# Integrating scale and space in 3D city models

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This paper presents the problem of the current separate treatment of levels of detail in city models. We propose a solution, detail the main principles, and present our initial results on the approach. We conclude with work in progress and explain the benefits of our approach.

# 1 Introduction

CityGML, the OGC standard for modelling and exchanging 3D city and landscape models [Open Geospatial Consortium, 2008], implements the level of detail (LOD) concept in a separated approach (with 5 LODs: from the terrain to the interior of buildings, including furniture), i.e. the different LODs of 3D city models coexist and individual objects are not explicitly linked together. For the storage, maintenance and analysis of these models, this is not optimal and has several limitations.

First, it is particularly difficult to query through different LODs and to keep different LODs consistent after updating. Second, the accuracy measures and structural complexity as described in Open Geospatial Consortium [2008] for each LOD ("lower than LOD1" in LOD0; 5m in LOD1; 2m in LOD2; 0.5m in LOD3; and 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). Third, 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.

To solve the first two problems, we propose integrating the different LODs of a 3D city model into one consistent four-dimensional data model. In this 4D hypercube, scale is treated as another dimension perpendicular to the three spatial dimensions. The availability of a 4D cube that integrates scale and space at a fundamental level offers the possibility to define semantic aspects of scale in the structure in a second step. This provides better ways to manage the scale concept in city models in an integrated manner, and offers a solution for the separate treatment of LODs in CityGML. Therefore the 4D approach provides solutions for the last two problems mentioned above. While the integration of space and scale has been discussed before, we are currently implementing the concept with a higher-dimensional data structure / data model and working on algorithms to populate the 4D hypercube. This offers the possibility to continuously zoom-in and out across levels of detail, without jumping to another representation (as in CityGML) because the LODs are integrated in the 4D data structure itself. The actual implementation is the main innovation of this research. In this paper we present our initial ideas and work in progress. We present in Section 2 a summary of our work. We conclude in Section 4 with some concrete examples where the benefits of our proposed integration of 3D space and scale are highlighted; this also includes tackling the semantic changes that can arise at scale steps by adding semantic knowledge to the hypercube.

# 2 A 4D data structure

The integration of the 3D space and 1D scale into a 4D hypercube creates a representation where no gaps and overlaps may be present. This approach is an extension and a generalisation of the work on variable-scale geo-information, where the different scales/LODs for 2D maps (for example a land use map) are integrated into a 3D structure and stored using a 3D data model [Meijers, 2011].

This contrasts with an approach where mono-scale data sets are independently stored at multiple, but fixed, scale points. The integrated nD approach aims at reducing redundancy to improve efficiency and to assure better consistency between different scales. Consistency means that the availability of data at different scales is free from contradictions, and this enables smoother zooming in and out.

Figure 1 shows examples of such integration for 2D maps and 1D scale in a 3D structure. It shows that when starting from a 3D model that is a space partition, a 2D derived map is again a consistent partition in which all representations fit without any gaps or overlaps.

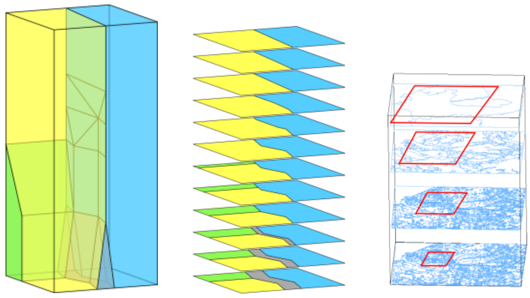



Figure 1: Examples of integrating the 1D scale dimension and 2D space into a 3D structure. (a) Every map object, 4 in this case, is represented as one polyhedron. (b) Maps are slices (cross sections) of this 3D model. (c) For interactive use, apart from taking a slice, also a bounding box filter should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

Current data models and data structures in GIS are limited to 3D, and higher-dimensional data models are often only theoretical and have not been implemented and used in practice (or only for grids and point data). This is despite the fact that conceptually and theoretically, the generalization of these concepts to one dimension higher, i.e. 3D space plus 1D scale, leading to a 4D model, is relatively straightforward. We are currently investigating higher-dimensional representations developed in other fields, for instance in computer graphics and computer vision, CAD/CAM, mathematics and topology. The approaches from GIS and combinatorial topology can be considered as opposite and mutually complementary. GIS uses mostly a top-down approach, building data models that are specifically designed for certain applications. These models are thus meant to support the particular operations required in it. In contrast, the bottom-up approach adopted in the fields previously mentioned has been focused on generic mathematical models valid in any dimension, having a solid mathematical background and well-known advantages, e.g. explicit storage of topology, no redundancy, and better quality guarantees under updates.

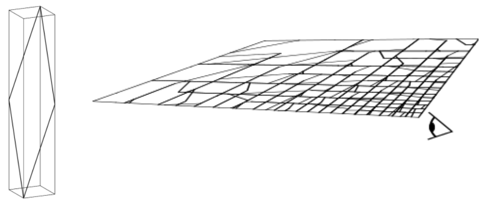
In our research we attempt to bridge this gap in order to allow higher dimensional modelling in GIS, and apply this to implement scale in city models. We have already identified the generalized maps of Lienhardt [1994], also known as G-maps, as a candidate data model to store 4D objects and perform operations on them. Other alternatives, such as the cell-tuple structure of Brisson [1989], could also have been used, but G-maps has the advantage of having been implemented in 3D (it is used in GOCAD for geological modelling and in Moka for geometric modelling), and of being proven to be able to represent a wider class of objects.

We are currently studying the necessary modifications to mathematical data models in order to implement a higher-dimensional GIS. These modifications include support for geometry at the point level, holes, spatial indexing, easy visualisation, and disconnected embeddings. These modifications are explained in more detail in Arroyo Ohori et al. [2012].

It should be noted that while G-Maps and other similar structures have been implemented in a 4D context, they use special operations to merely link a series of fixed LODs [Fradin et al., 2002]. Our integration is different since it uses all dimensions in the same manner, treating all dimensions as if they were spatial.

By doing so, were are able to create operations that operate on multiple dimensions simultaneously, such as mixed scale slicing (Figure 3), similarity and 4D distance computations, spatio-temporal validation, etc.

To build the hypercube, we plan to start with LOD3 models and perform automatic generalisation to obtain the LOD2 and the LOD1; algorithms such as the ones of Guercke and Brenner [2009] and Zhu et al. [2010] can be used. Since we control the generalisation process, it will be possible to build the hypercube in an incremental manner (and thus ensure its consistency).



(a) (b)

Figure 2: (a) Taking an arbitrary cross section in a 3D (2D space + 1D scale) cube 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 The benefits of the integration

The hypercube results in a scale-less, continuous representation of a city model, i.e. not restricted to 5 fixed LODs (in the case of CityGML for instance). Slicing this hypercube permits us to obtain a city model at a chosen LOD.

The data structure solves the integration of scale and space at a fundamental level. The next step is to add semantic knowledge to tackle semantic changes at scale steps and model these semantic changes via de 4D data structure. This requires the incorporation of operations that enable contextual generalisation of 3D data and will enrich the 4D data structure with semantic concepts. For example aggregation of single buildings when going from LOD2 to LOD1, which is an operation studied in Guercke and Brenner [2009] and Zhu et al. [2010]. To further support the semantic concepts of scale changes, we also plan to perform constrained generalisation. That is, if different LODs are available, we generalise between them but ensure that the resulting object at a given LOD is the same as the existing object at that LOD. This lays down an explicit link between existing LODs (also studied in the work of Bédard [2002]). This is a generalisation to 3D of work previously done in 2D [Dilo et al., 2009].

Examples of applications where an integrated approach is useful are noise and wind simulation. Simulations are rather complex and need city models as input. However, for performing a simulation efficiently more details is required close to the object under study, while far away a coarse model will often be sufficient. With the method we propose, it boils down to slicing in a particular way (e.g. for 2D+1D using a bell-shaped surface), and this generalizes into using a hypervolume for the 4D case, obtaining 3D data with the appropriate amount of detail. The intersection of this 4D hypercube with the hypervolume gives a perfect 3D topology: all representations fit without gaps or overlaps. Figure 4 shows an example of noise modelling that could benefit from having more details near the railway.

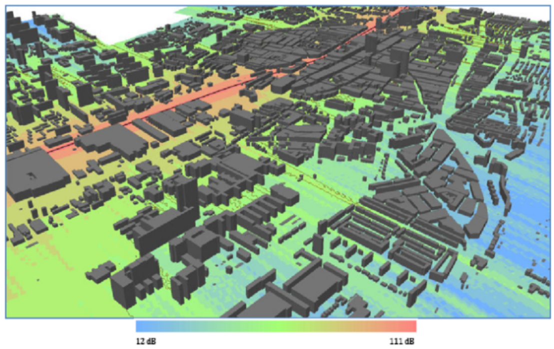



Figure 3: Noise modelling in 3D (caused by a railway in downtown Delft) would benefit from having more detail available close to the source of the noise, while further away less detail is needed.

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