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Current uses of topology in 3D GIS: An overview

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Abstract. 3D GIS has been widely used in various applications that require 3D visualisation and analysis. This has also been made possible by advances in data acquisition, which provide detailed and accurate spatial data as the basis for any task. Topology as a spatial property gives value to 3D GIS by maintaining connectivity, adjacency, and containment information. This study attempted to understand how topology is used in 3D GIS based on a literature review. SCOPUS databases were searched for journal articles, conference proceedings, and book chapters that implemented topology as part of their 3D GIS methodology. Keywords used to search for literature were "topology" and "3D GIS". The articles were selected based on the uses of topology in 3D GIS. The term 'uses' indicates topology being used in the methodology of a 3D GIS study to achieve the objective. Based on the review, we were able to categorise the literature into 3 main uses of topology, which are validation, data reconstruction, and spatial analysis or queries. The results of the literature review were also visualised using a network map of terms that also represents the connectivity and weightage between terms. This overview provided an awareness of future research areas in which topology assisted data validation, data reconstruction, and spatial analysis can be applied and fully utilised to further enhance 3D GIS capabilities.

1. Introduction

Spatial data consists of spatial attributes such as geometrical properties that describe the shape and positional properties that describe the location of the data in a space. Additional non-spatial attributes which describe semantic characteristics also provide information crucial in understanding real-world processes alongside accurate spatial representation of real-world objects. A Geographic Information System (GIS) is a system that creates, stores, manages, analyses, and displays geographically referenced data. Recent advances in the field of geoinformation provide a third dimension to spatial data that mandates the use of 3D GIS. This includes the handling of 3D spatial data [1], 3D visualisation, and 3D spatial analysis [2]. 3D GIS has been used in numerous studies with a variety of fields such as urban planning, environmental modelling [3]-[5], cadastre [6], indoor navigation [7], building information modelling [8]-[11] and utility management [12],[13].

As spatial objects have a location or position, the object is considered to reside in a topological space. Topology is defined as the study of topological transformations and the properties that remain unchanged by changes in space [14]. In other words, the topological properties of objects such as adjacencies, connectivity, and containment remain unchanged [15],[16]. Similar to how geometric properties describe the shape of an object, topological properties are also crucial to describe how objects within a space are related. In terms of topology for spatial objects, topology can be described as intrinsic topology and extrinsic topology. Intrinsic topology refers to topological properties and connectivity within a single object, while extrinsic topology refers to topological relationships between objects [17]. The uses of topology may differ between the two, whereby intrinsic topology usually handles geometric or topological validation of an object while extrinsic topology addresses how objects are related.

As previously mentioned, spatial properties describe the position and location as well as the geometric properties that describes the shape of objects. However, this representation of 3D data remains a "graphical output" of objects without topological information to provide meaning [18]. In other words, 3D objects within a space without topology are isolated in a sense that the geometric properties are limited and unable to represent the relationships between objects although being connected geometrically. Approaches to determine relationships between 3D objects without topology often utilises geometric properties such as calculating the proximity of related objects within a buffer [6] and using ray projection for ray-to-face intersection [19]. The mechanisms used to determine relationships and connectivity between objects affects the efficiency and accuracy of analysis results. The implementation of topology ensures that the relatedness and connectivity of objects are maintained as an accompaniment of objects in facilitating more complex functions.

This paper conducted a literature review on the uses of topology in 3D GIS. The methodology of the review is explained in Section 2. Next, the uses of topology retrieved from the literature search is presented in Section 3. A discussion of the literature review results is put forth in Section 4. Finally, the review is concluded in Section 5.

2. Methodology

This paper reviewed available literature on topology applications in 3D GIS for the past 15 years. Online journals, conference proceedings, and books were browsed for related papers. Keywords used to search for literature were "topology" and "3D GIS". The methodology implemented is described in Figure 1.

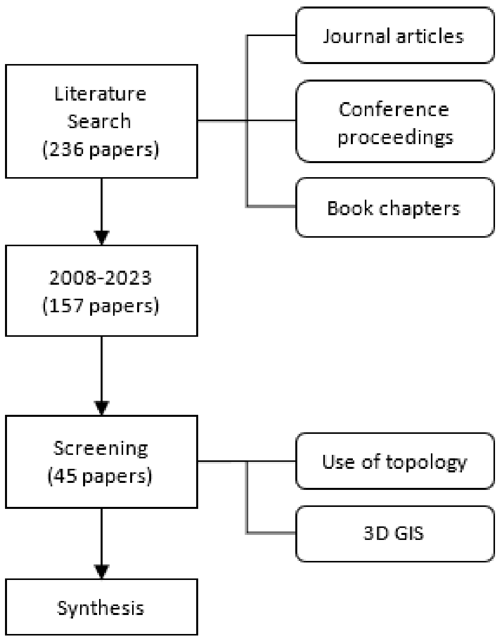

Figure 1. Flow chart of the literature review.

Scopus online databases were searched for related literature which included ScienceDirect, SpringerLink, Scopus, Taylor and Francis Online, Wiley Online Library, and Web of Science. A manual search was also performed using Google Scholar. This resulted in a total of 157 articles that were searched using the keywords mentioned earlier and filtered by year of publication (2008-2023). The articles were selected based on the uses of topology in 3D GIS. The term 'uses' indicates topology being used in the methodology of a 3D GIS study to achieve the objective. Therefore, studies that explain the development of topological data structures, topological rules, and 2D GIS applications are not included in this review.

3. Uses of Topology in 3D GIS

The full text screening of papers resulted in 45 papers that used topology in their methodology for 3D GIS applications. These papers can be synthesised to three main uses of topology, which are validation, data reconstruction, and spatial analysis or queries.

3.1. Validation

A result of 7 papers were found to utilise topology to data validation crucial for ensuring consistent and error-free data. A node-to-edge topology can be used to maintain the connectivity of a road network. Validation of the road network topology facilitates the detection of connectivity which allows decision makers and stake-holders to provide solutions [20]. The nature of topology, which also represents connectivity between objects, is key in validating any changes or updates made to an object. Transaction rules composed of conditions and actions ensure that any updates of surfaces in objects are topologically as well as geometrically valid [21],[22]. Violations such as intersecting or overlapping objects can be avoided [23]. Similarly, the maintenance of topological primitives for a 3D object also ensures geometrically accurate and valid 3D objects specifically in the updating or merging of 3D cadastral parcels [24]. In terms of 3D cadastre, topological information can ensure the validity of 2D parcel boundaries, 3D parcel geometries, connectivity between 3D parcels, uniquely shaped 3D parcels, input and update of 3D parcels [25]. The construction of 3D volumes for the 3D cadastre using a topological model ensures geometrically sound 3D volumes and valid topological relationships between objects [26].

3.2. Data Reconstruction

Based on the literature screening, a total of 16 papers which explain the topologically aided data aided by topology were retrieved. Parallel to recent advances in data acquisition technology, large volumes of data are processed to provide accurate representations of the real world. 3D scene reconstruction for virtual reality has also been widely researched. A method of fast fusion used topological relationships to locate and reconstruct objects within a 3D scene from multiple videos [27]. Topological information was also found to be able to preserve intersections between 3D spaces and reconstruct 3D scenes based on connected images [28]-[30]. Hidden facilities such as pipes can also be reconstructed within a 3D virtual environment using topological models that maintain connectivity information [31].

Data reconstruction processes are often aided by topology for more efficient automated reconstruction and space segmentation. Fundamentally, adjacent 3D objects can be segmented using 3D topological relationships [32]. For example, road networks consisting of elevated or multi-level roads can be complex to reconstruct automatically. Connectivity and adjacency allow segmentation of elevation data while generating and maintaining the shape of the road network [33]. Automated reconstruction of roof structures for 3D building models also uses topology as an algorithm to analyse 3D lines and reshape the roof [34],[35]. This is especially beneficial for buildings in close proximity to each other or a building complex composed of units with different roof structures. Similarly, objects adjacent to 3D buildings, such as trees or other structures, can be determined using topological relationships and segmented from the building [36]. The indoor walls of 3D models are also reconstructed using topological relationships to maintain adjacency and connectivity between rooms [37]. An example of reconstructed roof models and segmentation of objects adjacent to a building is illustrated in Figure 2.

Figure 2. Reconstructed roof structures [35],[36].

Furthermore, reconstruction of 3D buildings can also benefit from topological information. Building complexes such as a residential area is often modelled as a single volume composed of individual house units. A topological reconstruction of the building complex as separated units without altering the geometric structure was found to be a more accurate representation [38]. The resulting 3D building models after topological reconstruction are depicted in Figure 3. A similar approach was also able to profile complex 3D building elements and their semantic relationships using topological connectivity [39].

Figure 3. Topological reconstruction of individual building units [38].

In addition, 3D buildings can consist of many components such as windows, doors, rooms, building exterior, and others. The representation of these elements often requires semantics to give meaning and support information-driven semantic decisions. A scan-to-graph framework was proposed for the reconstruction of BIM geometries with semantic information that used a Building Topology Ontology to define how the building elements are related or connected [40]. The reconstruction of building facades from topologically guided point cloud data allows one to ensure semantic features such as walls and windows are accurately determined and constructed [41].

Apart from that, unique geometries such as bridges and tunnels can be difficult to model as a geometrically and topologically accurate solid. As the topological properties remain unchanged despite transformations of the space, different geometries can be topologically equal. A bridge or tunnel can also be defined as a topological handle. This allowed bridges and tunnels to be accurately as well as adhere to semantic classifications [42]. The reconstruction of the 3D bridge is illustrated in Figure 4.

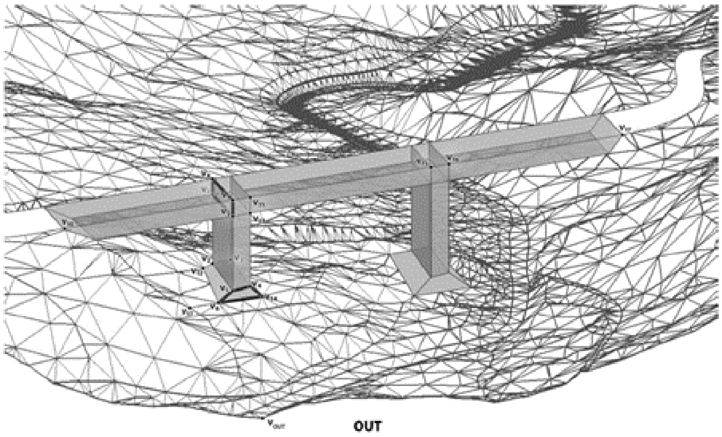

Figure 4. Reconstruction of a 3D model of a bridge as a topological handle [42].

3.3. *Spatial Analysis and Queries*

The selection of literature resulted in 22 articles which used topology for spatial analysis. This included network analysis, which is a well-established method of analysis that heavily relies on connectivity information. Networks of utilities, such as water pipes, can be constructed based on a node-to-edge topology. The water distribution pipes that are suitable for connection to buildings can be determined using spatial topology [43]. Similarly, the identification of pipe burst incidents can also be identified based on a water distribution network where isolation valves are represented by edges while pipe segments are represented by nodes [44]. Parallel to that, road networks that form a network topology can also be used to model links between transportation, spaces, and economy [45].

The topology can also provide connectivity information between all objects that reside in a space by treating the space as an external connecting component. A topological data structure which explicitly preserves topological properties of objects can be implemented to maintain connectivity between multiple subcomponents of a space [18] as illustrated in Figure 5.

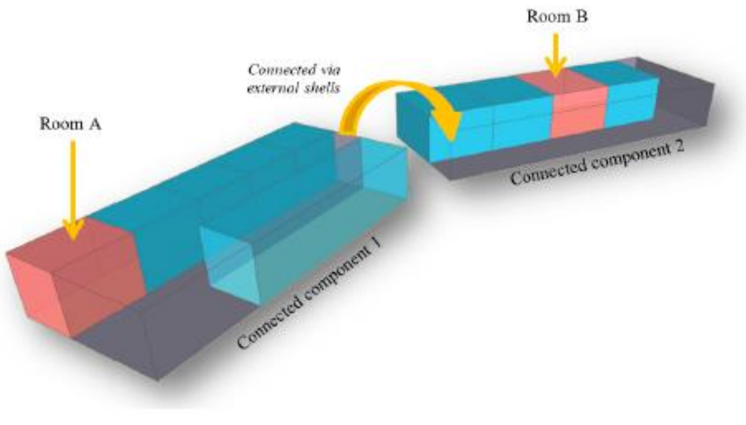

Figure 5. Traversal of connected components within a space [18].

3D indoor navigation composed of vertical levels and subunits such as rooms can also be represented by topology. A network model which consists of nodes, links, and paths can describe the indoor connectivity of components in multi-storey buildings [46]. Horizontal and vertical connectivity can be represented as a topological graph where horizontal nodes are rooms and corridors while vertical nodes are staircases, elevators, and escalators [47]-[50]. The connectivity model between nodes is described by links, as depicted in Figure 6.

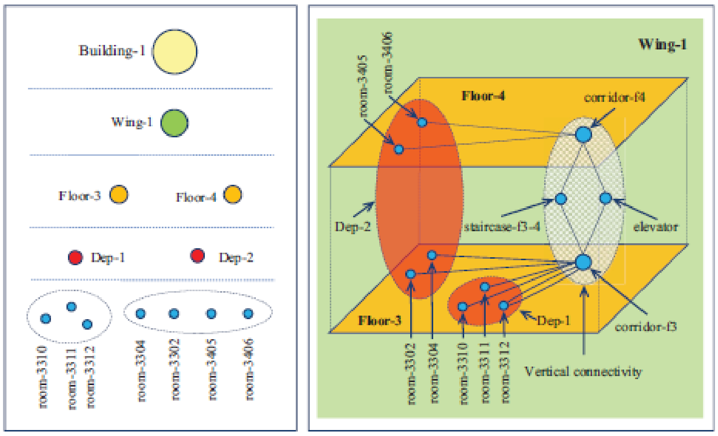

Figure 6. Hierarchical connectivity model for multistorey buildings [49].

However, connectivity information can also be preserved by a graph composed of grids. Pedestrian route analysis within a 3D indoor environment can be represented by grids where adjacencies are expressed by topological relationships [51]. In the event of emergencies, 3D route analysis is crucial in determining exit routes as described in Figure 7. Subdivisions of space can also be navigated using a volumetric connectivity graph that preserves 3D topological relationships between spaces [52]. Maintenance of connectivity information can also be extended for outdoor-to-indoor navigation [53].

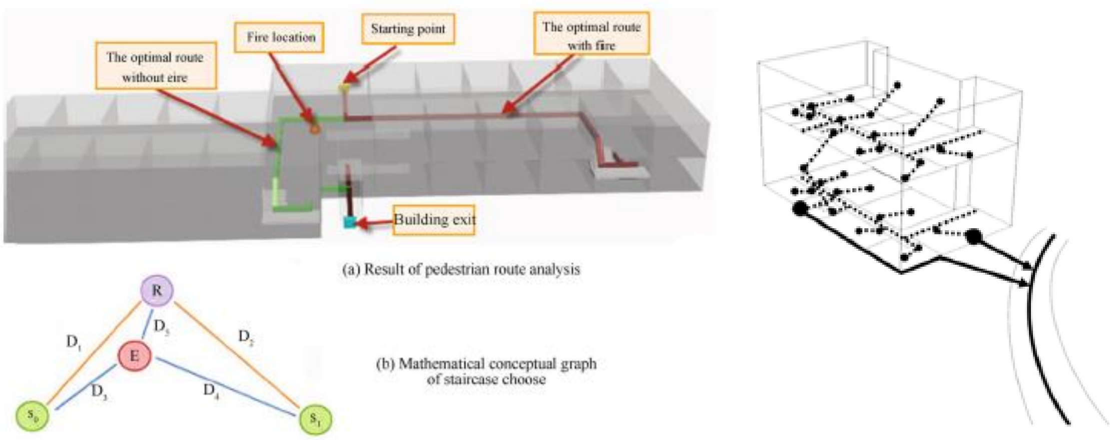

Figure 7. Emergency exit routes based on a grid-based connectivity graph [52] and outdoor-to-indoor connectivity [53].

Topological relationships can also be used to determine intersecting building elements that can be similar geometrically but consist of differences in semantic characteristics [54]. A similar study also found that topological relationships can also be used to query building elements [55],[56]. Adjacencies between building elements can be used to locate building elements that require repairs, as well as affected elements within proximity [57]. The connectivity between building elements is described in Figure 8.

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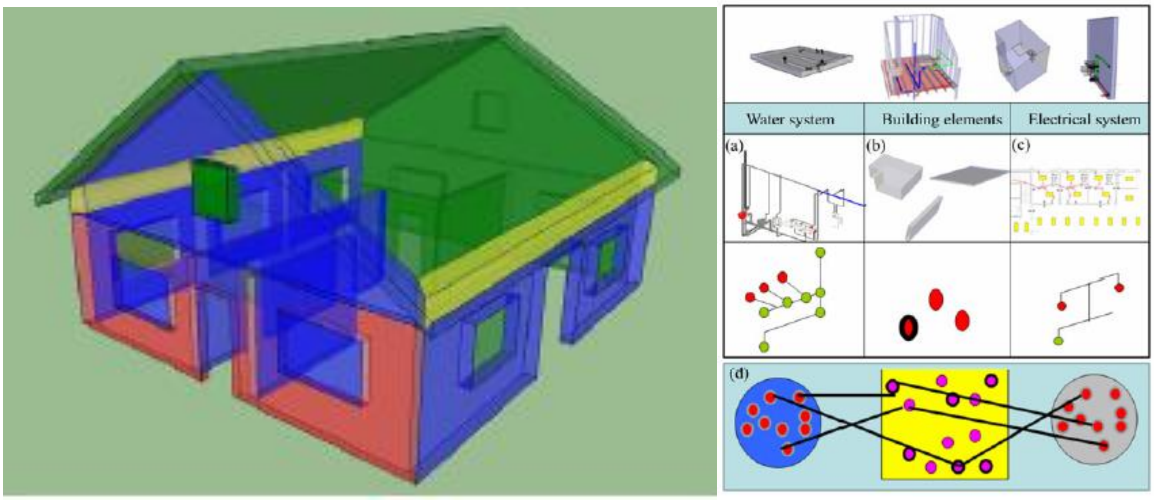

Figure 8. Intersecting semantic building elements [54] and connectivity model of building subelements [57].

In a broader sense, topology can also be used to model spatial relations between city regions to support smart city governance [58]. In addition to that, 3D geological objects represented by topological relationships can provide a better understanding of 3D geological systems [59]. Topological relationships describe in detail the geological structure based on interiors, exteriors, and boundaries of 3D geological objects [60], [61]. A similar study used topological relationships between 3D geological objects for mining exploration [62]. In addition to that, a topological analysis model also implemented topological points and connection lines around a ship to avoid collision with a marine vessel [63].

4. Discussions

As an overview of this topic, a network map visualisation was also generated based on articles on ‘topology’ and “GIS” ranging from the year 2008-2023. Bibliographic information and abstracts were exported from the Scopus database for 952 articles, which was used as input in a VOSviewer bibliometric network software. Based on this, terms related to ‘topology’ and “GIS” were selected and connected based on the weightage of occurrence for each term. Figure 9 shows a network visualisation that consists of 4 groups composed of 28 most occurring terms for studies related to ‘topology’ and “GIS”.

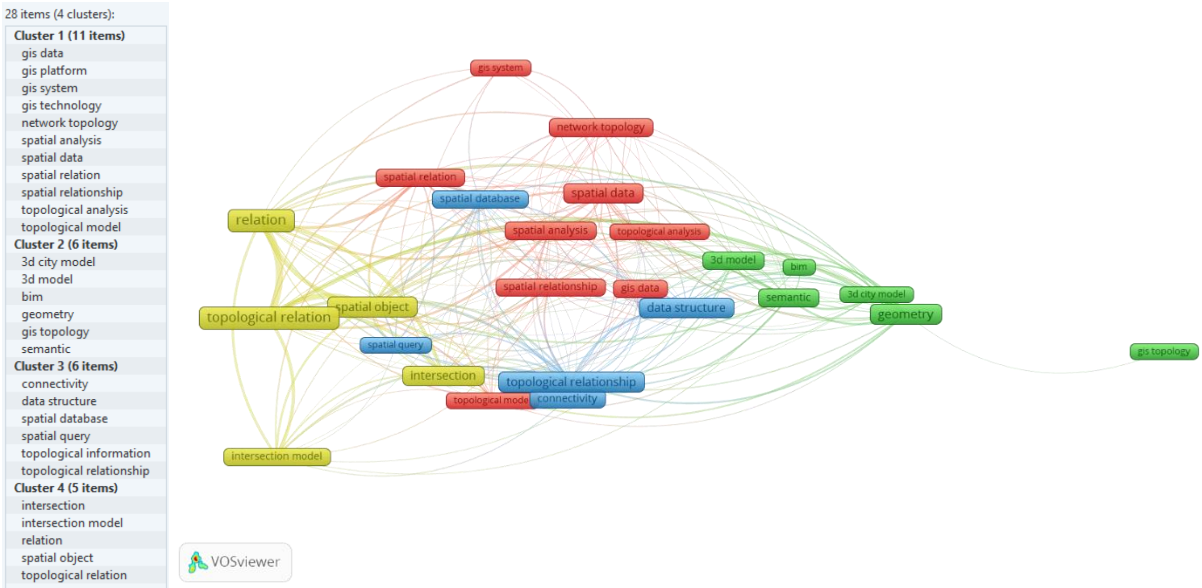

Figure 9. Visualisation of clusters in the network for studies related to 'topology' and "GIS".

The clusters of terms represent closely related studies based on the occurrence of terms. Cluster 1 consists of 11 terms, which are mainly 'GIS', 'spatial analysis', 'spatial relationships', and "topological model". This indicates that in order to carry out spatial analysis, GIS requires spatial relationships or network topology which are usually enforced by integrated or external topological models. This is parallel to the findings in Subsection 3.3 (Spatial analysis and queries) where GIS applications commonly utilise spatial relations and network topology for spatial analysis. Next, group 2 consists of terms such as '3D city model", "3D model", "BIM", "geometric", "semantic" and 'GIS topology'. This shows that 3D applications such as 3D city modelling and BIM focusses on geometric and semantic properties. The GIS topology is also loosely related to this cluster but only connected to geometry. This is in line with the previous subsection 3.1 (Data Validation) where topology is utilised for validation of 3D geometries for applications such as 3D cadastre. Cluster 3 consists of terms such as 'connectivity', 'data structure', 'spatial database', 'spatial query', 'topological information', and "topological relationship". This indicates that studies have been conducted on the use of topological information and relationships describing connectivity for the execution of spatial queries in spatial databases supported by additional data structures. This is consistent with Subsection 3.3 (Spatial Analysis and Queries), where topological data structures were also implemented to support connectivity for spatial queries. The smallest cluster consists of terms such as 'intersection model', 'spatial object', and "topological relation". This cluster was not included in the literature review process due to the fundamental focus of studies, which is determining topological relations between spatial objects using intersection models.

Clusters can also be visualised based on the year of publication, as shown in Figure 10. Studies related to 'GIS' and "topology" initially focused on spatial databases and 3D city models beginning in 2008 and moving to most recent studies focussing on GIS systems, BIM, GIS topology and intersection models. The clusters show that there is a gap in knowledge for a broader use of topology, especially for 3D GIS applications which commonly settle for the use of 2D topology such as network topology. This can also be observed in the network visualisation, where GIS topology is isolated from the other clusters and is only connected to geometry.

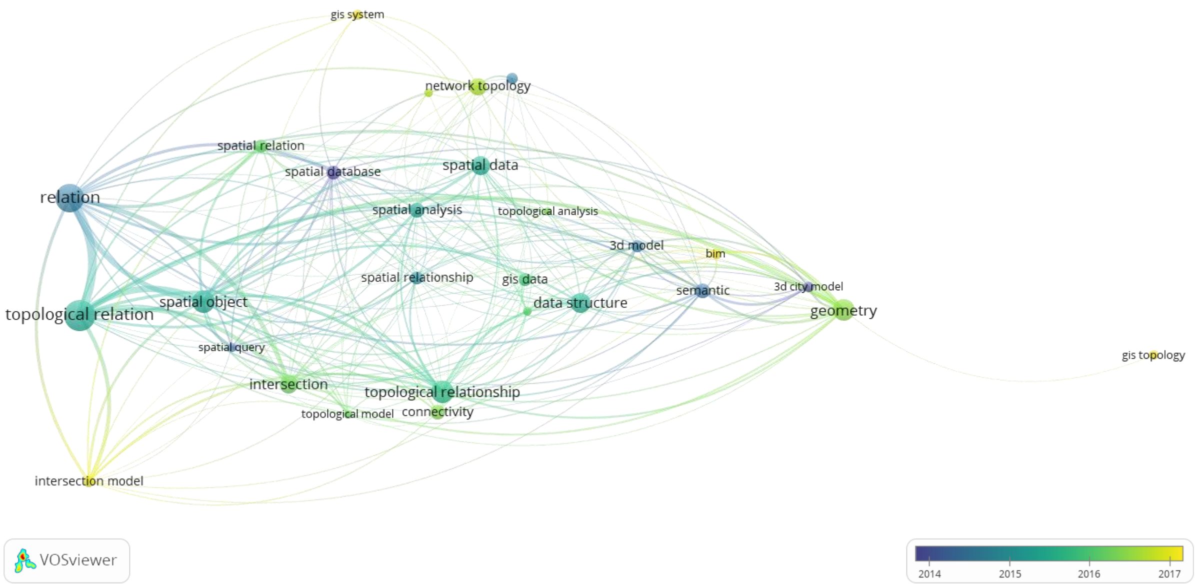

Figure 10. Visualisation of network clusters overlayed by year of publication.

5. Conclusion

This paper provided a review of the literature on the use of topology for 3D GIS. Online databases were searched for journal papers, conference proceedings, and book chapters that utilise topology for 3D GIS in the past 15 years. A total of 236 articles were retrieved and screened. The full-text selection of papers excluded papers that did not explicitly use topology as part of the methodology in 3D GIS applications. Developments in topological structures and topological rules were also not included. 45 papers were obtained and classified into 3 main categories describing the use of topology, which are validation, data reconstruction, and spatial analysis. Topological conditions could define valid interactions between 3D objects to ensure geometrically and topologically valid objects. Spatial analysis built on valid 3D objects provides a solid foundation for accurate results. Apart from that, topological properties can also be used to reconstruct 3D objects such as road networks, building structures, and entire city models. Automated reconstruction of voluminous data assisted by topological properties can also facilitate efficient reconstruction of geometric and semantic-rich 3D objects (see [64]). In addition, topology is the foundation of spatial analysis that requires connectivity and adjacency information. This includes 3D network analysis, indoor navigation or route analysis, geological exploration, and marine vessel safety. For future advanced applications, future research can incorporate topology in advanced spatial analytics (see [65]-[67]).

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