5D Modeling - applications and advantages

Jantien Stoter[1,2], Hugo Ledoux[1], Martijn Meijers[1], Ken Arroyo Ohori[1], Peter van Oosterom[1]

[1] GIS technology, OTB, TU Delft, The Netherlands,
{j.e.stoter|h.ledoux|B.M.Meijers|G.A.K.ArroyoOhori|P.J.M.vanOosterom}@tudelft.nl
[2] Product and Process Innovation, Kadaster, Apeldoorn, the Netherlands, jantien.stoter@kadaster.nl

1. Introduction

As explained in van Oosterom & Stoter (2012), the nD modeling approach allows us to include different aspects of geo-information in spatial modeling at a fundamental level, i.e. by treating these aspects as additional (geometric) dimensions. This paper explains how nD data models and data structures may solve the issues of redundancy and inconsistency caused by unconnected data sets at about the same location, in several time periods (4D) and scales (5D). The paper converts the 5D data modeling concept to practical cases and shows how the intermediate models, specifically 2D+scale (Section 2), 3D+scale (Section 3) and 2D+time (Section 4), already yield fundamental improvements compared to current independent management of 2D/3D and multiscale data. The paper ends with conclusions in Section 5.

2. How does the nD approach apply to 2D+scale

Modeling different scales of geo-data is related to the "coarse-to-fine" hierarchical structure of how we perceive, model and understand our environment. In some applications, less detailed but simpler data works better, especially when there is need for an overview. Meanwhile, in other cases, very detailed data is required.

Two approaches exist for maintaining data sets of the same real world at different scales. The first option is to separately maintain different databases at predefined scale levels. This option is practiced by many National Mapping Agencies that produce maps at different scales. The second option is to maintain only the most detailed data and to automatically generalize it to obtain the small-scale data, often pre-storing the results of costly geometric computations in multi-representation (as in the first option).

To provide and reuse multi-scale data within the Spatial Data Infrastructure (SDI), consistency between data at different scales is fundamental. Consistency means that the availability of data at different scales is free from contradictions, and the enabling of smooth zooming in and out. This is supported by multi-representation data models, which formally define the different scale states of the data.

Many researchers have studied multi-representation data models since it was introduced in NCGIA (1989) and Buttenfield et al. (1998). Examples are MRMS (Friis-Christensen and Jensen, 2003), MADS (Parent et al, 2006), Perceptory (Bedard, 2004), Modelling multiple geometries (Jones, 1996), Modelling scale transitions between pairs of objects (Devogele, 1996) and Modeling links between instances (Kilpelainen, 1997),

While these previous initiatives were mainly aimed at ***controlling*** the redundancy of multi-representations and multi-scale data, the nD approach aims at ***reducing*** redundancy to improve efficiency and to better assure consistency between different scales. Therefore, understanding how geo-information changes at a scale transition is required, and implementing this notion as a separate dimension in nD data structures and data models.

For 2D+scale, the tGAP data structure (van Oosterom, 1995; van Oosterom, 2006; Meijers, 2009) already showed good potential to include (vario)scale as separate dimension in 2D spatial data models. The concept of tGAP is shown in Figure 1.

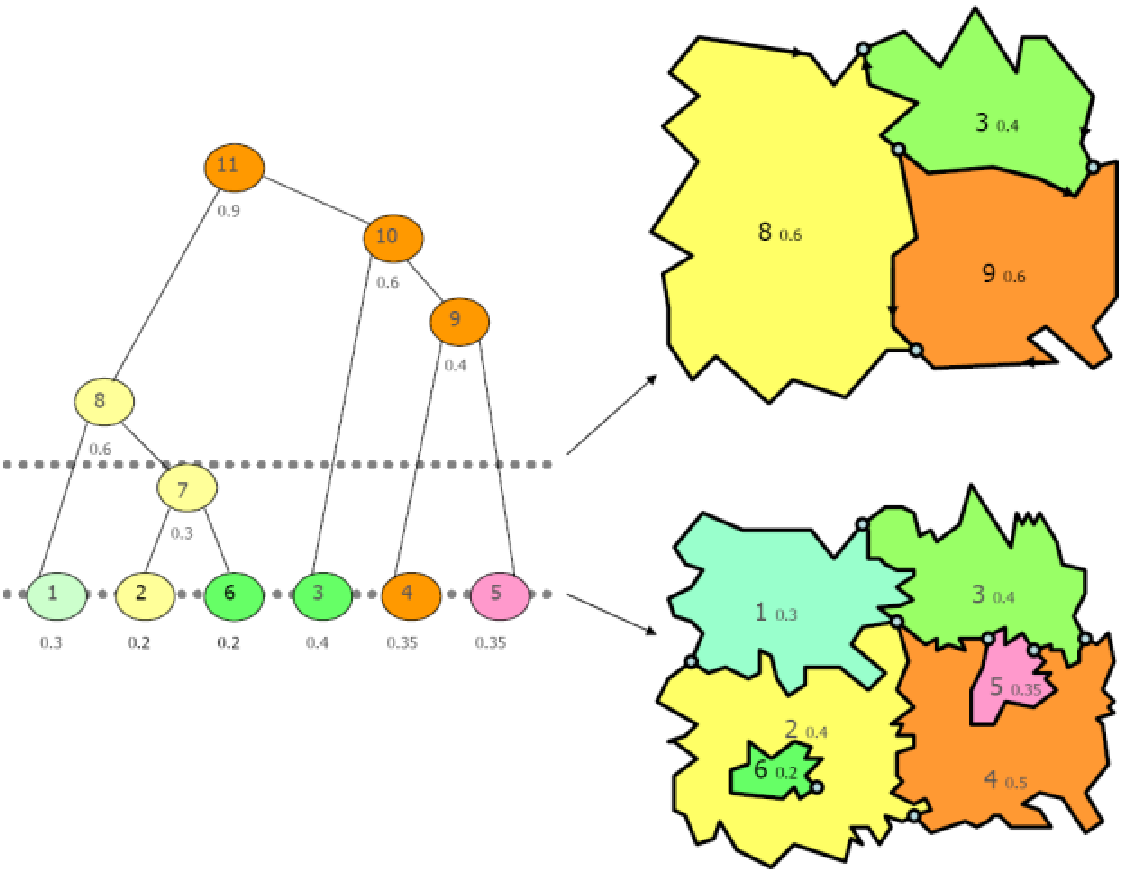


Figure 1: The working of the current tGAP structure. Based on the importance value of the objects, the data structure can be queried.

The vario-scale tGAP data structure enables objects to be stored once and to be displayed at an arbitrary scale, supporting smooth zooming and progressive transfer (Vermeij, 2003; Meijers, 2011). In the tGAP structure different scales/LODs for 2D maps (for example a land use map) are integrated into a 2D+scale structure and stored as a 3D cube (Meijers, 2011), as shown in Figure 2. Starting from a 3D model that is a space partition, a 2D map derived from it is again a partition, in which all representations fit without any gaps or overlaps. This 2D+scale topological structure shows exactly the fundamental benefits of an nD approach that integrates the notion of scale inside the data structure.

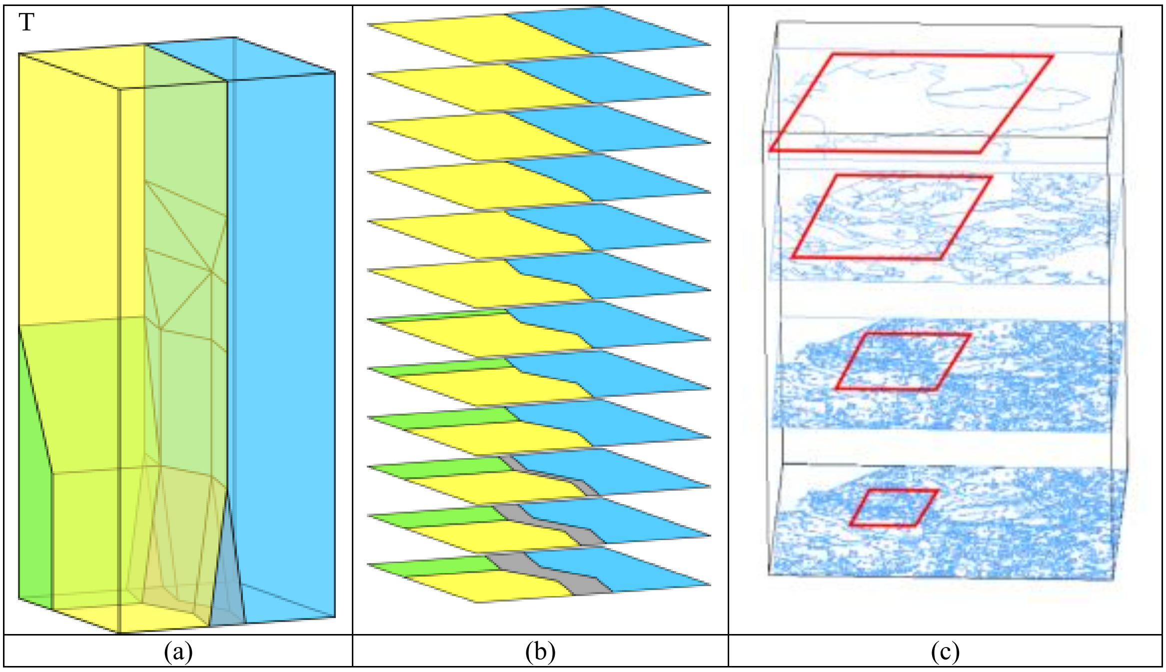


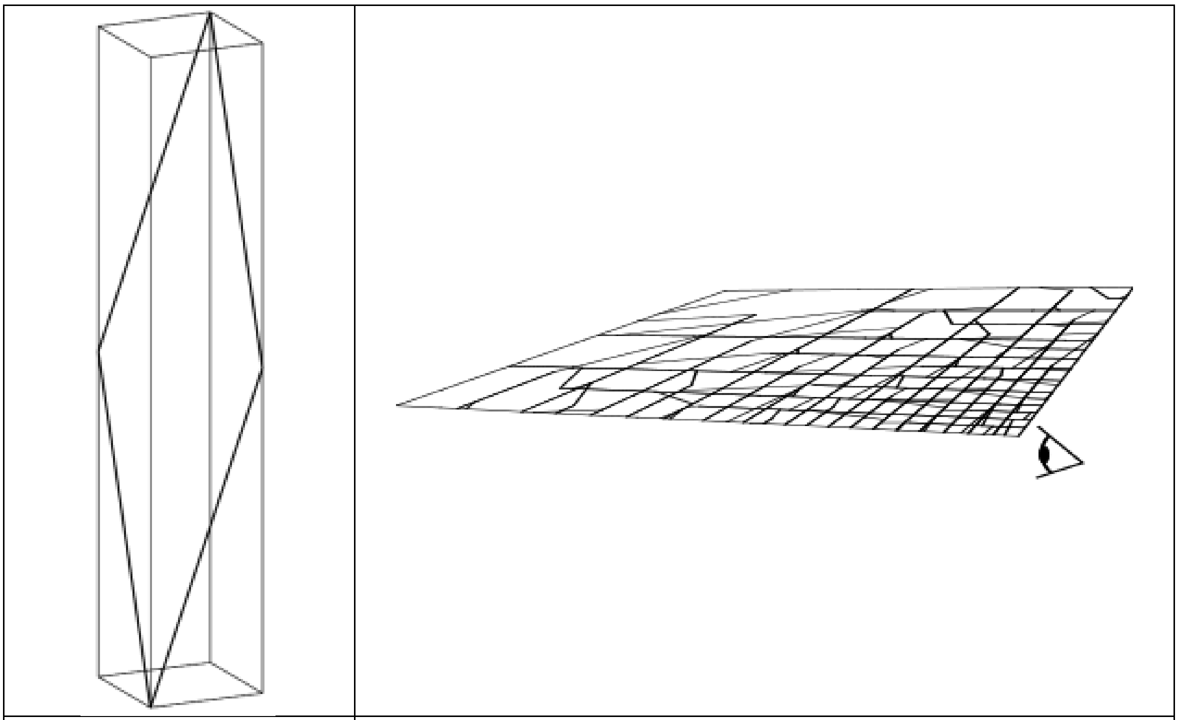
Figure 2. Examples of the integration of the 1D scale dimension and 2D space into a 3D structure. (a) Every map object, 4 in this case, is represented as one polyhedron. (b) 2D Maps are slices (cross sections) of this 3D model. (c) For interactive use, apart from taking a slice, also a bounding box filter should be applied.

Our previous research shows that the vario-scale implementation works well for data reduction. To apply the vario-scale approach for solving 2D+scale problems in the map generalization domain, several issues require further research.

Firstly, cartographic principles need to be embedded. This is not trivial, since symbolised objects may cover larger map areas than their geometric counterparts. In addition, the vario-scale principle of reducing data at smaller scales do not always coincides with the principles of cartographic generalisation, e.g. small objects may be enlarged at smaller scales until they suddenly (and not smoothly) disappear at a certain scale level and become part of the neighbouring object.

Another related topic that requires further research to better solve map generalisation problems is the support of more operations than the split, merge and simplify operators as currently embedded in the tGAP data structure. Also semantic constraints, such as generalisation linked to specific classes, need to be embedded in the data structure, e.g. rectangles in buildings should remain rectangular, while road and water networks should not be broken. Although the current tGAP data structure has ways to treat various classes differently by assigning importance and priority measures, the possibilities to apply different generalisation operators depending on specific classes are rather limited.

Finally, it is interesting to study how to obtain mixed 2D scale representations, i.e. representations where scale varies across the representation (for example highly detailed data close by and less detailed further away from the point of view of the user). Figure 3 shows an example of the slicing operation applied to the 2D+scale cube to obtain a mixed scale 2D representation.



(a) (b)

Figure 3. (a) Taking an arbitrary cross section in a 3D cube (2D space + 1D scale), leads to (b) a derived 2D representation that has mixed scale: close to the observer much detail is shown, while further away less detail is obtained. For 4D models (3D space + 1D scale), a similar operation can be performed

3. How does the nD approach apply to 3D+scale in city models

CityGML, the OGC standard for modeling and exchanging 3D city and landscape models (OGC, 2008) implements the scale (i.e. level of detail) concept in a separated approach. That is, CityGML includes five predefined independent levels of detail (LODs), ranging from only the terrain to the interior of buildings including furniture. This has several limitations. First, the accuracy measures and structural complexity as described for each LOD (5m in LOD1, 2m in LOD2, 0.5m in LOD3, 0.2m in LOD4) do not work in this differentiated manner in practice: many 3D models in LOD1 are created from high-accuracy data (e.g. 0.5m) and block models of buildings (LOD1) may have LOD2 semantics attached (i.e. roof and walls). Second, the different LODs refer to individual objects only, i.e. aggregation is not supported, and higher LODs cannot consist of parts from a lower LOD. Related to this problem is the lack of a notion of semantic change at a scale transition, for example the concept that single trees at a higher LOD may change to forest at a lower LOD is not supported. Another problem with the current LOD implementation in CityGML is that the different LODs are poorly connected, and on-the-fly derivation of lower LODs from a higher LOD is not supported. Therefore, consistency between different LODs cannot be assured. Finally, the indoor-level (LOD4) is not well defined. For example, what is the inside of building: a hole (inner polygon) in the building object or another world that should have its own LODs (Emgård and Zlatanova, 2008)?

Also here the nD approach, that integrates the different LODs of a 3D city model into one consistent 4D data model, will considerably improve storage, maintenance and analysis of 3D models. In this 4D cube, scale is treated as another dimension perpendicular to the three spatial dimensions. This approach will ensure that no gaps or overlaps will be present between representations in the 4D cube.

The 4D cube supported by generalization algorithms (such as Zhu (2010) and Guercke et al. (2011)) is a scale-less, continuous representation of a city model, i.e. not restricted to 5 fixed LODs (in the case of CityGML). Slicing this cube (as in Figure 3 for 2D+scale) permits us to obtain a 3D city model at any given LOD.

Examples of applications where an integrated approach is useful are noise and wind simulation. These simulations are rather complex and need city models as input. However, in order to perform a simulation efficiently, more detail is required close to the object under study, while far away a coarse model will often be sufficient. In an nD approach, it boils down to slicing in a particular way (e.g. for 2D+1D, it could be done using a bell-shaped surface), and this generalizes into using an appropriately chosen 3D volume for the 4D case, obtaining 3D data with the specified amount of detail. The intersection of this 4D cube with the 3D volume gives a perfect 3D representation: all representations fit without gaps or overlaps. Figure 4 shows an example of noise modeling that could benefit from having more details near the railway.

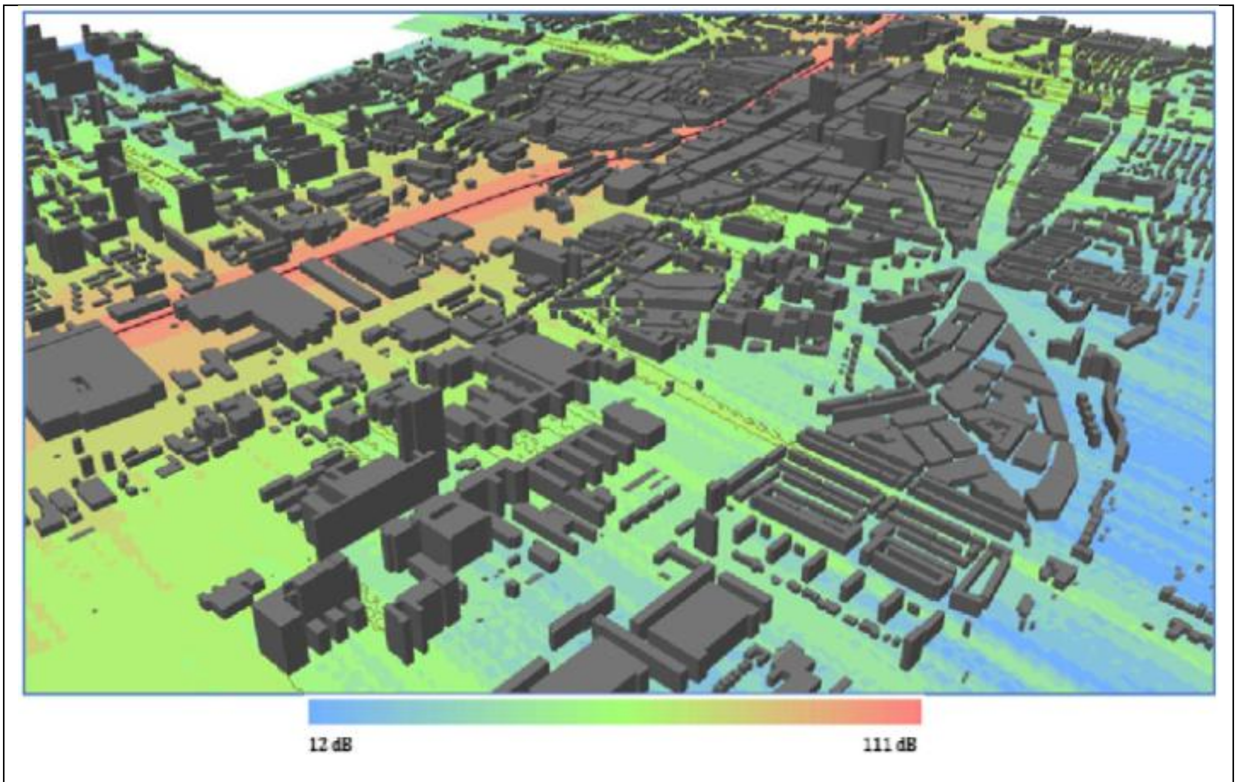


Figure 4. Noise modeling in 3D (caused by railway in downtown Delft) would benefit from having more detail available close to the source of the noise, while further away less detail is needed.

4. Spatio-temporal modeling

This section explains how the nD approach brings advantages for 2D+time (and 3D+time) modeling. The temporal aspects of geo-data are fundamental in recording or monitoring changes, describing processes, and documenting future plans. For example, monitoring the status change of a set of related features (Figure 5, left) or monitoring changes of moving objects (Figure 5, right).

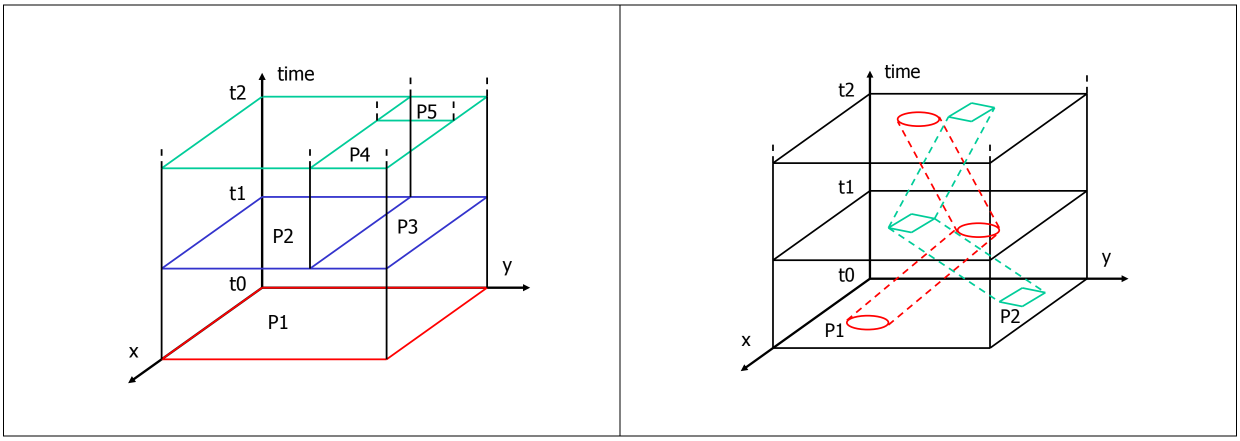


Figure 5: Visualisation of time as third dimension: division of parcels (left) and moving objects (right) (van Oosterom et al, 2006).

Many Spatio-Temporal (ST) data models have been designed to model changes of geo-information (Hornsby and Egenhofer, 2000; Peuquet, 2002; Raper and Livingstone, 2001). The semantics of the time dimension included in these models vary from model to model and generally address:

- *Temporal granularity* specifies to which units of data one temporal attribute is added, e.g. whole dataset, object class, object instance or attribute.
- *Temporal operations* for spatio-temporal analyses.
- *Modelling foundation for time* describes which type of changes can occur to the value of a thematic or geographic characteristic, i.e. discrete changes or more continuous/gradual change.
- *System (or transaction) time* indicates the time an event is recorded in the database.
- *Valid (or real-world) time* describes the time in which an event happened in the real world.
- *Lifespan* identifies the history track of real world objects. Some events last only one short moment, e.g. an explosion or a traffic accident, which are like point objects. Other situations last for a longer period of time, e.g. the fact that a building has a particular owner, which are like linear objects representing a time interval.
- *Representation of time* can differ from maintaining the duration of the status of an object (i.e. period) to recording events (i.e. start- and end-moment) that imply status changes.

For ten well-known ST models, Table 1 shows how they represent the time dimension (Pelekis et al, 2004).

Spatio-Temporal (ST) Data Models	***Representation of Time***	
	Models	***Time as***
Snapshot model	Layers-Snapshots	Attribute of location
Space-Time Composite	Polygon history	Integral part of spatial entities
Simple Time stamping	Object's Creation – Cessation	Attribute of the object
Event Oriented	Events, change	Attribute of an event
Semantics, space and time separately in 3 Domain	Temporal versions	Independent object
History Graph	Events, processes	Attribute of objects, events
ST Entity Relationship (STER)	Entity change	Attribute of entity, relationship
Object Relationship Model	ST phenomena	Attribute of object
ST Object-Oriented	Object Change	Attribute of object
ST UML	TimeUnit	Via the Specification box
Moving Object Data Models	Functions	Integral part of spatial entities

Table 1: Representation of time in ten well-known ST models, after (Pelekis et al, 2004).

The deep integration of time with the space and scale concepts in an nD approach will fully handle changes upon position, attributes and/or extent of the objects in the unified space-time-scale continuum. Some aspects require specific attention for the time dimension in this deep integration. At first, all possible changes of geo-information at varying scales should be well represented, i.e. change in geometry, topology (in all dimensions), attributes, any combination of these, or no change at all. In addition, the integrated representation of time should not only support changes at discrete moments, as currently supported by most of the ST models via timestamps and versioning, but also continuous temporal changes to describe the movement or morphing of objects, independently from their object identification. Also the integrated space-time-scale approach requires specific attention for topological relationships between (continuously) evolving geographic objects. Finally, the difference between system time and real-world time needs to be addressed, which could eventually lead to two separate dimensions in the nD modelling approach.

More researchers have identified the need for a generic spatio-temporal data model. A theory on a unified spatial-temporal data model was proposed in Worboys (1994) and a generic spatio-temporal data type in a relational DBMS was suggested in Jon et al. (2005) and van Oosterom et al. (2002). These studies are relevant when extending temporal models with the other dimensional concepts of geo-data, also incorporating the syntax for a (fuzzy) time dimension as specified by ISO for Geographic Data Files (GDF) in the transport domain (ISO, 2004).

5. Conclusions

This paper describes how geo-applications highly benefit from an nD data modelling approach. This approach offers a fundamental new way for handling geo-information. Having highly formal data modeling and a deep integration of the multi-dimensional concepts of geo-data, provide a solid foundation for the SDI, since essential knowledge of how geo-information behaves is stored at the computer level.

Several users would benefit from this approach. First, the providers of geo-information, who are responsible for maintaining and providing large amounts of geo-information at different scales for which it is increasingly important to keep a history track record. An integrated approach for multi-dimensional concepts of geo-data enables these organisations to be optimally prepared for the provision of geo-information in the Semantic Web in the future (important semantic aspects are formally modelled). A second group of stakeholders that benefits from an nD approach are vendors of geo-ICT systems that can implement thorough spatial modelling approaches in their systems. A final group of stakeholders, and perhaps in the long term the most important group that benefits from nD modelling approaches, are the end-users of geo-information, who are being served by improved and new nD aware applications and services. Therefore the information society at large benefits, because huge amounts of geo-information become accessible for the large public. The nD approach allows any user to zoom in and out and to query spatial data across different time-spans without having to jump to other datasets. This will offer new, sophisticated ways for data integration and data mining.

Despite the high potential, many developments are still necessary, both in science and practice, before the 5D (or nD) concept can be fully operational. However, this paper shows that nD modeling offers the possibility to extend currently available single-dimensional models in a step-wise approach, i.e. 2D+scale, 3D+scale and 2D+time. Therefore, the intermediate models that integrate multiple but not all dimensional concepts come in reach in the short term and are important first steps in the development of higher dimensional modelling in GIS.

In the future, the step-wise process will show how these intermediate models can be extended to include, for example, the time dimension in multiscale models, to process time changes efficiently and to include the complete history in the same data structure. This will enable to query geo-objects at any arbitrary scale and moment in time.

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