Towards 3D Topography using a Feature-based Integrated TIN/TEN Model

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SUMMARY

This problem paper describes a PhD research started in the spring of 2004 and focuses on the realization of a 3D topographic terrain representation in a feature-based integrated TIN/TEN model. Though current 2.5D terrain representations often give satisfactory results for visualization purposes, these representations do not support real 3D analyses, such as volume computations. In order to solve these problems a model using a 3D primitive (volume) is required. TINs and TENs, respectively 2D and 3D representations using simplexes, are selected in this research as they reduce computational complexity. Basic idea of the proposed model is to model the (2.5D) terrain in a Triangular Irregular Network (TIN) and to 'glue' the 3D volume features on top or below of the TIN as connected Tetrahedronized Irregular Networks (TENs). One of the major advantages of using such a data structure is that it enables validation during edit operations, both on data structure level and on feature level. The data structure will be implemented in a geo-DBMS environment.

KEYWORDS: *3D modelling, TIN, TEN, Topography*

INTRODUCTION

The current Dutch topographic products are limited to representing the real world in only two dimensions. As the real world exists of three dimensional objects, which are becoming more and more complex due to increasing multiple land use, accurate topographic models have to cope with the third dimension. Several true 3D applications can be recognised for these accurate models. In the Dutch situation real estate tax is based (amongst other criteria) on a building's volume. Multiplying its base (derived from a 2D map) with the building's height will result in a very rough estimation, often causing owners to write an appeal. Registering the rough shape of buildings might be the solution. Another group of applications of 3D topographic models is related to buildings, namely modelling noise and odour contours. The derivation of these contours can be done more accurately when modelled in 3D, as for instance a large building may shield houses lying behind this building. As space is scarce in the Netherlands, modelling (and if possible reducing) these kinds of nuisances is very important in maintaining a sustainable urban environment. Due to the space scarcity in the Netherlands multiple land use becomes more and more important, thus requiring fit-for-purpose planning tools. These tools need to be able to deal with three dimensional planning. Applications of 3D modelling are not limited to the terrain surface, as geological features or airplane and communication corridors can be modelled too. As a last application modelling disasters like floodings or earthquakes can be mentioned. In order to facilitate such applications three dimensional data is needed.

Data sets

In the current Dutch situation topographic products are limited to two dimensions. The printed maps do hold some height information, but only in cartographic representations such as contour lines, relief shading and symbols for road and railroad banks. Three dimensional geometries are not available. At the moment (end 2004, beginning of 2005) the Dutch Topographic Survey is transforming its digital

TOP10*vector* into a new object-oriented data format called TOP10NL. The TOP10NL contains the topographic data set at a scale of 1:10.000. Although this new format is capable of handling objects with 3D geometries this functionality will not be used at this time.

At the same time a high density height data set of the Netherlands is available, the so-called AHN (in Dutch: *Actueel Hoogtebestand Nederland*) (Van Heerd, 2000). The AHN is a data set of point heights obtained with laser altimetry with a density of at least one point per 16 square meters and in forests a density of at least one point per 36 square meters. The AHN contains only earth surface points: information such as houses, cars and vegetation has been filtered out of the AHN. However if the unfiltered data is available, one could combine these height data with the two dimensional topographic data set in order to build a three dimensional data set. Up to now these combinations are often made for visualisation purposes by draping the topographic map over the unfiltered laser data, see figure 1. These drapings do not support any real 3D computations.

Figure 1: Draping the topographic map on top of unfiltered laserscan data

So the development towards 3D topography is both supply and demand driven. The required data sets -both topography and height data- are available and at the same time increasing multiple land use and rising awareness of the importance of sustainable urban development increase the need for real 3D topographic data sets. This paper will focus on the design of such a 3D topographic data model.

PROPOSED DATA STRUCTURE

Introducing the third dimension in modelling is not trivial and therefore it is often tried to avoid the usage of real 3D models by using 2.5D representations. This approach is very suitable for modelling terrain heights, as generally speaking the earth surface has a single height value at every x,y location. The main drawback of the 2.5D approach is its incapability of modelling vertical faces and multiple surfaces at the same x,y location. This drawback is surmountable as long as one wants to represent natural surface terrain heights in not too much detail (medium/small scale), but modelling man-made complex features as buildings crossing roads, highway interchanges and viaducts will be almost impossible. Figure 2 illustrates the planned multiple land use at Amsterdam WTC Station, where a train station, highway tunnel and offices will be build on top of each other.

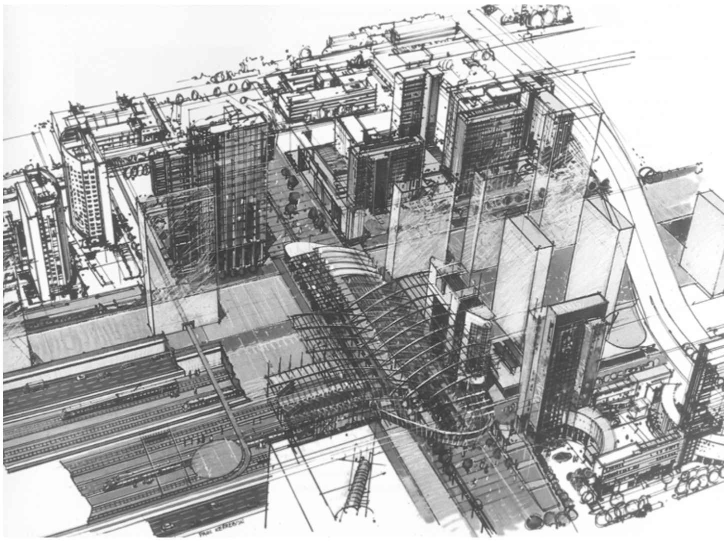

Figure 2: Multiple land use: building tunnels, stations and offices on top of each other

Proper modelling of these objects requires usage of a 3D primitive (volume) besides usage of points, lines and surfaces, as available in 2D and 2.5D modelling. An important design question is the selection of the 3D modelling method, as each method has its own strengths and weaknesses. A lot of different approaches to 3D modelling exist, such as primitive instancing (describing an object by a set of parameters), boundary representations (describing an object by its boundary elements such as vertices, edges and faces), constructive solid geometry (decomposing an object in a set of simpler shapes, for instance as a cube intersected by a cylinder) and spatial-partition representations (decomposing an object in a set of cells, by which the object can be described using only the union operation). Two kinds of representations could be used, i.e. the polyhedron approach, which is an example of a boundary representation, and the TEN approach, which is an example of an irregular spatial-partition representation.

Polyhedron vs. Tetrahedron

A well known boundary representation (b-rep) is the polyhedron approach. Earlier research of Arens (2003) showed the implementation of a polyhedron primitive in a DBMS, including update and validation procedures. This polyhedron approach fits well to the user's perception of reality, for instance describing a house by its walls and roof seems logical. Describing the same house by a collection of tetrahedrons, as one would do in a TEN, appears to be a more complex way of modelling. It is clear that if one compares the polyhedron approach with the TEN approach, the advantages of using polyhedrons are that modelling is easier and will result in a 1:1 relationship between a feature and its representation. In return for the 1:n relation in a TEN between a feature and the tetrahedrons and the increased modelling complexity, TENs have the important characteristic that they reduce computational complexity due to their well-defined character (Pilouk, 1996). A TEN is composed of nodes, edges, faces and tetrahedrons. These building blocks are all the easiest possible shape (simplexes) in their dimension (0D – 3D). The relationships are well-defined: a k-D simplex is bounded by k+1 (k-1)D-simplexes, e.g. the tetrahedron (3-simplex) is bounded by 4 triangles (2-simplexes), a triangle (2-simplex) is bounded by 3 edges (1-simplexes) and an edge (1-simplex) is bounded by 2 nodes (0-simplexes). The reduced computational complexity can further be illustrated with the example of computing volumes. Implementing a volume calculation formula for polyhedrons is complex, if not impossible due to the almost unlimited variations in shape, whereas in the TEN case a single formula for a tetrahedron volume is sufficient. This simple formula needs to be applied several times, but that is exactly what computers are best for. Another important operation that is easy to implement in a TEN structure is the point-in-polygon test, as all simplexes are convex.

However, the decisive argument is not mentioned yet. Each single 3D modelling approach has its own strengths and weaknesses. Some approaches are best for visualisation, others are best for computations. The discussion on selecting the best approach is a never ending story, as its outcome will be influenced by the planned application. A topographic data set is a multiple purpose data set and is positioned high in the spatial data infrastructure hierarchy. A wide range of application domains needs to benefit from the data set and therefore it is important to develop a data model capable of having several types of output, such as polyhedron, surface TINs, etc. This required capability is the decisive argument to use simplexes (TIN/TEN) as the data structure for the 3D topographic data set. Deriving output formats from simplexes is relatively easy.

Integrated TIN/TEN

An important feature of the proposed data structure is the integration of a TIN with multiple TENs. Basic idea of the proposed data structure is to model the (2.5D) terrain in a TIN and to 'glue' the 3D volume features on top or below of the TIN as TENs. As both TINs and TENs are using triangles they can be 'put together' by ensuring that they both contain the corresponding triangles. At first the choice for combined 2.5D/3D modelling was mainly based on the fit-for-purpose principle, as a feature-based TIN would suffice for large areas. Modelling all these areas in a TEN would increase complexity without any benefit. Along the research a second important argument was found for the combination of TIN and TENs. It turned out that extensive research is performed on storing objects within a TIN, resulting in a wide variety of algorithms for constrained Delaunay triangulation, conformal Delaunay triangulation and refined constrained Delaunay triangulation (Shewchuck, 1997; Shewchuk, 2005). Triangulations are capable of handling both point and edge constraints, thus enabling the reconstruction of surface objects. Constrained tetrahedronization is a relatively unexplored field of research. For a topographic data set stored in a single TEN, constrained points, edges and faces are required to enable handling topographic features of all dimensions. This functionality is not yet available. Therefore the TIN is used to stored all 0D, 1D, 2D and 2.5D topographic features, whereas for each 3D feature a separate TEN is created, thus sidestepping the problem of a lack of constrained tetrahedronization algorithms. The (2.5D) terrain will be modelled as a TIN and the separate 3D features will be glued 'on top' or 'below' of the TIN as TENs (see figure 3).

As the 2.5D topographic constrained TIN is created, the volumes can be modelled as TENs and added to TIN. An important product design question is which features has to be modelled in 2.5D and which features in 3D. Generally speaking two different approaches can be distinguished, a pragmatic one and a more formal one:

- pragmatic approach (keep it as simple as possible): Always model in 2.5D, unless this is absolutely impossible (for instance use the where buildings are modelled in 2.5D by slightly enlarging the footprint)
- formal approach: Let the feature's nature be decisive: terrain (including dikes, banks, etc.) can be considered also in the real world as being 2.5D and thus being modelled as a TIN, whereas buildings, viaducts etc. are true 3D features and thus will be modelled as TENs. An advantage of this approach is the possibility of preservation of the feature's characteristics, such as volume. Volume can be calculated in 2.5D by subtracting a TIN without buildings from the TIN with buildings (a double 2.5D TIN approach, having a layer 'top' and a layer 'bottom'), but its outcome will not always be accurate.

Feature-based integrated TIN/TEN

The topographic features are included explicitly in the data model. The basic principle is that the user will be handling features only, the underlying 2.5D TIN / 3D TEN architecture will not be visible. As a result addition or removal of a feature by the user needs to be translated internally into adding or

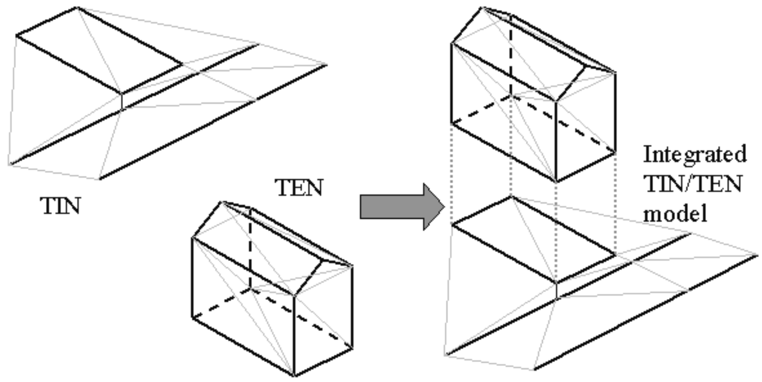

Figure 3: Combining 2.5D TIN and 3D TEN into a combined TIN/TEN model

removing constraints in the data model. This will lead to the desired geometrical presence or absence of the feature in the topographic data model. In addition to this geometrical presence the resulting primitives (nodes, edges, triangles, tetrahedrons) have to be linked with the features to establish the semantic presence of the features in the model. This link exists bidirectional, i.e. an area feature is represented by a set of triangles (linked by triangle IDs) and for each of these triangles the link to the feature by its feature ID is present too.

IMPLEMENTATION

Database approach

In order to enable storing large amounts of data in the model, while data integrity is maintained, implementing the topographic model within a geo-DBMS is a logical design decision. Although Oracle Spatial offers some topological data storage (Penninga et al., 2005) in its latest release (Oracle 10*g*) the assumption is that the data structure needs to be implemented using the regular functionality of the current geo-DBMSs. This implies the creation of the node, edges, faces and tetrahedron tables as well as tables for point, line, area and volume features and their mutual relationships. At first the idea was to store the integrated TIN/TEN data structure by only using four tables, i.e. a node, edge, triangle and tetrahedron table. However quite soon it showed that a TIN edge is not the same as a TEN edge and the same holds for TIN triangles and TEN triangles. This difference lies within the relationships that these edges and triangles have with other simplexes in the TIN or TEN. For instance, a TIN (directed) edge has a reference to its left and right triangles, whereas a the number of bounded triangles of a TEN edge will vary. As a result it is necessary to model the TIN and TEN separately (and when appropriate link its components). In case an objects occurs both in the TIN and TEN, for instance a building placed on top of the terrain, the corresponding nodes, edges and faces in TIN and TEN should have an 'IsIdentical' relation in order to capture this integration on data structure level.

Another important part of the model are its tables with the actual topographic features. Four different feature types can be distinguished, i.e. point, line, area and volume features. The first three types will be represented by the TIN, the fourth type by the TENs. The integration of the 2.5D and 3D world exists on data structure level, by linking identical nodes or edges in TIN and TEN, but can also be accomplished at feature level. As generally speaking the volume features will be placed on top or below the TIN surface, the footprint of these volumes can be added to the surface representation, thus resulting in a terrain level representation consisting of point, line, area and volume footprint features.

In Figure 4 an UML class diagram is given, in which the integration on both data structure level as feature level is illustrated. In this diagram the IsIdentical relationship is available only between the TIN node and TEN node, as this might be the only location in which geometry is stored, but during implementation one might chose to apply this relationship also on edge and triangle level.

Within the geo-DBMS approach the DBMS is not only used to store the data, but it will also be used to create and maintain the topographic data model. As a result algorithms for triangulation (such as the STIN-method for high quality triangulation (Verbree, 2003)) and tetrahedronization need to be implemented within the DBMS environment. As the model requires the possibility of updates, these algorithms will be incremental algorithms. In a later stage it might be an option to also implement faster algorithms for the initial creation of the model. Exchanging the data requires supporting data formats as XML and GML3 or X3D, but possibly also native GIS formats.

Integrating 2D objects and height data

Besides implementing the data structure and accompanying algorithms a 3D topographic data set has to be created. First the existing topographic and height data sets and their specifications have to be studied. Based on this results the product specifications of topographic data sets have to be extended from 2D into 2.5D or 3D. For instance terrain features such as fields or pasture land are currently described by their boundary geometry, whereas in 2.5D the actual shape will be present, including for instance also a hill that lies completely within the object boundary. After converting specifications for all existing feature types, the step is to answer the question whether the creation of additional 3D topographic features is needed. One might think of (height) features such as slopes or road/railway banks, but it is not sure whether an explicit storage as topographic feature is necessary. These height changes will also be present in the shape of the current feature, for instance pasture land.

After formulating the extended product specifications the actual integration of topographic and height data can start. One of the issues that will come up during this integration is the question how harmonize the spatial resolution of the different input data sets. On earth surface level the current terrain surface features have no height component, although for instance the TOP10vector holds two or three characteristic height points per square kilometre and in some cases (dunes and Limburg hills) also contour lines. As the AHN offers about 62,500 height points per square kilometre, a method is needed to determine the number of required height points in order to harmonize the spatial resolution. This will result in the desired spatial resolution. Now a method is required to adapt the spatial resolution of the AHN to the desired level, i.e. some kind of generalization is needed. Several techniques can be examined, such as slope based filtering (amongst others the one introduced in (Stoter et al., 2004)) or 3D Douglas Peucker. Runtime will be an important criterion in the selection of the filtering approach for these large data sets, as for instance the surface equivalent of Douglas Peucker is expected to have a $O(n^2)$ runtime. Another issue is the type of filtering, as one can choose to delete irrelevant points from the full TIN (top-down) or use the inverse approach and only add relevant points to an initial one-triangle TIN (bottom up).

Another important issue in integrating 2D topographic data with height data is to integrate these data sets semantically correct. Earlier research of Koch (2004) showed the importance of semantically correct data integration, as can be seen in one of his figures (figure 5). In this figure a 2D lake is integrated in a height model, but due to the non-correspondence of the outlines of this lake, the lake is not flat, whereas one might expect water to be flat. In order to prevent situations like this additional constraints can be added to the integration process, for instance: lakes, sport fields and canals should be flat. Constraints are also possible for non-horizontal objects, one might for instance define constraints on the maximum slope of roads and railroads.

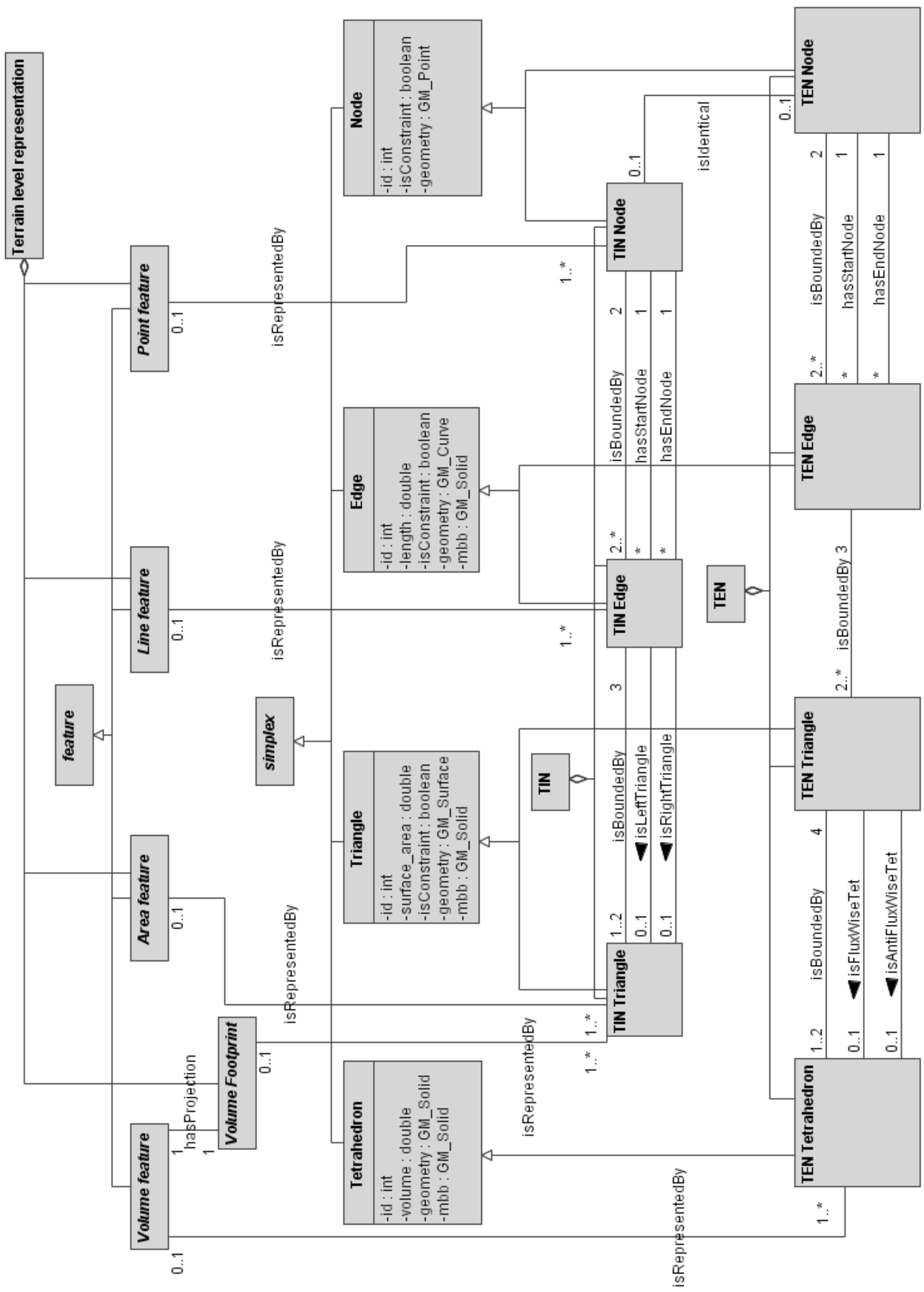

Figure 4: UML class diagram of the feature-based integrated TIN/TEN model

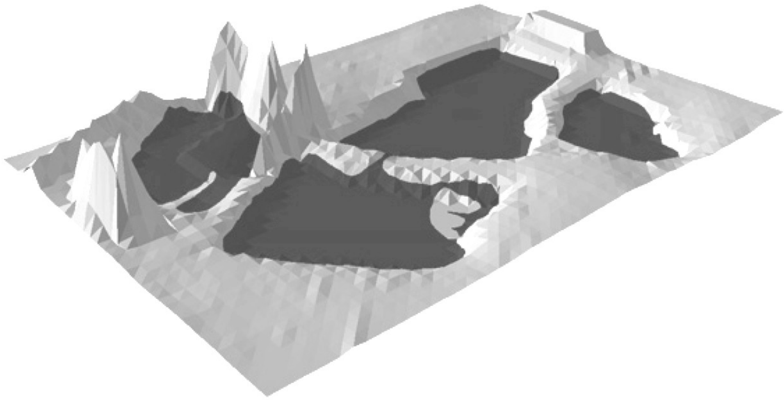

Figure 5: Erroneous data integration due to neglecting semantics (Koch, 2004)

Implementation requirements

The success of the new method depends on the improved usability of the new topographic data model. This requires populating the model with actual data by integrating data from different sources, such as for instance current 2D topography and height data from the AHN. Based on this new 3D topographic model several queries and applications will be tested. Proper visualisation, both in 3D as in 2D (map view) should be supported by the model, as well as for instance buffer selections, neighbour queries, numerical analysis and line-of-sight analysis. Updates like adding or removing features should also be possible and data integrity should be remained.

CONCLUSIONS

In this paper a future data model for 3D topography data sets is introduced. The proposed data model integrates a 2.5D TIN and multiple 3D TENs. It enables validation as well as 3D computations such as volume computations, line-of-sight analysis and modelling noise and odour contours. The choice for TIN/TEN modelling is made as these simplexes can be easily transformed into several other formats, such as boundary representations (polyhedrons). This is an important feature as the 1:10.000 topographic data set plays an important role in the spatial data infrastructure and serve a wide variety of applications. A second important argument is the reduced computational complexity, thus moving the focus of 3D GIS from visualisation to analysis, the traditional GIS strength. Once finished, 3D topographic data sets will play an important role in fit-for-purpose planning tools in multiple land use and sustainable urban development.

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BIBLIOGRAPHY

Arens, C., Modelling 3D spatial objects in a GeoDBMS using a 3D primitive. In: Proceedings of the 6th AGILE Conference on Geographic Information Science, Lyon, 2003.

Heerd, R.M. van, et al., 2002, Productspecificatie AHN 2000 (in Dutch). Technical Report MDTGM 2000.13, Rijkswaterstaat, Delft, 2000.

Koch, A. en C. Heipke (2004), Semantically correct 2.5D GIS data: the integration of a DTM and Topographic vector data, In: Proceedings 11th International Symposium on Spatial Data Handling, Leicester, 2004.

Pilouk, Morakot, Integrated Modelling for 3D GIS. PhD-thesis, Enschede, 1996.

Penninga, F., Wilko Quak, Theo Tijssen and Peter van Oosterom, Storage and Querying of Topological Structures in Oracle Spatial. Proceedings Topology and Spatial Databases Workshop , GISRUK 2005, 2005

Shewchuk, Jonathan Richard, Delaunay Refinement Mesh Generation. PhD-thesis, Pittsburgh, 1997.

Shewchuk, J.R., General-Dimensional Constrained Delaunay and Constrained Regular Triangulations I: Combinatorial Properties. To appear in: Discrete & Computational Geometry. Available at: http://www-2.cs.cmu.edu/jrs

Stoter, J.E., F.Penninga and P.J.M. van Oosterom, Generalization of integrated terrain elevation and 2D object models. In: Proceedings of 11th International Symposium on Spatial Data Handling, Leicester, 2004.

Verbree, E., The STIN-method: 3D surface reconstruction by observation lines and Delaunay TENs. In: Proceedings of the ISPRS working group III/3 workshop '3D reconstruction from airborne laserscanner and InSAR daya', Dresden, 2003.