TOPOLOGICAL REQUIREMENT FOR 3D CITY MODELLING – A REVIEW

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ABSTRACT:

In the development of 3D city modelling, attention has been directed to the visualization and geometric components of a 3D city model. Less focus has been directed towards the topology and semantics of a 3D city model which led to dissatisfactory performance of visualization and analysis for specific applications in which topological information is significant. This paper provides a brief overview on city modelling and 3D city model as a means of representing the actual urban system. A review of the requirements of topology for city modelling in terms of visualization and analysis is also put forth in this paper. This review found that visualization of urban objects requires a comprehensive topological model to support a seamless and accurate visualization regardless of the objects' dimensionality. Moreover, topological properties or topological relations was also found to be a requirement in providing support for analysis in order to obtain accurate results. Conclusively, the importance of topology for city modelling should be highlighted and aspire efforts to improve topological components of city modelling parallel to the constantly evolving dimensionality of city models.

KEY WORDS: City Modelling, 3D City Model, Topological Model, Topological Primitives

1. INTRODUCTION

The 21st century is known as the century of development where urbanization is happening in countries all over the world. Existing cities are expanding while more areas are undergoing rapid development and growing into full-blown cities. Although there are numerous cities in a country let alone the world, each city is unique as it has its own physical and social elements (Horne, Thompson, & Podevyn, 2007). This shows the need for representing each city exclusively with respect to all elements of the city. Currently, more than fifty percent of the global population is residing in urban areas (Chen, 2011). Most often this occurs when residents of developing countries migrate from rural areas to the city in hopes of a better quality of life (Ujang, Anton, & Rahman, 2013). Cities will continue to undergo changes as brought by the social and economic growth (Egger, 2006). In other words, changes in the structure of a city are unavoidable. Therefore, it is crucial that decision-makers are able to understand these changes and plan or resolve problems for a better city. Hence, each city must be represented as close to reality as possible to assist decision-makers in understanding the significant urban structures with regards to the issue at hand (Whyte, 2002).

This paper reviews the requirements of topology for city modelling. Firstly, a brief explanation of city modelling, 3D city model and topology is presented. Next, the topological requirements for 3D city modelling which includes visualisation, and analysis and topological relations is discussed. Following that, a review regarding the implementation of topology in visualisation and analysis is put forth. Ensuing that, a brief discussion of the issues reviewed in the paper is presented. Finally, a summary concludes the issues discussed in the previous sections.

2. MOTIVATION AND RELATED WORKS

2.1 City Modelling

One of the many ways to represent a city in forms that can be understood by users of different backgrounds of knowledge is by visualising a city in the form of a model. A city model is defined as a representation of the urban structures and spatial properties that depicts the actual city (Billen et al., 2014). Therefore, city modelling can be defined as a replication of the actual urban structures that makes up an urban system or city (Zhu, Hu, Zhang, & Du, 2009). In other words, a city model is a representation of a real city where the model can either be in 2D or in 3D depending on what is required by the user. As an effort to model cities, computer-generated city models are being used as a means of visualization for the representation of a city and its elements (Horne et al., 2007). So far, digitized representations of cities in two dimensions (2D) have assisted in the management and storage of information regarding the city's

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components. The most common form of 2D city representations are maps, building or city plans and other forms of representation made up of geometries in 0D to 2D (Zhu et al., 2009). However, the 2D representation of a city is only able to provide users with a rooftop view of the city which restricts the users' ability to understand and assess the effects of changes that occurs within the city at a scale appropriate to real life perspective (Thompson, Horne, & Fleming, 2006). Parallel to the advances in technology, city modelling has also shifted towards modelling in three dimensions (3D). This is due to the capacity of 3D modelling in offering a more realistic view of a urban structures as compared to a 2D model (Ujang & Rahman, 2013). A 3D city model refers to the integration of 3D geographical data and thematic characteristics of the urban structures within a geographic database (Chen, 2011). Besides that, Zhu et al. (2009) also defined 3D city model as a digital visualization of a city in 3D which includes both geometric and semantic components. Apart from allowing users to experience a city model that is up to scale, a 3D city model also provides users with the means to envision and work with 3D information more effectually (Chen, 2011).

2.2 3D City Model

As the technology of acquiring data in 2D has moved towards 3D, the representation of cities in 3D have also become essential for better comprehension of the city. The need for a 3D city model emerged as cities rapidly developed to form a complex urban system where urban structures can no longer be considered as isolated objects (Zhu et al., 2009). A 3D city model was defined by Billen et al. (2014) as a 3D replica of the urban entities in a city that can be used to study the urban system. On the other hand, a 3D city model can also be defined as a model which represents a city with the usage of 3D spatial information as well as semantic information within a single framework (Chen, 2011). This definition also refers to a semantic 3D city model which is a 3D city model that is composed of not only geometric components but also semantic information such as attributes of features and relationships (Billen et al., 2014). In addition, a 3D city model is also known as a virtual reality urban model where a city and its features are graphically visualised within a digital environment (Thompson et al., 2006). A similar definition of a 3D city model was also presented by Döllner, Baumann, and Buchholz (2006) where 3D georeferenced data is visually represented by a 3D virtual environment which has the capability of creating, managing and integrating the many aspects of a city within one framework. In other words, a 3D city model is a form of representation in 3D which includes 3D locational information of the city as well as semantic information that describes the city seamlessly within a digital environment.

The developments in visualisation and data collection technology have brought to light the needs for a city or urban system to be represented in 3D. Current technology that can now collect 3D data has given visualisation a data source that can provide optimum support for the construction of 3D models. The availability of 3D data and 3D graphical visualisation within a 3D city model has given users the opportunity to do simulations that allows them to interact with the virtual model as they would interact in the real world (Zhu et al., 2009). Thompson et al. (2006) also found that 3D models are able to improve and ease user interactions in exploring the urban system in different resolutions or level-of-detail. This was also supported by Kaňuk, Gallay, and Hofierka (2015) who stated that 3D models are better for user interactions and warrant complete representation of spatial information compared to 2D representations. Besides that, 3D city models also allow the integration of qualitative data and information from different disciplines to best replicate the actual conditions of a city (Thompson et al., 2006). This also provides the opportunity for experts from different disciplines to acquire information from the same 3D city model and contribute to improve the city.

2.3 Topology

The real world is considered as a space or topological space whereby an object resides in the space. One of the most important characteristics of this object is its location which describes its position within the space. The geometric components of the object also describe the form or shape of the object. This allows the determination of the spatial properties of the object and what the object looks like. Apart from the geometrical component of the object, the topological component is also important in the representation of the elements. Topology is defined by Worboys and Duckham (2004) as the study of topological transformations and the properties that are left invariant by the transformations. Therefore, the topological component is known as the characteristics of an object that remain unchanged by topological transformations of the space (Worboys & Duckham, 2004). This refers to the changes of the space which will cause changes to the geometrical component of the object or form of the object but, these changes will not change the topological properties of the object. The way in which the components of the object are related are not changed and are still related the same way albeit the form of the object changed. On the other hand, topology can also be defined as properties which define the relative relationships between objects within the space (McDonnell & Kemp, 1995). This means that topological properties of an object are properties that remain unchanged despite transformations of the space and define the qualitative properties of the object in terms of relationships to other objects. Therefore, the representation of these spatial objects are in need of sufficient support for geometric and topological components (Kumar, 2014).

3. TOPOLOGICAL REQUIREMENT FOR CITY MODELLING

3.1 Visualization

In moving towards 3D modelling of cities or urban structures, a requirement for the preservation of topological properties to be used in the visualization of the model has surfaced. Skyscrapers are complimented with underground tunnels, bridges and many other structures. Gröger and Plümer (2011) found that a similar linking of objects such as tunnels and bridges to connect isolated areas was unable to be represented accurately with the occurrence of errors such as detachment of objects from the terrain. Therefore, a unified city model where objects are linked to terrain is necessary to provide a topologically accurate model of the buildings (Boguslawski & Gold, 2015). Besides that, a study by Ghawana and Zlatanova (2012) also found that topological inconsistencies occurred when above surface and below surface features were integrated. The results of the study as shown in Figure 1 shows obvious discrepancies in the integrated display of both above surface and subsurface objects (Ghawana & Zlatanova, 2012). Xie, Zhu, Du, Xu, and Zhang (2013) also found that a comprehensive topology of the 3D objects was required in ensuring consistency and connectivity of objects including its individual elements.

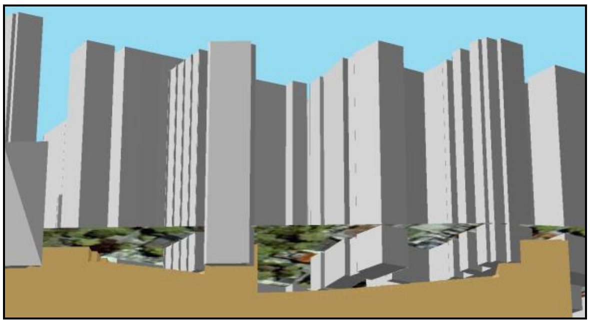

Figure 1. Example of detached above surface and sub-surface objects (Ghawana & Zlatanova, 2012)

Topologically, subsurface parts of buildings or objects cannot intersect with the surface or above surface buildings (Ghawana & Zlatanova, 2012). Correspondingly, a building which intersects with the terrain is topologically inaccurate if the area of terrain-building intersection is not removed (Boguslawski & Gold, 2015). However, the removal of the shared surface will consequently remove the link between the building and terrain. The developed subsurface objects application domain extension (ADE) catered for the semantic aspects of the subsurface objects which were represented by geometrical primitives and not topological primitives (Ghawana & Zlatanova, 2012). On the other hand, Gröger and Plümer (2011) used the 2.8D map surface model as the topological model in order to identify and topologically verify handles on surfaces as bridges. However, this required a conversion of 3D models to a 2.8D map and does not support the interiors of buildings. Similarly, Boguslawski and Gold (2015) utilized the dual half-edge (DHE) structure and introduced and external cell to establish connectivity between the objects and terrain as an integrated topological model.

It is apparent that the absence of a concise topological model in the modelling of a city not only affects the superficial quality of visualization but also affects the accuracy of the model in terms of topological properties. These properties are also crucial in describing the object and ensuring accurate interaction between objects as a replication of the real world. Hence, Ghawana and Zlatanova (2012) stated that a 3D model that maintains accurate and correct topology is necessary for accurate visualization of above and subsurface objects. This is also supported by Gröger and Plümer (2011) who stated that a topological model that supports the integration of all objects and terrain is able to avoid errors as mentioned before.

3.2 Analysis and Topological Relations

As the significance of visualizing objects in 3D is now recognized, most city modelling approaches support 3D primitives in the construction of objects. Topology assists in describing the topological structure of an object which is important in supporting exploratory analyses (Ellul, 2007). However, without the support of 3D topology, the outcomes from analyses carried out will remain in 2D (Hyeyoung, Geunhan, Chulmin, & Hyunjin, 2009). Ellul and Haklay (2006) stated that analytical queries related to adjacency, intersection, connectivity, containment and disjointedness requires information that includes topological properties. Additionally, 3D analyses regarding 3D proximity also rely on the support of a complete 3D topological structure (Moser, Albrecht, & Kosar, 2010). A study by Isikdag, Zlatanova, and Underwood (2013) also found that the maintenance of topological relationships which is also a topological property of the features will support exploratory analyses such as queries regarding related building elements. On the other hand, Li, Luo, Zhu, Ying, and Zhao (2016) stated that with the maintenance of topological primitives, dimensionality of relations between objects can also be identified. This shows that analyses are dependent on the supported dimensionality both geometrically and topologically.

Although topology can be utilized in both semantic and geometric levels (Li et al., 2016), the role of topology varies according to the application. A study by Isikdag et al. (2013) found that topological relationships determined by algorithms assisted in the deduction of semantic information between building elements crucial for indoor navigation. This information is extracted based on the hierarchies of building element classes in CityGML (Isikdag et al., 2013). Another study by Li et al. (2016) also developed an extension of CityGML specifically to determine topological relationships between elements such as intersects, overlaps and others which were derived from the geometric primitives using algorithms. However, the topological properties are not explicitly stored within the model. Another use of topology at a geometric level was as a means of checking the consistency and integrity of the geometric primitives (Li et al., 2016). Hence, the absence of a 3D topological structure needed in a consistent 3D profile will cause discrepancies and incomplete topological connectivity of objects which will hinder computational analysis (Xie et al., 2013).

4. IMPLEMENTATION OF TOPOLOGY IN 3D CITY MODELLING

4.1 Topology for Visualization in 3D City Modelling

A study was carried out by Boguslawski and Gold (2015) utilised the DHE topological data structure to model and link buildings together with terrain. The connection or unified modelling between buildings and exteriors is important to ensure a continuous and consistent city model (Boguslawski & Gold, 2015). An illustration of the connection between building and terrain is shown in Figure 2. An example of how to connect buildings and terrain is shown in Figure 3.

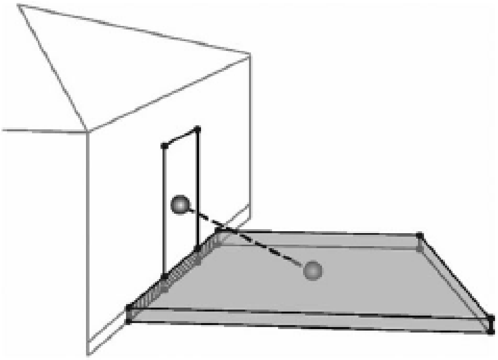

Figure 2. Connection between building and terrain (Boguslawski & Gold, 2015)

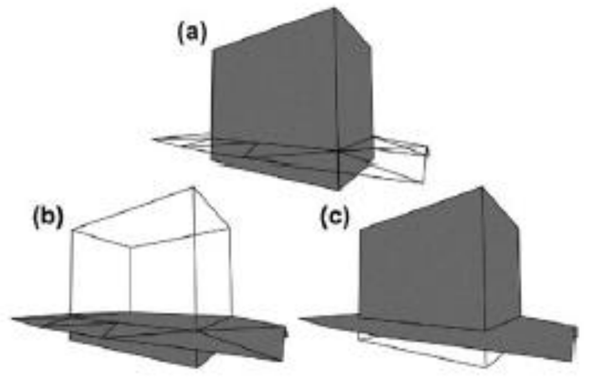

Figure 3. Polygon mesh method of modelling buildings and terrain together (Boguslawski & Gold, 2015)

As shown in Figure 3, the building is modelled as a single solid while the exterior is divided into two parts which are the above-surface exterior and the underground exterior (Boguslawski & Gold, 2015). This method of modelling using the DHE topological data structure to link buildings to terrain results in the maintenance of connectivity as well as taking up the least storage and memory (Boguslawski & Gold, 2015).

Another study by Li et al. (2016) implemented a topological model to determine topological relationships between elements of an object. This model was developed as an application domain extension for CityGML which consisted of the topological relationships and topological primitives (Li et al., 2016). An example of modelling topological relationships in a 3D city model is shown in Figure 4.

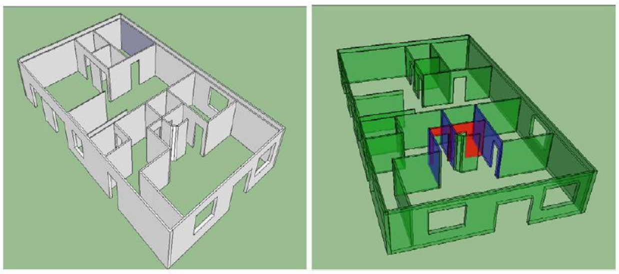

Figure 4. Topological relationships explicitly shown in 3D city model (Li et al., 2016)

In Figure 4, the illustration on the left shows the 3D city model without the implementation of the topological model while the illustration on the right depicts the 3D city model with the implementation of the topological model. It is apparent that the implementation of the topological model is able to explicitly show the different topological relations between building elements (Li et al., 2016). The feature of interest which is queried in the example shown in Figure 4 is a wall which is represented in red while blue solids represents features that share a common surface (touch relationship) and green solids represents features that are disjointed from the feature of interest (Li et al., 2016). Therefore, the explicit visualisation of topological relationships between features is able to be realised with the implementation of a topological model.

4.2 Topology for Analysis in 3D City Modelling

Given that topology is a required component in support for analysis, topological models are relied on for providing a structure from which the results will be derived. A study by Lee and Zlatanova (2008) implemented a network-based topology in for emergency response as a support for 3D optimal route analysis. In the case of emergency response, it is crucial to be able to get to the area of emergency in the shortest amount of time. Emergencies or natural disasters can also cause unexpected changes such as damage and blockages of the routes which also includes the accessibility of the building and its interiors. As an effort to reduce the amount of time for emergency responders to arrive at the scene, a network-based topological model was used to integrate both road networks with the building interior (Lee & Zlatanova, 2008). This integration extended the 2D nature of a road network to a 3D network analysis with the capability to include the building interiors or also known as indoor navigation. The building which is the area of emergency is shown in Figure 5 and the results of the implementation of a network-based topological model in determining the optimal route for emergency response is shown in Figure 6.

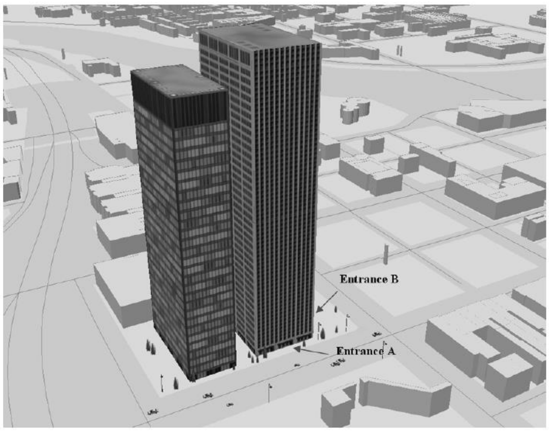

Figure 5. Building as area of emergency (Lee & Zlatanova, 2008)

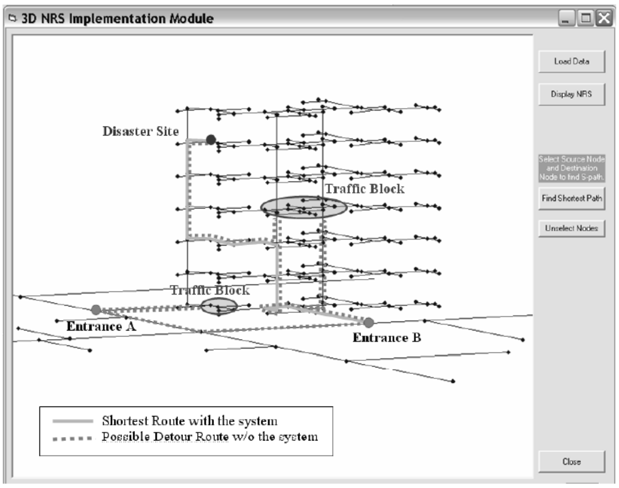

Figure 6. Optimal route to emergency site using network-based topology (Lee & Zlatanova, 2008)

As shown in Figure 5, the building which emergency responders need to access has two entrances. In the event of an emergency, it would be time-consuming to try each entrance by turn and disadvantageous in terms of manpower to try both entrances simultaneously to determine the best route. Therefore, the system utilising topology was able to determine the optimal route in reaching the destination as represented by the solid gray line in Figure 6 which shows Entrance B as the entry point and avoiding the blocks to reach the destination. It is apparent that the optimal route (shown as the solid gray line in Figure 6) is shorter than the usual route (shown as the dotted line in Figure 6) the responders would take without the system. Hence, the implementation of the network-based topology which integrated street network and building interiors was able to reduce the time for emergency responders to arrive by 86% of the total travel time (Lee & Zlatanova, 2008).

Another study by Boguslawski, Gold and Ledoux (2011) implemented the dual half-edge (DHE) structure as a topological model which is able to explicitly preserve connectivity information and support 3D analysis. The significance of maintaining connectivity information is obvious for indoor navigation where adjacent rooms that share walls but the door to the room is positioned on a non-shared wall. The DHE structure used in the topological model stores the connectivity information as a dual graph that connects the elements of the building which includes doors, walls, windows and others as cell nodes (Boguslawski, Gold, & Ledoux, 2011). The connectivity can also extend to the exterior of the building which is represented as an external cell which also has a matching node in the dual graph (Boguslawski, Gold, & Ledoux, 2011). This provides an integration of building and terrain in a single model. An example of analysis is shown in Figure 7 where a shortest path between two rooms is calculated without taking into account the exterior of the building. Meanwhile, Figure 8 shows an example of shortest path analysis between two rooms with the inclusion of the building exterior.

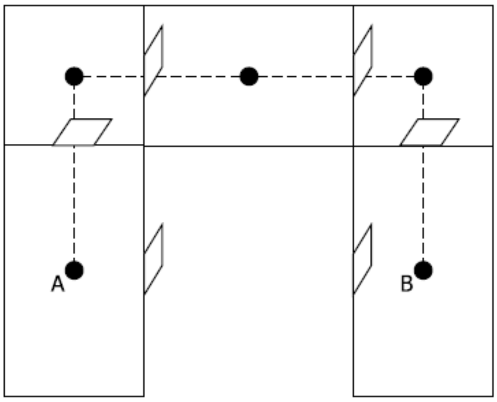

Figure 7. Calculation of shortest path from room A to room B without building exterior (Boguslawski et al., 2011)

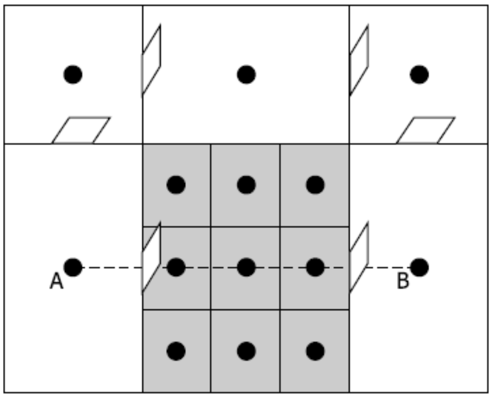

Figure 8. Calculation of shortest path from room A to room B with building exterior (Boguslawski et al., 2011)

As shown in Figure 7, a longer path from room A to room B is derived from the connectivity information without the building exterior. Whereas in Figure 8, a more direct and shorter route is available by exiting the building from room A and cross the exterior to enter the building again from room B. Therefore, the topological model is able to preserve the connectivity between building elements and also between interior and exterior to improve efficiency of rescue simulations that require analysis of direct escape routes (Boguslawski et al., 2011).

5. DISCUSSION

The previous sections have put forth issues that require the use of topology for city modelling and also some implementations of topology. Table 1 presents the topological requirements learned through the review in this paper.

Topological Requirement	Problems	Implementation of Topology Results
Visualisation	• Detachment of building and terrain	• Connection of building to terrain
	• Inconsistencies in visualisation of above surface and underground objects	• Seamless integration of above surface and underground objects
	• Inaccurate representation of interactions between objects	• Interactions between objects are explicitly preserved
Analysis	• Analysis supported by 2D topology results remains in 2D	• 3D analysis results are available
	• Inability to support 3D exploratory analyses based on to adjacency, connectivity, containment and disjointedness	• 3D analysis is supported (e.g: analysis between 2D street network and 3D building interior)

Table 1. Topological requirements for city modelling

Based on Table 1, topology is required in visualisation and analysis for 3D city modelling. The visualisation of urban structures can be improved by implementing a topological model. Problems such as detached buildings from terrain and inconsistencies in visualisation of above surface and underground objects is solved by establishing connections through the usage of topological models that explicitly store topological properties. This advantage of the implementation of a topological model is also able to accurately represent topological relations between objects which describe how the objects interact. Apart from that, a topological model can also support 3D analysis that has the ability to extend from 2D to 3D and provide accurate results in 3D. The preservation of topological properties such as connectivity, adjacency, containment and disjointedness is also able to contribute to semantic information of the objects.

6. SUMMARY

The nature of urban features or objects that together forms an urban system is proof that a comprehensive topology to link the entities of the city is required to accurately visualize and model the actual city. This paper has presented a brief explanation of city modelling and 3D city models. An overview of topological requirements for city modelling in terms of visualization and analysis was also put forth in this paper. It was discussed that visualization can benefit from an explicit storage of topological properties within a topological model from not only a superficial sense but also to ensure an accurate representation of the objects. Besides that, topological properties and topological relations was also discussed as a means of performing analysis related to connectivity, adjacency, intersection, and containment of urban objects. This analyses also provides a foundation for more complex and application-specific uses such as indoor navigation, simulations, and others. In conclusion, as city models are moving towards n-dimensionality to best represent the nature of real-world phenomena, the requirement for a comprehensive topological model is crucial to facilitate and yield accurate results from n-dimensional visualization and analysis.

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