# A Comprehensive Temporal Model for Geometric and Topological Data Management in 3D Space

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**Abstract**

Advanced analysis of spatio-temporal data is improving our knowledge about natural phenomena such as landslides and volcanic activity. Furthermore, it can contribute to a deeper understanding of the built environment by predicting city development. However, the data produced by the modelling of these observations can easily rise to terra bytes of 4D (3D space plus time) data. Also, the repeatability of such analysis is essential. Thus, repeatable and reliable access to big spatio-temporal data, models and simulation results should be guaranteed. However, today´s Geographic Information Systems (GIS) are not prepared to meet these requirements. Therefore, we present a comprehensive spatio-temporal data model for GIS and geodatabase management systems that can be used as the "heart" of 4D GIS. The comprehensive model enables a flexible management of time-series-based geometric and topological data. It cares of storage reduction and computational efficiency when storing, retrieving, and processing surface- and volume-based data in 3D space plus time. Furthermore, the model can handle geometry and topology changes of 4D data, i.e., mesh changes of triangulated surfaces and tetrahedral volumes over time. The model also allows the attachment of detailed semantic information to geometric and topological entities. The various concepts, implementation and the benefits of our comprehensive model are presented. Finally, conclusions are drawn from the approach and an outlook is given on future research including demanding applications based on multi-scale digital elevation models.

## 1. Introduction

The continuous monitoring of environmental phenomena (such as glacier movements or volcanic activity) can easily produce terabytes of data due to the extension of 3D data with time as the fourth dimension. Efficient management of such *spatio-temporal* geodata is crucial for advanced analysis and decision-making in domains ranging from geosciences to urban planning. Traditional Geographic Information Systems (GIS) methods often do not adequately focus on the temporal dimension, leading to redundant data storage and potential slow queries when handling temporally extended 3D models, i.e. 4D models (4D = 3D + time). There is a clear demand for data management models that can handle large 4D datasets in an efficient and flexible manner, both in terms of storage and computational performance.

The management of spatio-temporal geodata introduces new unique challenges. For example, if each time step of an evolving 4D model is stored independently (also referred to as the *snapshot model*), the dataset quickly becomes massive due to duplicated geometry and topology storage across multiple time steps. On the other hand, if spatio-temporal data is not handled carefully, there is a risk of losing the continuity and integrity between consecutive time steps of a spatio-temporal model. Efficient *spatio-temporal* data management is therefore a key demand for 3D/4D GIS. The goal is not only to reduce the needed storage, but also to preserve the ability to perform spatial, temporal and spatio-temporal queries, analyses, and visualizations.

In this paper, we present a comprehensive model for managing geodata, based on simplicial complexes, that addresses these challenges. The model extends previous research on spatio-temporal databases, geometry data structures and topological concepts. Simplicial complexes (e.g. triangle meshes in 3D space) are a fundamental representation for spatial objects and are used to model natural structures such as terrain and geological volumes. By extending the spatial representation with time, we obtain a flexible *4D model* capable of describing the evolution of such structures over time. The proposed data management model introduces several innovative concepts: point tubes, mesh components, a pre/post object topology management scheme motivated by Polthier and Rumpf (1994), a delta storage concept, and a flexible handling of thematic and semantic data to efficiently manage *d*-simplicial complexes (with spatial dimension $d \in \{0,1,2,3\}$) through time in a 3D space. The remainder of this paper is structured as follows: We first review recent research and related work in section 2. Then we describe each component of our model in detail (section 3) and discuss the implementation aspects and benefits in section 4. Finally, in section 5 conclusions are drawn from the approach and an outlook on future enhancements is provided.

## 2. Related Work

Early research recognized that extending GIS to the temporal dimension requires the rethinking and extension of the existing data models. Langran and Chrisman (1988) introduced a model to represent continuous change via a sequence of discrete snapshots, where each snapshot is a complete spatial state at a given time. This *snapshot model* is conceptually simple and has been adopted in multiple systems (Renolen, 1997; Le et al., 2013; Gabriel et al., 2015). However, it leads to redundancy and large storage requirements, because for every time step, a full copy of the model is stored. Modern database systems that manage spatio-temporal data often still follow this approach, treating time as an attribute and store duplicate geometry for each time step. The inefficiencies of this approach led to the development of more efficient data models.

A survey of large language models and pre-trained models - inclusive temporal knowledge graphs - used to analyze time series and spatio-temporal data in real-world scenarios and spatio-temporal data mining has been presented by Jin et al. (2023). Zlatanova et al. (2004) give a relevant summary of topological models and frameworks used for 3D objects including formal data structure (FDS), Tetrahedral Network (TEN), Simplified Spatial Model (SSM), Urban Data Model (UDM) and different object-oriented models. Simplicial complexes have long been used for modeling 3D geospatial objects of natural phenomena, e.g. geology models. For instance, Breunig et al. (1999) and Mallet (2002) demonstrated how tetrahedral networks (3-simplicial complexes) can represent geological layers. These early works provided the foundation for *n*-dimensional GIS data models. Xing et al. (2015) showed the feasibility of handling large 3D meshes (with millions of elements) for geological applications. Extending such models to 4D (3D space + time) impose additional challenges in data handling and require efficient algorithms to manage the temporal dimension.

Another important development in geospatial data management has been the use of object-oriented and service-based architectures to handle complex spatio-temporal data (Balovnev et al., 1999). Breunig et al. (2016) presented *DB4GeO*, a service-based geodatabase architecture designed for multi-dimensional data management, analysis and visualization. In DB4GeO, spatio-temporal data based on *d*-simplicial complexes can be managed and multiple geo-services can be used for advanced querying and visualization.

In the CityGML standard (CityGML, Version 3) also the concepts of “Space” and “Boundary Space” are existing. However, temporal change is only modelled by a versioning concept providing a fixed number of city model versions.

Ohori et al. (2015) and Jahn et al. (2022) use graph-based data models to represent topological relationships in *nD* objects with the aim to enhance *nD* topological analysis. A related approach was presented by Boguslawski et al. (2011), introducing the Dual Half-Edge (DHE) data structure for explicit modelling of 3D topological relationships.

Hitherto, research on spatio-temporal data management has been conducted in single aspects, such as spatio-temporal requirements, spatio-temporal indexing, spatio-temporal updation, and spatio-temporal applications (Pant et al., 2018; Breunig, 2020; Raj, 2024). The next section, however, introduces an approach of a comprehensive data management model that consolidates multiple concepts and addresses the key requirements for efficient spatio-temporal data handling in temporal GIS according to Yuan (2008) and for applications such as temporal digital elevation and city models. It supports an efficient management of geometric change over time as well as topological and geometric queries across multiple time steps.

## 3. A Comprehensive Model for Spatio-temporal Data Management

### 3.1 Requirements and Challenges

To efficiently handle spatio-temporal geodata such as temporal digital elevation models or city models, multiple requirements must be satisfied:

- Support of variable subregions: the model should support subregions of a 4D model that evolve with individual time steps, allowing different areas to have different update frequencies.
- Computational efficiency: computation processes should be optimized and spatio-temporal operations accelerated.
- Storage efficiency: redundant storage of data across multiple time steps should be minimized to reduce the overall storage demands.
- Advanced analysis capabilities: the model should be a solid foundation for advanced spatio-temporal analysis (e.g., simulations or trend detection) by maintaining rich topological and semantic information.
- Continuation of time in 4D models: discrete 3D time steps should be linked into a continuous 4D model, ensuring that the temporal dimension is fully integrated with the spatial data.
- Interpolation of intermediate states: the provided data structure should be able to offer the option to interpolate the geometry and topology between time steps, enabling the construction of intermediate states at arbitrary times within the model’s time interval.

Our proposed model targets these requirements through a combination of data structures and (topological) concepts. It manages geospatial information as *d*-simplicial complexes (with *d* ranging from 0 for point clouds up to 3 for tetrahedron meshes) that evolve through time. The key components of the model are described in the next sub-sections.

### 3.2 Point Tubes: Separating Vertices from the Mesh Topology

A core idea of our comprehensive model is the point tube concept, which separates the geometric data (vertex coordinates) from the topological data (mesh connectivity). In a traditional approach, if a vertex within a 3D mesh moves over time, its coordinates would be stored duplicated in each simplex this vertex is part of. By contrast, in our model each vertex is represented as a point tube (pt), i.e. essentially a temporal data structure that traces the vertex’s trajectory through all the time steps and can be referenced by multiple simplices, see Figure 1. All vertices of the simplicial complex are managed in these point tubes, while the mesh´s topology (the connectivity of vertices forming the edges, faces, and volumes) is handled separately. Details of this approach have also been presented in (Kuper, 2018).

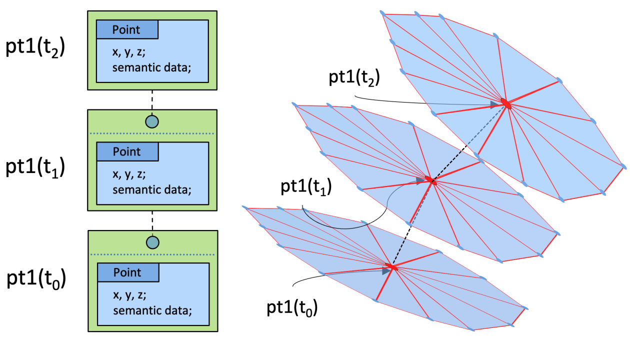


Figure 1. Point tube approach of a 2-simplicial complex.

A point tube can be thought of as a container holding the coordinate of a particular vertex at each recorded time step. By decoupling the vertex positions from the mesh topology, we gain two main advantages. First, redundant storage is eliminated: a vertex that is used by multiple simplices is stored only once. Second, it becomes easier to reconstruct the state of the mesh at any given time. The topology of the mesh (the mesh structure formed by a *d*-simplicial complex) is stored just once for the period of time during which it remains valid. The actual coordinates for a specific point in time are fetched from the point tubes and combined with the mesh whenever a representation of the model is needed. With the help of an interpolation between the stored coordinates in a point tube, it is possible to derive an


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intermediate 3D model at an arbitrary time $t_s$ that can also lie between explicitly stored time steps. Therefore, the point tube structure provides a continuous 4D trajectory for every point in the model, which greatly facilitates queries like tracking the movement of a specific point in time within the mesh topology.
By maintaining stable vertex identities over time, the point tube concept also simplifies certain computations. Transformations or analyses that apply to the entire object can be performed by updating the point tubes, without having to rebuild the spatial relationships. The mesh topology consists of references to point tubes that individually deliver the valid coordinates during a query for a specific state of the object, e.g. state of then 4D model at time $t_s$. Moreover, this separation of the geometry from the topology lays the groundwork for handling more complex changes of the model over time, as described next.

### 3.3 Mesh Components: Adaptive Spatio-Temporal Partitioning

Spatial processes often do not evolve uniformly across an entire region. Some subregions may change more rapidly and require a finer temporal resolution (more frequent time steps), while other regions remain relatively static and can be updated more sparsely. To accommodate this heterogeneity, our model integrates the mesh component concept (Kuper, 2018). A mesh component is a subset of the 4D model that is modeled and stored with its own temporal discretization. Each mesh component has an independent sequence of time steps, which can be as frequent as needed for that particular region.

$$4D\ model\ m = \sum_{i=1}^{n} mc_i \quad \text{with } mc_i = \sum_{j=1}^{m} 3D\ model\ m_j$$

This approach allows a 4D model to be divided into subregions with different temporal resolutions, providing an adaptive handling of time based on local dynamics. For example, a 4D geological model of a mountain landscape that includes a slow-moving hillside and an active open pit mine nearby. The hillside might be updated yearly (if changes are minimal or not of particular interest), whereas the mine area might be updated monthly or even weekly. Using mesh components, these two areas can be managed as two mesh components within the overall 4D model, each with its own timeline of time steps. This approach leads to significant storage and processing savings: the management of the relatively stable hillside does not encounter the overhead of a high-frequency time series, and the rapidly changing mine can be managed in detail without affecting the entire dataset's size.
Each mesh component is internally managed via a collection of point tubes for the vertices with their own temporal discretization (see Figure 2). If the mesh topology does not change over multiple time steps, it is stored only once for the entire 4D model and references the corresponding point tubes.

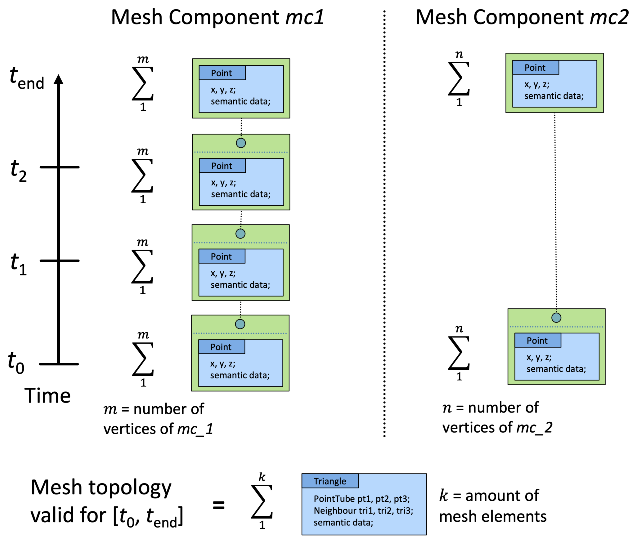


Figure 2. Mesh component structure realized with point tubes.

The border between adjacent mesh components requires special attention. If two subregions have different time step intervals, we must ensure that their border region is consistent at shared moments in time. Our model addresses this by using point tubes: a vertex lying on the boundary between two components is managed by a specific point tube and can be used by multiple mesh components, therefore the boundary vertex has a well-defined position. This mechanism maintains the consistency of the border region between two mesh components with different temporal resolutions. The mesh components provide a flexible temporal partitioning of the dataset, while the point tube concept ensures that the net topology remains consistent over time.

### 3.4 Topology Management with Pre- and Post-Objects

When managing 4D data, another challenge is the handling of topology changes over time. A topology change means that the mesh structure, i.e. the connectivity between the vertices (to form a $d$-simplicial complex) is altered over time. The mesh topology might change at a certain time step to increase the model's detail or to integrate a new spatial object. Such changes are common in long-term modelling using incremental model updates. If not handled carefully, such a topology change can disrupt the continuity of the 4D model, because a simplex (e.g. a triangle or tetrahedron) in one time step might not directly correspond to one specific simplex in the next time step.
Our model adopts a strategy based on the integration of pre- and post-objects to manage such topology transitions, based on the work of Polthier and Rumpf (1994). The idea is to introduce intermediate objects that ensure a one-to-one correspondence between time steps. When a topology change is about to occur at a new time $t_n$ a so-called pre-object for the time step $t_n$ is introduced. In this pre-object of time step $t_n$ each simplex of the model $t_{n-1}$ (post-object of $t_{n-1}$) has a 1 to 1 relationship. Therefore, the topology between the two following time steps $t_{n-1}$ and $t_n$ remains the same and is exclusively changed between the pre-object and the post-object of the same time step $t_n$, see Figure 3.

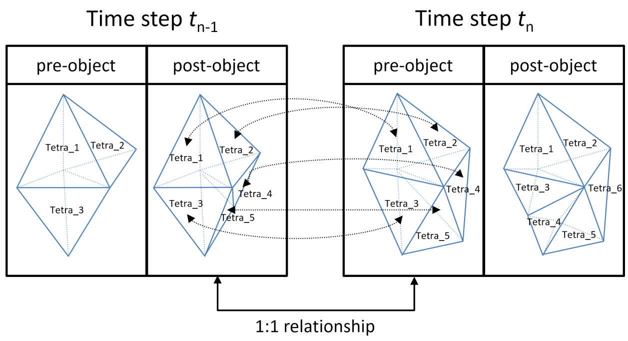


Figure 3. Integration of pre-objects to establish a 1:1 relationship between the triangles in the time steps $t_{n1}$ and $t_n$.

With the introduction of pre- and post-objects, changes of the mesh topology in 4D models can be properly managed. For example, if a mesh is refined at time $t_n$, e.g to increase the details in a specific region (Lautenbach and Berlekamp, 2002; Kuper et al., 2016), with our model it is possible to introduce a pre-object $t_n$ with the same net topology of post-object $t_{n-1}$ and a geometry similar to the post-object $t_n$. One approach to create such pre-objects, if they are not properly built during the modelling process, is to project the geometry of post-object $t_{n-1}$ onto the geometry of post-object $t_n$, see Figure 4.

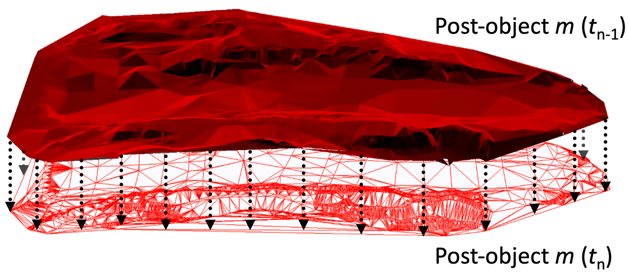


Figure 4. To create a pre-object for time step $t_n$ the geometry of post-object $t_{n-1}$ can be projected onto the geometry of post-object $t_n$.

Due to this concept, the topology and the transition between time steps can be properly managed. The point tubes ensure that the geometry (vertex positions) interpolate consistently. This directly supports robust spatio-temporal analysis, since operations like volume calculations or tracking of changing geometries remain well-defined across topology changes.

### 3.5 Delta Storage: Storing Only the Changes Between Time Steps

To further optimize storage and to improve the efficiency of calculations, our model integrates a delta storage concept. With this concept the storage of duplicate data can be avoided by storing only the *differences* (deltas) between successive time steps. Therefore, during the construction of a 4D model, each new time step is compared to the previous one to identify parts of the dataset that remain unchanged. Unchanged vertices are then referenced and not stored anew. Altered vertices are properly handled by extending the corresponding point tubes. The mesh topology also remains valid for the entire time interval until it changes. This approach is e.g. analogous to the management of successive versions in software repositories such as GIT-repositories (Chacon S. and Straub, 2025). Rather than storing every version in its entirety, an initial full version is stored, and subsequent versions are stored as deltas.

The delta storage concept leads to a significant reduction in the overall data volume, especially for scenarios in which the changes between successive time steps are relatively small. By merging the delta concept with point tubes and our topology management, we achieve an efficient and compact management of 4D models. In practical terms, delta storage means that for each mesh component, the first time step is stored completely, and thereafter each subsequent time step only contributes a set of updates. If a vertex moved, i.e. the geometry changes, its new coordinates at the new time are added to the corresponding point tube (which is effectively a delta for that vertex's position). If a topological element changed (e.g., an edge split into two), that change is managed via the pre/post-object mechanism, but everything unchained is referenced from the previous time step. Therefore, large areas of the model that remain static or undergo only minor changes over time, do not lead to a storage overhead. This not only saves disk space but also accelerates queries that include multiple time steps, because the system can propagate through the time sequence by applying a small set of changes at each step rather than loading a full snapshot for every time step involved. Internally such deltas are managed efficiently by point tubes. This also facilitates the handling of border regions (yellow) between a new delta (blue) and the static part of the model (red), see Figure 5.

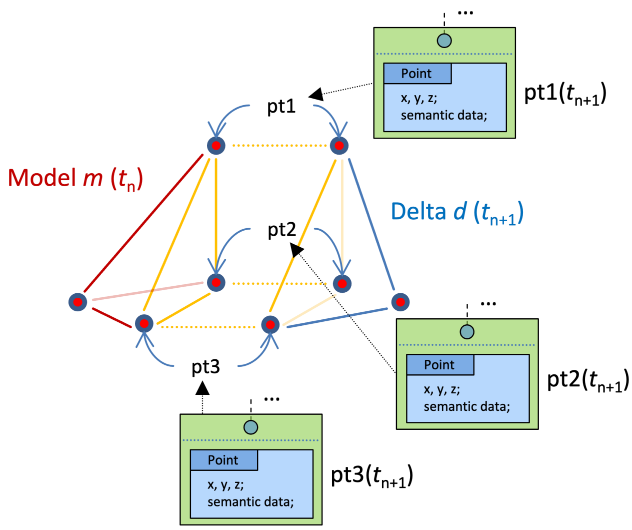


Figure 5. Representation of a delta *d* ($t_{n+1}$) managed by point tubes.

The delta concept also integrates with mesh components, therefore each component maintains its own set of deltas.

### 3.6 Semantic Data Management

Apart from geometric and topological information, geospatial models usually include multiple thematic and semantic information. For example, material properties for a geological model, sensor information, or additional annotations describing the history or origin of (certain parts of) the model. A robust and modern data management model should be flexible to allow such information to be attached to different parts of the 4D model. Therefore, our model provides a flexible framework for managing such semantic data by allowing attributes to be attached at different levels of the simplicial complex structure. This means that any simplex (point, segment, triangle, or tetrahedron) in any time step, as well as any construction element, may have associated attributes, see Figure 6. The use of such construction elements (e.g. segments and/or triangles forming a tetrahedron) is optional and can be adjusted depending on the application.

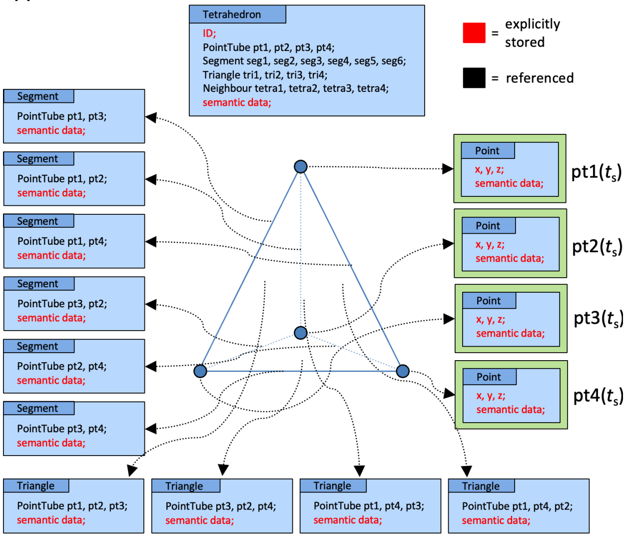


Figure 6. Internal representation of a 3-simplex (tetrahedron) with all possible (but optional) attribute storage locations.

By not "hard coding" the location of attributes, we ensure a maximum flexibility that is suitable for several different applications.

### 3.7 Combination of Concepts to form the Comprehensive Model

With the combination of the five key concepts, our data management model can meet the requirements for an efficient management of spatio-temporal data based on *d*-simplicial complexes. Point tubes mainly manage geometry changes and ensure topological consistency, mesh components allow temporal flexibility for partial regions, pre/post-objects handle topological changes between time steps, delta storage minimizes the storage of redundant data, and a flexible attribute management enriches the model semantically.
The different concepts have been integrated in a way that they complement each other. For example, the benefit of point tubes (no duplicate vertex storage within the mesh topology) is amplified by the delta storage concept (no duplicate storage in successive time steps). Combined with the use of pre- and post-objects, changes of the mesh topology can be managed, while the point tubes of unchanged points can be reused, see Figure 7.

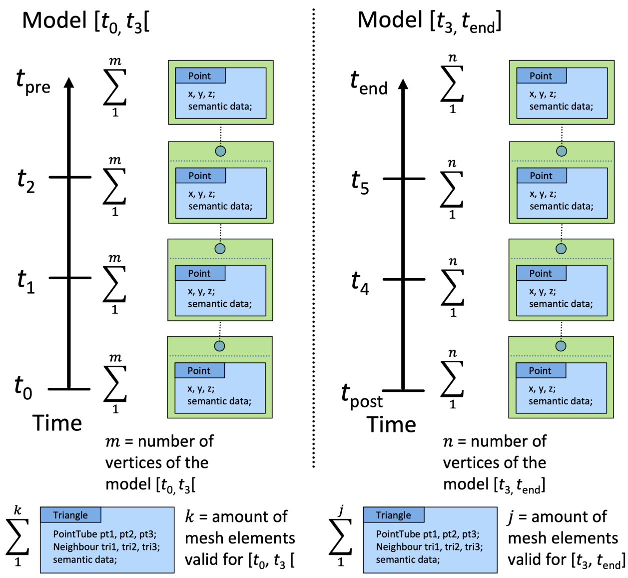


Figure 7. Handling of a 4D model with point tubes and a mesh topology change at time step $t_3$. Due to the delta storage concept, unchanged triangles and points can be reused in both the pre- and post-object.

The complexity introduced by the introduction of multiple mesh components is reduced by using point tubes that ensure the border alignment. The result is a unified model capable of managing complex spatio-temporal datasets with significantly reduced storage requirements and an improved performance for updates, queries and analysis.

## 4. Implementation and Benefits

**System Overview:** The concepts of our model have been implemented within a prototypical GeoDBMS system, based on the service-oriented architecture of DB4GeO (Breunig et al. 2016). The system itself is built in layers: the lowest level handles the persistent storage of point tubes, the mesh topology, and the delta storage concept. On top of this, an object model is installed for assembling 4D models from multiple 3D models, each representing a distinct point in time. Here the mesh components and pre- and post-objects are provided. The top layer handles spatio-temporal queries. For queries at a given time $t_s$, the system determines the mesh components that are valid for $t_s$, constructing the result model $m(t_q)$ in the requested data format. Therefore, the model can be used in geoscientific applications for further analysis.

**Data Structures:** Internally, the point tube concept is realized as a dynamic data structure based on associative storages. Each entry stores the coordinates and optional attributes of the vertex at a given time. The mesh topology is stored for each mesh component in adjacency lists for the given interval between a post- and pre-object, representing *d*-simplicial complexes, with references to the corresponding vertices together with optional explicit construction elements and attributes for thematic and semantic data.

**Representation of Spatio-temporal Objects:** Our comprehensive spatio-temporal data management model has been implemented in DB4GeO (using an object-oriented database as underlying storage system) with the object model as presented in Figure 8.

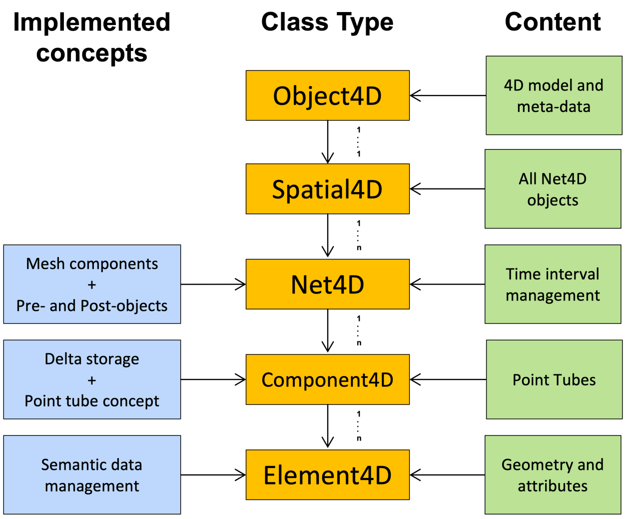


Figure 8. Representation of spatio-temporal objects in DB4GeO.

**Storage Efficiency:** Conceptually, the proposed model achieves a high degree of storage efficiency by reducing duplicate data. Static data (geometry and topology) are stored only once. Changes are stored incrementally. If a region of the model remains unchanged for multiple time steps almost zero storage for those periods is used.

**Query Performance:** The data model is designed to accelerate spatio-temporal queries. Spatial queries can benefit from the topological organization of the data since simplicial complexes can be managed including their construction elements.
Temporal queries (e.g., the state of the model at a given time $t_s$) are accelerated by the incremental storage approach. To retrieve the state at a given time just involves applying a sequence of delta updates, which is typically faster than loading entire snapshots.

**Interoperability:** Although internally we use our own data model, our approach is compatible with existing geospatial standards such as the *Web Feature Service* (OGC, 2025). Therefore, the system can be integrated into existing workflows using standardized interfaces. Since the model is based on *d*-simplicial complexes, it can also output data in other common formats (e.g. GOCAD[1] and WebGL) for visualization and further analysis. Therefore, external software can interact with the data without knowing or implementing its internal data structure. A typical client request could be "give me the 3D representation of the 4D model at time $t_s$ in the GOCAD format". In addition to the export functions, corresponding import functions are also available.

| Concept | Storage costs | Computational costs |
|---|---|---|
| Point Tube | O(n) | O(n) |
| Delta Storage | O(n) | 0 |
| Topology changes | N/A | N/A |
| Mesh components | O(n) | 0 |
| Attribute management | N/A | N/A |

Table 1. Maximal benefits in storage and computational costs compared to the snapshot approach.

In summary, the implementation of the proposed model meets the requirements stated in section 1. Table 1 presents the individual maximal benefits in storage and computational costs for the different concepts from point tubes to attribute management. The storage costs were significantly reduced, and computations were accelerated.

**Application Scenario:** Our comprehensive temporal data model is particularly well suited for applications in geology. Figure 9 shows the high plateau of the so-called Piesberg, located near the city of Osnabrück in North Germany. The geological formation was formed over 300 million years ago during the Carboniferous period. Through the uplift and subsidence of landmasses over long periods, a recurring arrangement of sandstone, claystone and coal seams has been formed under the influence of the sea, which is well visible today in the still existing quarry.

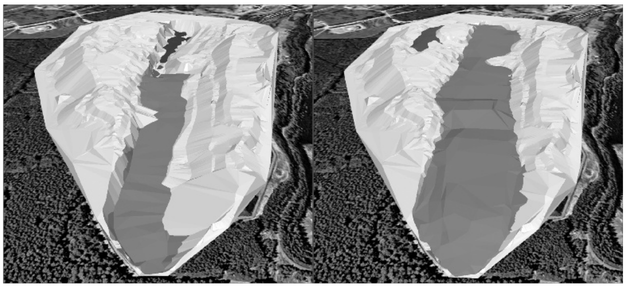

Figure 9. Geological application of the comprehensive temporal model: Development of the "Piesberg landfill" in North Germany showing the difference between two timesteps (cf. Butwilowski (2015)).

Internally the geometry (x-, y-, z-coordinates) is represented as temporal simplicial 2-complexes, i.e. temporal surfaces in 3D space. Each triangle "knows", geometrically speaking, its three associated points according to the point tube model (see section 3.2) and the IDs of its direct neighbour triangles. To represent the temporal development of the landfill model, i.e. its changes of geometry and topology over time, temporal simplicial complexes are implemented as pre- and post-objects (see section 3.4, Figure 4) according to the model of Polthier and Rumpf (1994). Furthermore, the definition of multiple mesh components can be realized (see section 3.3) to highlight specifically important parts of the model.

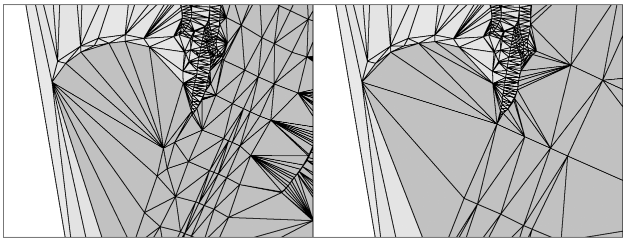

Figure 10. Detailed topological structure of the Piesberg landfill at two different timesteps.

Finally, delta storage (see section 3.5) is used to reduce the storage requirements for the temporal simplicial complexes.

[1] GOCAD® Mining Suite 3D geological modelling software
https://www.mirageoscience.com/mining-industry-software/gocad-mining-suite/

## 5. Conclusions and Outlook

We presented a comprehensive model for the efficient management of spatio-temporal data based on the integration of multiple concepts. The approach supports the management of continuous natural phenomena as well as city development based on discrete time steps in a GeoDBMS, establishing a data handling framework to support advanced analysis. This includes the management of surfaces and volumes (triangle and tetrahedron meshes) in 3D space plus time being represented by *d*-simplicial complexes.

The model improves the robustness of the mesh topology by separating the vertices from the mesh topology by the point tube concept. Delta storage reduces the redundant storage of spatio-temporal objects. To handle and ensure the topological consistency of rapidly changing data over time, pre- and post-objects were integrated to manage mesh topology changes. With the introduction of mesh components, multiple temporal resolutions for subregions are supported. Therefore, natural phenomena such as landslides and urban development can be represented in different temporal resolutions within the same model. Finally, the model offers a flexible framework for the management of semantic information.

In the future, the model will be intensively used in demanding applications using Digital Elevation Model (DEM) data. DEM data typically involve large amounts of data across large regions with spatio-temporal dynamics. Using our comprehensive model makes it possible to represent and analyse terrain changes over time. For example, with the point tube concept, geometry changes can be managed as vertices over time. Mesh components can be used to represent different temporal resolutions, with more frequent updates for areas of particular interest, such as urban or landslide regions. The use of pre- and post-objects guarantees topological consistency when spatial resolution changes occur over time. Due to the delta storage concept only the changed parts of a DEM are explicitly stored, thus minimizing data redundancy and optimizing storage efficiency.

Another field of future work is the integration of a spatial level of detail (LoD) management for DEM data. While mesh components address multiple temporal resolution for subregions, a similar concept might be applied for the management of multiple spatial resolutions. For instance, when monitoring terrain changes, if an earthquake occurs in a region, a higher spatial resolution would be needed to assess the specific change in that area, while maintaining a lower resolution in other regions. The spatial discretization could be achieved by multiple LoDs, where LoD 0 represents global characteristics of a region, and higher LoDs can reflect more local details. Integrating the multi-scale approach can not only discretize the spatial details required by different subregions at a current time step, but it also enables the characterization of spatio-temporal dynamics at multiple levels. Taking up again the earthquake example, lower LoDs can provide a global perspective to identify changes in geological structures, while higher LoDs offer detailed insights into localized terrain changes, e.g., interior damages within individual buildings caused by the earthquake. Based on our current model, the multi-scale approach could be integrated by a graph structure in our further research, where edges represent spatio-temporal relationships between different subregions and scales.

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