework that considers both surface and subsurface characteristics.

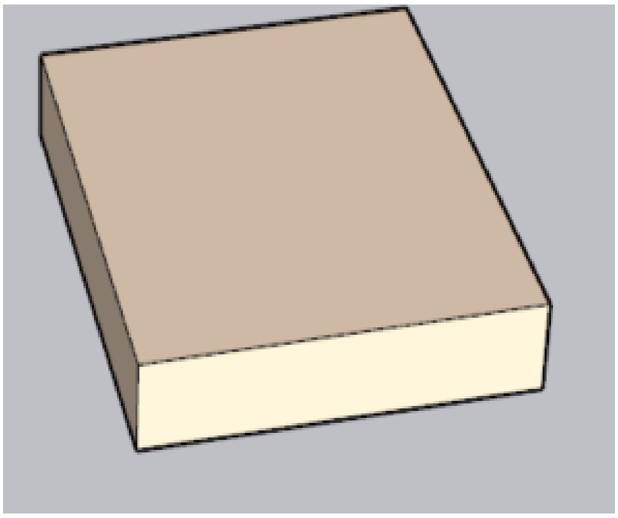

Figure 4. Basement Compartment of building (representing the Subsurface object).

4. EXPERIMENT

The experiment encompasses the utilization of both 3D generation and Triangulated Irregular Network (TIN) generation. Typically, it involves the formation of three-dimensional models from two-dimensional data, such as footprints. Subsequently, these models are reconstructed utilizing the TIN structure. The structural and topological aspects of the two-dimensional and three-dimensional data will be the central area of focus for future endeavours.

4.1 3D Model Generation

For data structure to be harnessed effectively especially in the current geospatial trend, the three-dimensional model especially of the building is pertinent. Based on the available data from footprints, the 3D model of the building was generated in QGIS environment. The 2D footprints representing the study area was exported to QGIS while utilizing the 3D interactive tools with functionality of extrusion. The height of the building was used to create z-dimension of the building at LOD 1.

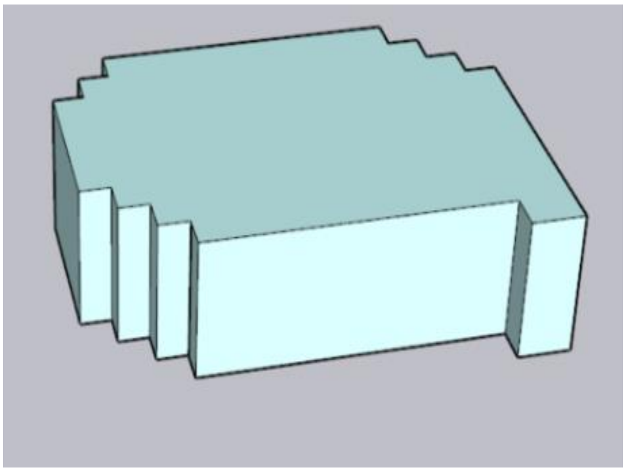

Figure 5. 3D model of UTM library building.

Figure 5 depicts the 3D model which serves as a step for the onward processing for generating data structure for the building (objects). This approach broadens the dimensions of the footprints vertically, integrating height information to convert them into three-dimensional forms. Through the extrusion of the 2D footprints using height data, the resulting 3D model precisely portrays the physical elevation and volume of the corresponding real-world structures. This technique of height extension is crucial in generating authentic and geospatially precise 3D representations, offering valuable insights into the vertical aspect of the constructed environment. Similarly, the same procedure was applied to the combination of 3D building of the UTM library and 3D of the basement compartment of same building as illustrated in Figure 6. Furthermore, Figure 7 illustrates the terrain together with a three-dimensional model of the subsurface—that is, the basement compartment. This figure provides a crucial hint for comprehending how terrain and subsurface are integrated at the model level. The 3D model becomes more detailed and provides insights into the complex interplay between the subsurface objects and terrain. This serves as the foundation for further utilization that will serve as input for TIN data structure.

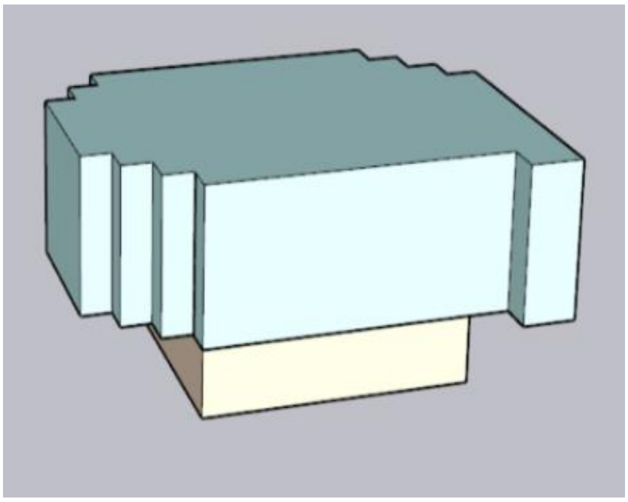

Figure 6. 3D Model of UTM library building and subsurface basement compartment.

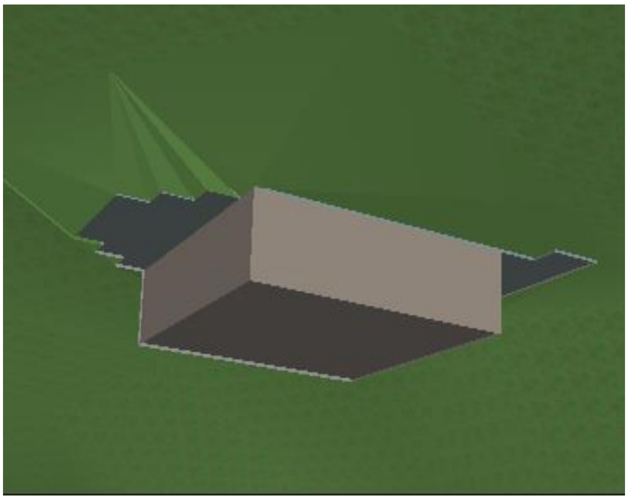

Figure 7. 3D of basement compartment and the terrain

4.2 Data Structure for Spatial Objects (Building, Terrain and Subsurface)

The TIN data structure is efficient in representing 3D spatial objects. While conducting this experiment, the 3D building model that had been previously generated, along with the 2D representation of the terrain and the 3D subsurface objects, were all exported to the process of encoding entities into primitive geometry, specifically in the form of standard triangles in CityGML. This was achieved by utilizing Feature Manipulation Engine's (FME's) CityGMLWriter transformer to effortlessly transform 3D geometries into CityGML surfaces. Furthermore, adjustment such as the settings, assign attributes, and execute the workspace to produce a CityGML file that complies with the established standards were carried out. The transformation in a CityGML viewer was validated to ensure that an accurate representation of 3D objects with precise geometric surfaces is attained.

This encoding format, which is primarily based on triangles, serves as a commonly employed geometric representation that effectively streamlines the storage and exchange of 3D spatial information. In Figures 8, the representation displays how the 3D building and 2D terrain are encoded into CityGML using primitive geometry, particularly standard triangles. CityGML adopts a geometric method to illustrate 3D city models, where these standard triangles act as the basic elements for creating intricate surfaces. These triangles visually depict the connection between the building and terrain, demonstrating the geometric connections and interactions within the CityGML representation while In Figures 9, the illustration shows how the terrain and subsurface features, particularly the basement compartment, are integrated using basic geometry in the CityGML format. The representation utilizes standard triangles, which are essential geometric elements within the CityGML framework. These triangles serve to establish the geometric connections and relationships between the 2D terrain and the 3D subsurface, resulting in a consistent and standardized model.

In the future stages of our research, our intention is to broaden our attention towards improving the data organization of both two-dimensional and three-dimensional spatial objects. We will specifically emphasize the importance of topological factors. This expansion entails a thorough exploration of the relational and connectivity aspects within the structures of these spatial entities. Our goal is to create strong and reliable topological tables for both two-dimensional and three-dimensional components. This will facilitate a deeper comprehension of the interrelationships between these components.

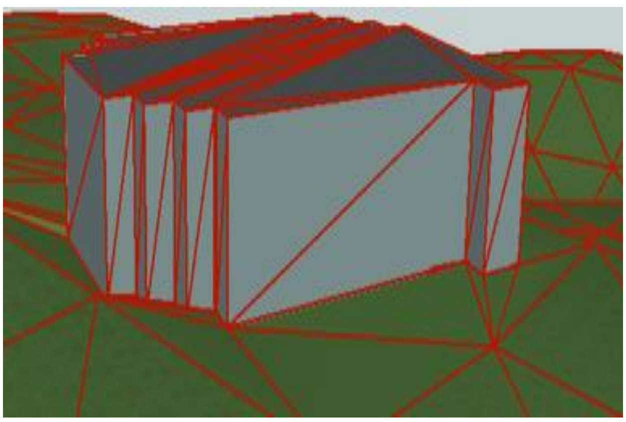

Figure 8. 3D library building and terrain encoded in CityGML standard triangles.

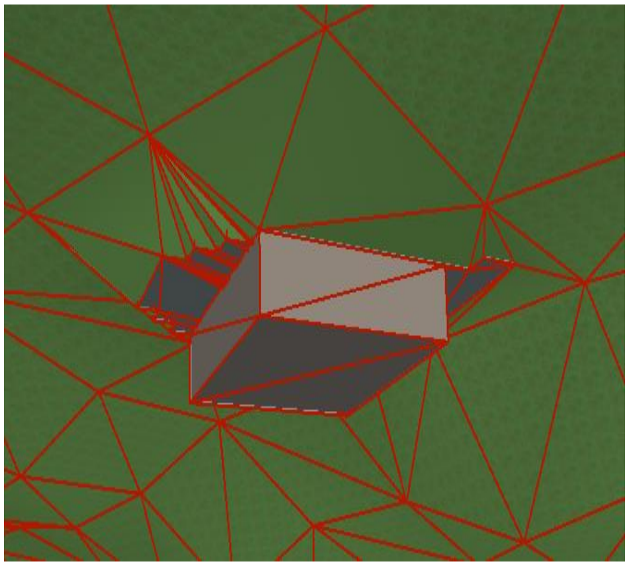

Figure 9. 3D basement compartment and terrain encoded in CityGML standard triangles.

4.3 Near Future work (experiment) on Data Structure

This future effort aims to expand the overall representation of surface and subsurface objects by including topological aspects in the spatial data model. This procedure entails a careful analysis of the topological connections between the 2D representation of the terrain, the 3D representation of the subsurface (the basement compartment), and the 3D model of the building. We hope to develop a knowledge of the relationships between the spatial entities.

The defining characteristic of spatial entities, regardless of whether they exist in three-dimensional or two-dimensional space, resides within the determination of their vertices. Vertices, which are pivotal points within the spatial domain, serve to establish the geometric properties and form of these entities. Tables 1 to 7 reflects the replica (example of potential tables) in the near future work. Tables 1, 2 and 3 represents the data structure for 3D building, 2D terrain, and 3D basement compartment respectively. Tr ID represents the triangle ID for the building, terrain, and the simulated basement compartment while Vertex 1, Vertex 2, and Vertex 3 represents the vertices defining triangles of the building, terrain, and the basement compartment.

Tr ID	Vertex 1	Vertex 2	Vertex 3
1	(10, 5, 0)	(15, 5, 0)	(15, 10, 5)
2	(10, 5, 0)	(15, 10, 5)	(10, 10, 5)
3	(5, 10, 0)	(10, 15, 0)	(5, 15, 5)
4	(5, 10, 0)	(5, 15, 5)	(0, 10, 5)
5	(0, 5, 0)	(5, 5, 0)	(0, 0, 5)

Table 1. TIN Data Structure of 3D Building.

Tr ID	Vertex 1	Vertex 2	Vertex 3
1	(5, 0)	(10, 0)	(10, 5)
2	(5, 0)	(10, 5)	(5, 5)
3	(0, 5)	(5, 10)	(0, 10)
4	(0, 5)	(0, 10)	(5, 10)
5	(5, 10)	(10, 15)	(5, 15)

Table 2. TIN Data Structure of 2D Terrain

Tr ID	Vertex 1	Vertex 2	Vertex 3
1	(10, 5, 0)	(15, 5, 0)	(15, 10, 0)
2	(10, 5, 0)	(15, 10, 0)	(10, 10, 0)
3	(5, 10, 0)	(10, 15, 0)	(5, 15, 0)
4	(5, 10, 0)	(5, 15, 0)	(0, 10, 0)
5	(0, 5, 0)	(5, 5, 0)	(0, 0, 0)

Table 3. TIN Data Structure of 3D Subsurface Basement Compartment.

Furthermore, the data structure representing their topologies (example of future work) are as illustrated in Tables 4, 5 and 6. Table 4 represents an expected topology table of 3D library building, Table 5 represents that of the 2D terrain while Table 6 represent that of subsurface basement compartment of the building. The topology tables represent the triangles that are common to spatial objects such as in building, terrain, and the subsurface basement compartment in this case. These triangles are adjacent to one another in a clockwise direction.

Tr ID	Adjacent Triangles (Clockwise)
1	2, 3, 4, 5
2	1, 3, 4, 5
3	1, 2, 4, 5
4	1, 2, 3, 5
5	1, 2, 3, 4

Table 4. 3D Topology of Building

Tr ID	Adjacent Triangles (Clockwise)
1	3, 4, 5, 6
2	2, 4, 5, 6
3	2, 3, 5, 6
4	2, 3, 4, 6
5	2, 3, 4, 5

Table 5. 2D Topology of Terrain

Triangle ID	Adjacent Triangles (Clockwise)
1	2, 3, 4, 5
2	1, 3,

Table 6. 3D Topology of Subsurface Basement Compartment

All these topological tables are simulated. For the future work, all these tables and the connections of these TIN based objects (2D and 3D) will be created or generated from the algorithm automatically.

Finally, the integration of their topologies is presented in table 7. The integration of 2D and 3D topology is the next step, which leads to the development of a single spatial model. A visualization tool then makes this unified model understandable and accessible, offering an interactive and comprehensive representation of the integrated surface and subsurface spatial objects.

Building Tr. ID	Terrain Tr. ID	Subsurface Tr. ID
1	101	201
2	102	202
3	103	203
4	104	204
5	105	205

Table 7. Integration of 2D and 3D Topology:

The expected data structure will be organized and documented carefully to ensure a comprehensive representation of the spatial objects. The tables that follow will demonstrate the organized format by defining the linkages and configurations inside the 2D and 3D spatial models, as well as their respective topologies.

5. CONCLUSIONS

In summary, the research has taken a comprehensive approach to utilizing 3D geospatial data structures, with a focus on buildings, terrain, and subsurface objects. The first step involved creating a 3D model of the building using data from footprints. This model was generated in the QGIS environment using 3D interactive tools and extruding 2D footprints based on building height to establish the z-dimension at LOD 1. This 3D model is a crucial component for implementing effective data structures for spatial objects.

The use of standard triangles to encode 3D building, 2D terrain, and 3D subsurface objects into CityGML allows for effective storage of 3D spatial information. Figures 8 and 9 show how geometric connections are formed inside the CityGML framework, emphasizing the relevance of triangles as fundamental elements.

In the future, we will concentrate on improving data organisation, with an emphasis on topological considerations for both 2D and 3D spatial objects. The upcoming experiment will help us better grasp the relational and connection elements of such structures. We aim for a more thorough understanding of interrelationships between components in multiple dimensions by constructing topological tables. As indicated in the tables, the envisioned data structure would be carefully organized and documented, promoting a comprehensive representation of spatial objects.

The near future work is consistent with our aim to improve the representation of surface and subsurface objects by adding topological aspects to the spatial data model. The combination of 2D and 3D topology creates the foundation for a unified spatial model that provides an integrated surface and subsurface spatial objects.

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