3D Topography

Realization of a three dimensional topographic terrain representation in an integrated TIN/TEN model

Research plan

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Summary

This report contains the research plan for the PhD research 'Realization of a three dimensional topographic terrain representation in an integrated TIN/TEN model'. It describes relevant backgrounds, goals, phasing, research questions and a planning. The research will be carried out in the period 2004-2008. It is the PhD research project of Friso Penninga and it is closely related to the PhD research of Edward Verbree (both section GIS Technology). Both projects are part of the larger research project 3D Topography within the Bsik Space for Geo-information framework (Order subsidies investments knowledge infrastructure, in Dutch: Besluit subsidies investeringen kennisinfrastructuur).

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Contents

1 Introduction

This report describes the planned PhD research in the field of the Bsik (Order subsidies investments knowledge infrastructure, in Dutch: Besluit subsidies investeringen kennisinfrastructuur) Space for Geo-information 3D Topography research project. It focuses on the realization of a three dimensional topographic terrain representation in an 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, noise and odour modelling and coverage optimisation of mobile phone antenna networks. In order to solve this problem a model using a 3D primitive (volume) is required. Several approaches to 3D modelling are available, such as primitive instancing, boundary representations, constructive solid geometry and spatial-partition representations. TINs and TENs, respectively 2 and 3D representations using simplexes, are examples of the last group and selected in this research as they reduce computational complexity.

Basic idea of the proposed model is that the (2.5D) terrain will be modelled as a Triangular Irregular Network (TIN) and the 3D volume features will be 'glued' on top or below of the TIN as connected Tetrahedronized Irregular Networks (TENs). As this combined data structure incorporates a certain level of complexity, its user interface should preferably handle features only, thus masking the internal TIN/TEN data structure. These features should be in- and exported in open formats, such as GML3 or X3D. One of the major advantages of storing data in an explicit data structure is that it enables validation, both on data structure level and on feature level.

In order to demonstrate the possibilities of the model current topographic data sets like the TOP10 will be expanded into 3D. As a first step the product specifications has to be extended into 3D descriptions, followed by the question whether the creation of additional height features (such as slopes) is necessary. One might choose to store these features explicitly or that the implicit presence in the terrain model is sufficient. As one chooses to create additional features they can be created based on data in amongst other things the current TOP10 (converting map symbols into features), DTBs (large scale maintenance maps of major roads and rivers), unfiltered AHN (laser data) and railroad data. As a last step height values are assigned to all features and characteristic terrain points.

The data structure will be implemented in a geo-DBMS environment. On top of this DBMS, functions for building and updating the model will be built, as well as Input/Output functions. As mentioned earlier these I/O functions will handle features in an open format like XML in combination with GML3 or X3D. Internally these functions will use SQL and DBMS APIs to interact with the database. We intend to make this implementation available as open source software.

This report is structured as follows. It starts with relevant backgrounds and the need for three dimensional terrain modelling in Chapter 2. The research itself will be discussed in Chapter 3, where the research project is split into four different tracks in an attempt to identify manageable topics. This research plan ends with an initial planning in Chapter 4.

2 Background

2.1 Introduction

This chapter starts in paragraph 2.2 with a short sketch of recent developments causing the need for modelling in the third dimension. Paragraph 2.3 will go into more detail as it describes several possible applications of three dimensional topographic models. The current 2.5D models and the available techniques to expand into 3D are introduced in paragraph 2.4. The chapter ends with an overview of current data sets that contain height information in some form and a sketch of the future data set in paragraph 2.5.

2.2 The need for the third dimension

The current topographic products are limited to the representation of the real world in only two dimensions, with some additional point heights and contour lines. As the real world exists of three dimensional objects, combined with the given increase of multiple land use, for instance buildings crossing highways, such as at the Utrechtse Baan in The Hague (part of highway A12) and the plans for the Amsterdam Zuidas (spanning the southern part of the ring way A10) and Utrecht Leidsche Rijn (A2), accurate topographic models have to cope with the third dimension (see figure2.1, [6]).

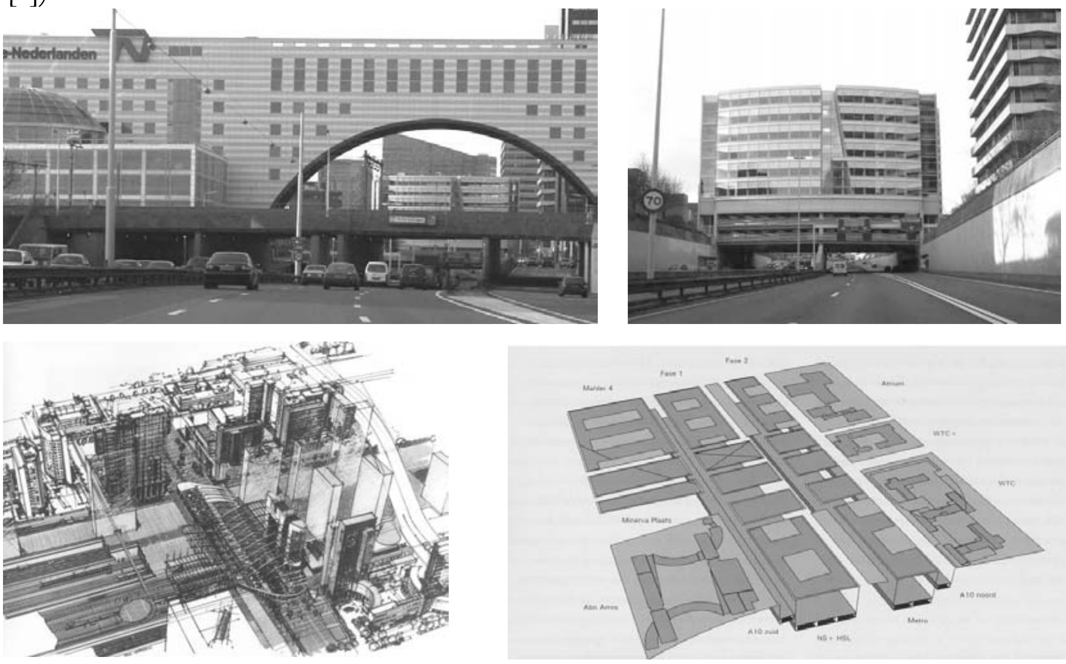

Figure 2.1 Utrechtse baan with offices built above the highway (top) and some plans for the Amsterdam Zuidas project, including covering the highway for over a mile

Modelling these features in only two dimensions will result in hard to interpret projections onto the 2D plane, thus creating faces with multiple descriptions, for instance both highway and building. As being hard to interpret is not an insurmountable problem of 2D projections, the absence of the third dimension becomes real problematic in amongst other things volume computation, noise and odour modelling and the coverage optimization of a network of mobile phone antennas. In order to solve these problems one should involve the third dimension, thus being able for instance to define a highway at the surface height and defining a building 10 metres above the ground. From the pictures one might get the impression that using the third dimension is only required in case of some exceptional prestigious building projects. This is however not the case, as figure 2.2 will illustrate. More common features like viaducts, tunnels and aqueducts and the more complex features like these highway interchanges can be modelled more accurate when the height of the separate infrastructure parts is taken into account. The heights of these features will affect the results of the real 3D analyses such as noise analysis.

Figure 2.2 Accurate modelling of road or river crossings on different levels requires 3D modelling

As one can see in figure 2.3 the 2D projection of a viaduct with two crossing roads, the actual crossing does not illustrate which road lays on top of the other road. In the current Dutch topographic products this is solved by duplicating this crossing and adding a code stating whether the road surface is visible from above or not.

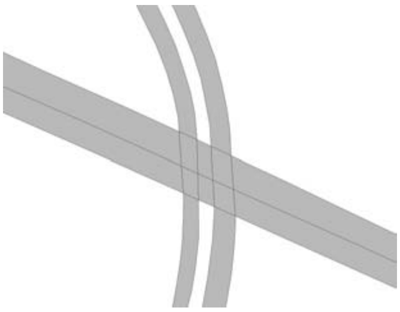

Figure 2.3 Crossing in two dimensions: not directly visible which road lays on top

As each face has a code indicating its characteristics, the last digit of this four digit code is used to indicate whether the face is visible from above (2) or not (3). In the new object-oriented approach (TOP10NL) of the Topografische Dienst Kadaster (TD Kadaster, = Dutch Topographic Survey) this code is replaced by levels, where level 0 represents the top level, level –1 the level beneath level 0, and so on [2]. The new method has the advantage that it is capable of recording the order of more than two crossing roads, whereas the old system was only capable of determining which face is the top face, but not the order of the underlying faces. Its drawback is that a single road (for instance the bottom road of the highway interchange in figure 2.3) is divided in segments on different levels (for instance level 0, level –1, level –2, level 0), which makes it hard to determine whether these segments form a single road or not.

2.3 Possible applications of a 3D model

Although 3D is often associated with modelling terrain heights, several true 3D applications can be recognised [3, 4]. 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 a solution. Another group of applications of 3D terrain 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 high quality 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. Above or beneath the terrain surface geological features or airplane and communication corridors can be modelled. As a last application modelling events like floodings can be mentioned.

In order to facilitate such applications three dimensional data is needed. For the tax purpose laser scan data is needed to acquire roof shapes. The height of buildings plays an important role in noise and odour modelling. For all applications this height data is needed in addition to planimetric data. A height data set representing only terrain surface heights is not suitable, because of the importance of building heights. These applications require the support of multiple operations, amongst others metric operations (such as length, area and volume computations). Other operations are 3D buffering and 3D intersection, for instance for noise and odour modelling and cut-and-fill analyses. Line of sight computations are important for planning communication corridors, as no large buildings may block the direct path between emitter and receivers.

2.4 Modelling heights: from 2.5D to 3D

As shortly illustrated in the previous paragraph, the third dimension becomes increasingly more important in accurate topographic modelling. Introducing this third dimension in modelling is not trivial and therefore it is often tried to avoid the usage of real 3D models by simulating heights in the so-called 2.5D representations.

2.4.1 Current solution: 2.5 D representations

In current GIS practice 2.5D representations are often used when height information is required for accurate modelling. Whereas 2.5D might sound strange, one has to realise that in modelling two kinds of dimension are of importance, i.e. the internal and external dimension. The internal dimension represents the maximal dimension of the data types used for object modelling: point (0D), line (1D), surface (2D) or body (3D). The external dimension defines the dimension of the space the objects are embedded in, for instance R^3 for the three-dimensional space. In ordinary language these two different dimensions are combined in one term: 2D modelling means modelling 2D objects in R^2, 2.5D means 2D objects in R^3, 3D means 3D objects in R^3, and so on. However often a stricter definition is used: 2.5D modelling can be considered as a single height value for every x,y position, thus ruling out the possibility of for instance a curved surface (2D data type) with multiple heights at a certain x,y position, for instance on a cylinder. I will refer to this strict definition when using the term 2.5D modelling. This approach is very suitable for modelling for instance terrain heights, as generally speaking the earth surface has a certain height at every x,y location. The main drawback of this 2.5D approach is its incapability of modelling vertical faces and leaning over terrain. Vertical faces occur on buildings. A workaround is to slightly enlarge the footprint of a building or shrinking the roof size, thus removing the vertical faces. Leaning over terrain is not easy to solve, but occurs less frequently. As no workaround is available one might use an attribute indicating the presence of leaning over terrain. Both situations are illustrated in figure 2.4. The house is triangulated in a TIN by enlarging the footprint. The problem of leaning over terrain is visible in the cross section of a terrain that illustrates that at 2D point location P_0 multiple heights (H_0, H_1 and H_2) are required for accurately modelling this terrain feature, whereas 2.5D modelling is only capable of handling one height per x,y location.

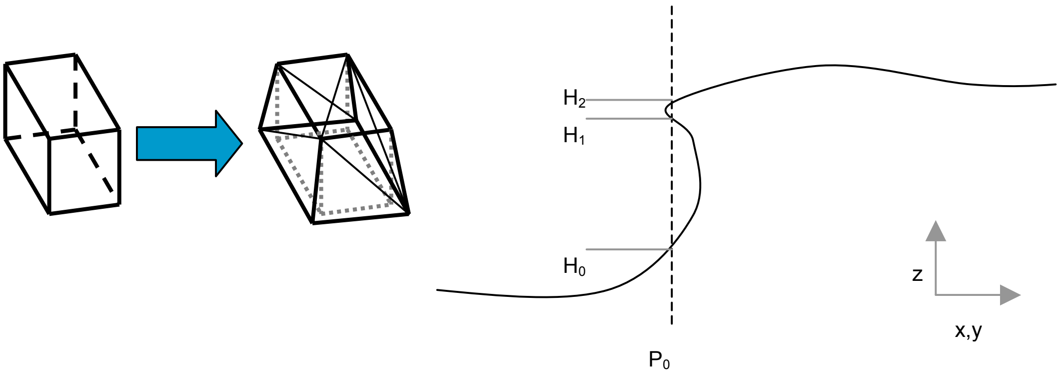

Figure 2.4 **Cross section of leaning over terrain requires multiple heights at one x,y location**

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 features (as illustrated in the photographs in the previous paragraph) will be almost impossible. Figure 2.5 illustrates three relevant heights at a single x,y location and thus demonstrates the shortcomings of 2.5D modelling techniques for accurately modelling man-made complex features as buildings crossing roads, highway interchanges and viaducts.

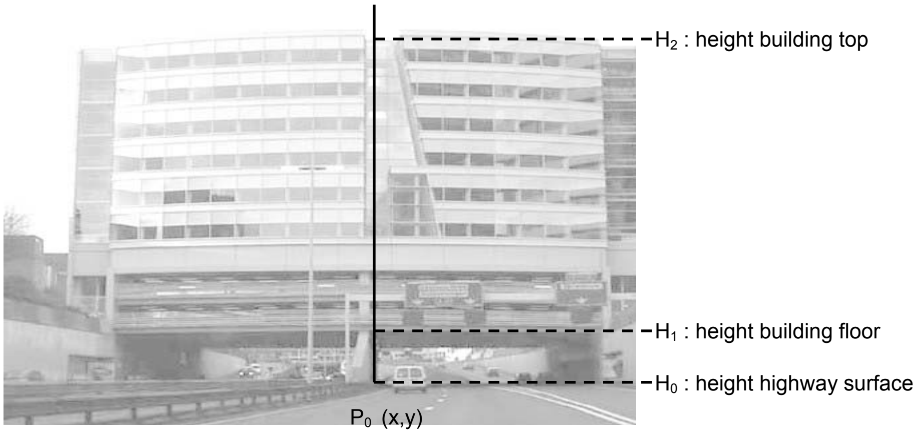

Figure 2.5 Three important heights at a single x,y location when modelling complex manmade features

2.4.2 True 3D modelling for accurate modelling and analysis

The previous paragraph illustrated that modelling objects with 2D data types in R^3 might be useful for modelling terrain elevations, but has some shortcomings for modelling volume objects. The models of 3D objects can be approximated by combing several 2D faces, but it is very hard to validate such combined models. Therefore an accurate validated model requires 3D models of objects using a true 3D primitive (a volume). 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).

A well known boundary representation (b-rep) is the polyhedron approach. Earlier research of Arens [1] 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. Several spatial-partition representations exist, both regular and irregular ones. One type of irregular spatial-partition representations are the irregular tessellations, for instance Triangulated Irregular Networks (TINs) and Tetrahedronized Irregular Networks (TENs). Both representations are using simplexes to model objects, i.e. TINs use triangles and TENs tetrahedra. 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-simplixes), a triangle (2-simplex) is bounded by 3 edges (1-simplixes) and an edge (1-simplex) is bounded by 2 nodes (0-simplex).

If one compares the polyhedron approach with the TEN approach the advantage of using polyhedrons is 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 between a feature and the tetrahedrons and the modelling complexity, a TEN offers easy computing, also due to the well-defined character, as all faces are flat as they are defined by three points. This can further be illustrated best with the example of the volume computations in the real estate tax case. Implementing a volume calculation formula for polyhedrons is complex, whereas in the TEN case a single formula for a tetrahedron volume is sufficient. This simple formula has to be used several times, but that is exactly what computers are best for. Another operation that is easy to use in a TIN/TEN structure is the point-in-polygon test, as all simplexes are convex. The easy computations are possible due to the well defined structure of a TEN. Two points define a line, three points define a plane, four points define a volume.

A triangulated irregular network can deal both with 2D and 3D points. If dealing with 3D points a 2.5D TIN is a good example of a 2.5D representation and this representation is often used in digital elevation models. In this case the triangulation is calculated in 2D only, the z-value is considered as attribute. Further a multiple layer 2.5D TIN approach might be used to further improve 2.5D modelling capabilities. However, a TEN is a real 3D volume representation as it adds the tetrahedron to the available simplexes as point, line and face, thus enabling one to model volumes. As these volumes are bounded by triangles, a close relationship can be identified in combined TIN/TEN models. One can imagine that in our topographic representation a real 3D TEN model (for instance a model of a building) is placed on top of the terrain, represented by a 2.5D TIN. If the 2.5D TIN and base triangles of the TEN model are identical, the TEN model can be placed on top of the 2.5D TIN by 'glueing' the triangles with the same geometry onto each other.

This TIN/TEN combination can even be stored in a single data structure. A tetrahedron holds references to its four bounding triangles, a triangle holds references to its three bounding edges and an edge holds reference to its two spanning points. If for every triangle, edge and point it is recorded whether these elements are part from the TIN, the TEN or both, it is possible to extract not only the combined model, but also the separate TINs and TENs. In order to model topographic features references can be given to which topographic object (feature) the k-D simplexes belong.

2.5 Towards a 3D topographic model

Until now real 3D topographic products are rare and do not offer a complete coverage of the Netherlands. In this paragraph several current products with some potential height information will be discussed. At the end the way in which this data can be used to come to a 3D model is described.

2.5.1 DTB Nat and DTB Droog

The DTB Nat and the DTB Droog can be considered as closest to 3D products. Although it does not use a 3D primitive 3D coordinates are available for all features. These topographic products of the Survey Department (AGI – Geo-Information and ICT Department) of the Ministry of Transport, Public Works and Water Management are detailed (1:1,000) topographic maps of the main water and road infrastructure of the Netherlands, but they are limited to a strip on both sides of these roads and rivers, thus covering only small parts of the Netherlands. The DTBs are produced from aerial images, combined with some terrestrial measurements.

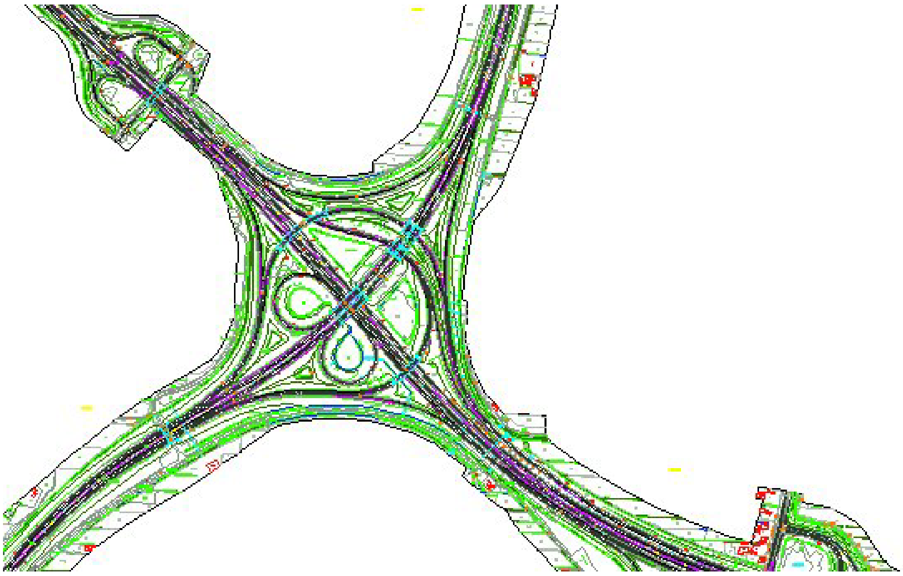

Figure 2.6 DTB Droog of highway interchange Hoevelaken (source: AGI, Ministry of Transport, Public Works and Water Management)

Both data sets consist of non-overlapping polygons, combined with point and line features. All these geometries are stored with 3D coordinates. An example of the DTB Droog can be found in figure 2.6. Figure 2.7 shows a bird-eye view generated from the height model of the DTB Droog. Figure 2.8 shows also a bird-eye view, but now generated from the DTB Nat.

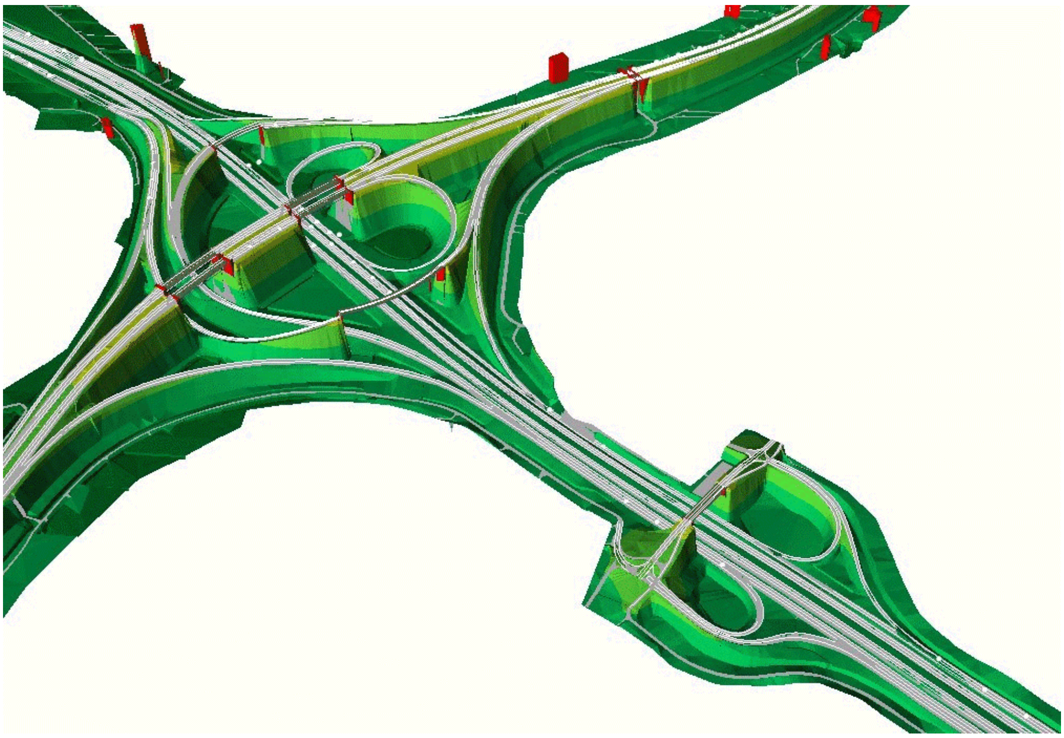

Figure 2.7 Bird-eye view of the height model of highway interchange Hoevelaken (bridges are overlapping polygons, probably modelled in a different layer) (source: AGI, Ministry of Transport, Public Works and Water Management)

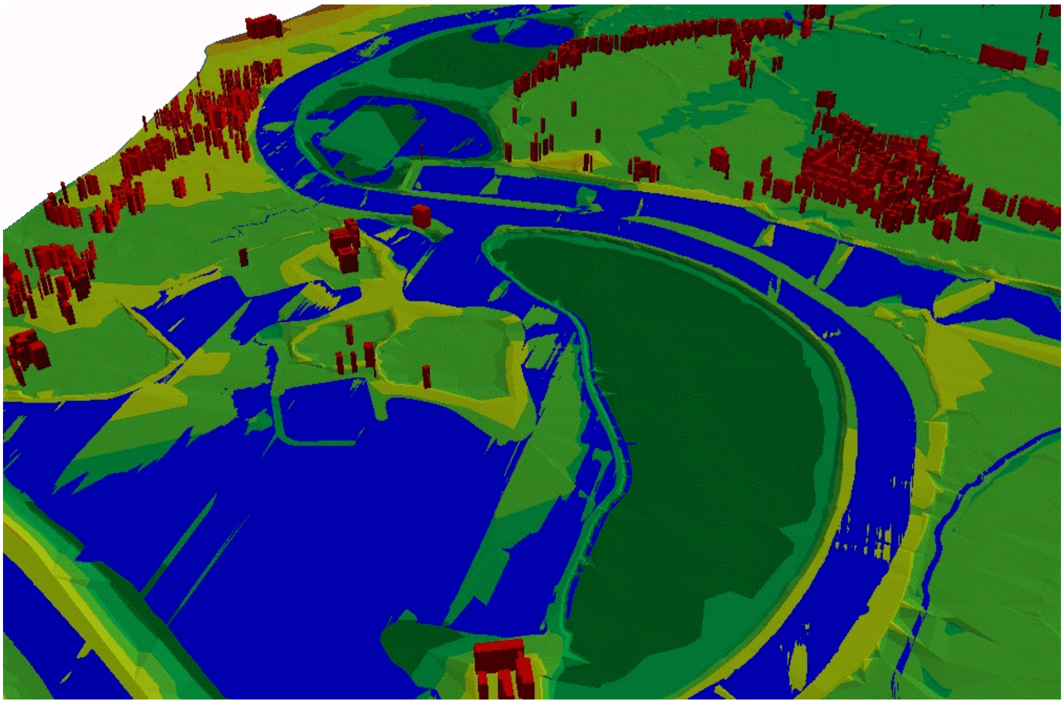

Figure 2.8 3D Visualization of the DTB Nat (source: AGI, Ministry of Transport, Public Works and Water Management)

2.5.2 TOP products

The current product range of products of the TD Kadaster consists of 2D topographic products. However, these products (and particularly the TOP10) hold height information, mostly in cartographic form. One can think of contour lines in the dunes and Limburg hills, some single characteristic height points and cartographic symbols. These symbols indicate for instance slopes or dikes. This is illustrated in figure 2.9, showing a highway exit on a dike. The length of the hatches indicates the size of the slope. Another height indication in the TOP10 is the distinction between low-rise and high-rise buildings. A complete inventory of cartographic height visualization can be found in [9].

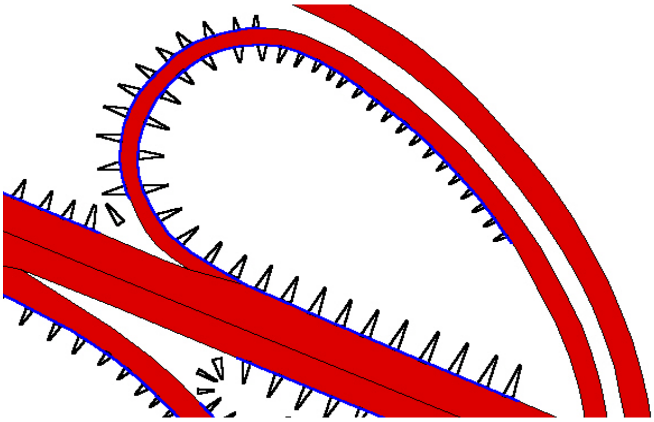

Figure 2.9 Cartographic indication of road lying on a dike

In the previous TOP10 product, TOP10vector, crossing roads like on viaducts were coded (by changing the last digit of the object code from 3 to 2) indicating whether a face was visible from above or not. In the example in figure 2.10 the wide road (coded 2003) lies on top, the parts of crossing road 3243 get code 3242 under the viaduct. One can image that it is sometimes difficult to reconstruct which road is on top, specifically when both roads have the classification (for instance both 2000). In the new product specification of TOP10NL each object has a height value attached and the coding system of overlapping polygons is improved in order to store the order of these polygons from top to bottom using levels 0, -1, -2, etc. With these two new attributes reconstructing roads from the different polygon parts has become easier.

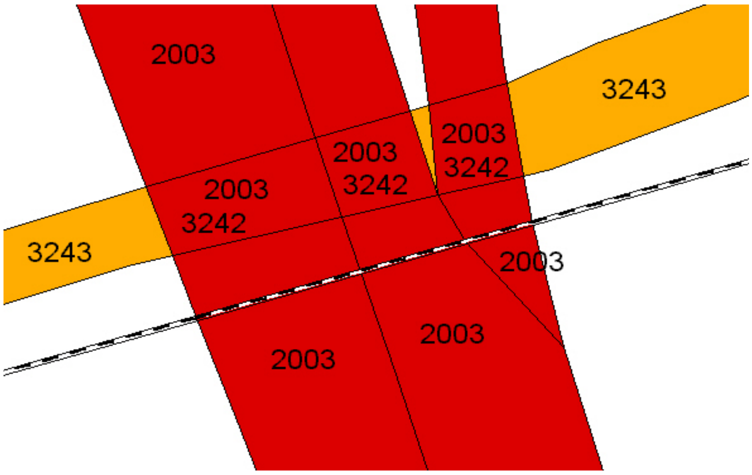

Figure 2.10 Viaduct in TOP10vector: road polygons coded with a 3 as last digit are visible from above, codes ending with 2 not

2.5.3 Large-scale Base Map of the Netherlands (GBKN)

The large scale base map (in Dutch: Grootschalige Basiskaart Nederland, GBKN) is a joint effort of municipalities, Kadaster, KPN and utility companies to produce a large scale base map (scale 1:500 or 1:1,000 in urban areas and 1:2,000 in rural areas).

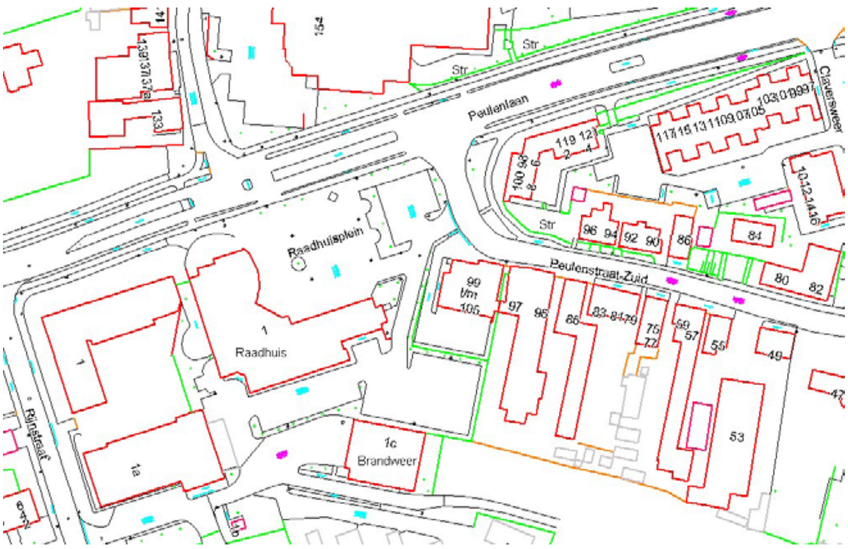

Figure 2.11 Example of the GBKN

This product does not contain height information, but does contain 2D projections of for instance road banks. Therefore the GBKN is a possible products that can be extended into 3D by combining it with height data from several sources. However, the line-oriented structure should first be upgraded to an object-oriented structure.

2.5.4 Actual Height model the Netherlands (AHN)

At the same time the AHN (Actual Height model the Netherlands) is available, a high density laser scanning point set describing terrain heights, with on average one height point per 16 square metres. As the laser pulses are often reflected on roof tops or tree tops, not all points in the raw data set describe the terrain surface. Therefore the data is corrected to obtain a data set describing the terrain surface. This filtered data set is a commercial available product, which does not contain any hard topographic features such as buildings or viaducts. However, if one wants to use laser scan data for 3D models or visualisations, these topographic features are precisely the information one is interested in. This unfiltered data set is an intermediary product in the AHN production, but unfortunately not commercial available. Figures 2.12 and 2.13 illustrate how aerial images and topographic maps can be draped on top of such an unfiltered data set. Although these drapings might be visually attractive, one can not speak of a truly integrated 3D model, as no explicit relationship between both models is made. Topographic features are visually recognisable, but not explicitly present. As a result no analyses like 'return all buildings within 50 metres' can be performed on this model. However, during this PhD research an unfiltered (but with blunders filtered out) data set is needed.

Figure 2.12 Aerial image of the centre of Amsterdam draped on top of unfiltered AHN (source: AGI, Ministry of Transport, Public Works and Water Management)

Figure 2.13 TOP10vector draped on top of unfiltered AHN (source: AGI, Ministry of Transport, Public Works and Water Management)

If one wants to perform real 3D analyses, such as 'Find all buildings in this search area that lie beneath sea level' or 'Find the shortest path with a maximal slope of x% between these two points', a truly integrated model is required as the drapings can not be used to find the answers.

2.5.5 Creating a 3D topographic terrain model

In order to create an integrated topographic model additional height information for the topographic features is required as well as height information to describe the terrain surface between the topographic volume features. In the Dutch practice four relevant height sources are available:

- the AHN, but from the images on the previous page one can conclude that the commercial AHN product with buildings and trees filtered out is not very useful for retrieving 3D information about topography. A data set is required that only has errors filtered out, but still contains height information about the relevant topographic features,
- the DTBs, as they contain already 3D data for (amongst others) dikes and highway banks,
- the current 2D topographic data set, as cartographic symbols and contour lines do hold some height information,
- Railroad data, as they probably contain 3D data for railway dikes (more research into this product is needed first).

Another option will be that the research carried out by other participants in the large Bsik research (see paragraph 3.3 for the context of this PhD research) will lead to new 3D data models, for instance based on terrestrial laser scanning. If all these height data sources can be combined with current 2D topographic products, 3D products could be derived. The next chapter will go into more detail on this process.

3 Research project

3.1 Introduction

The need for a 3D topographic terrain model is underlined in the previous chapter. This chapter will describe the research to get to such a model in more detail. In paragraph 3.2 the goal of the research project is described. Paragraph 3.3 will discuss the context of the research. The next paragraph will split up the research into different research tracks and these tracks will be described separately. Based on these tracks several research questions are defined in paragraph 3.5. The chapter ends with a paragraph with limiting conditions to the research.

3.2 Goal

With the circumstances described in the previous chapter in mind the aim of this research is to develop a method to create a 3D topographic data model by combining current 2D topographic data sets, such as TOP10NL or GBKN with 3D data (DTBs) and height data from different data sets or from new 3D model sources. In order to enlarge the capabilities on analysis and validation the data will be stored in a TIN/TEN data structure. The (2.5D) terrain will be modelled as a Triangular Irregular network and the 3D features will be glued 'on top' or 'below' of the TIN as connected Tetrahedronized Irregular Networks (TENs, see figure 3.1).

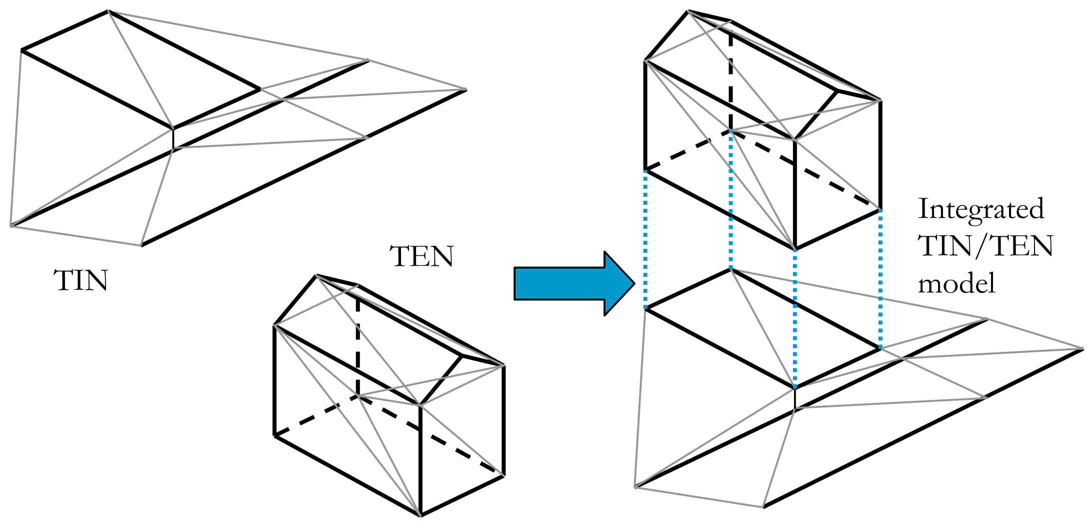

Figure 3.1 Combining 2.5D TIN and 3D TEN into a combined TIN/TEN model

In figure 3.2 a potential UML class diagram of the feature based TIN/TEN model is given. It shows the relationship between different types of features, the TIN and TENs. Especially the connection between the TIN and the TENs will be subject of extended research and thus might this structure change over time.

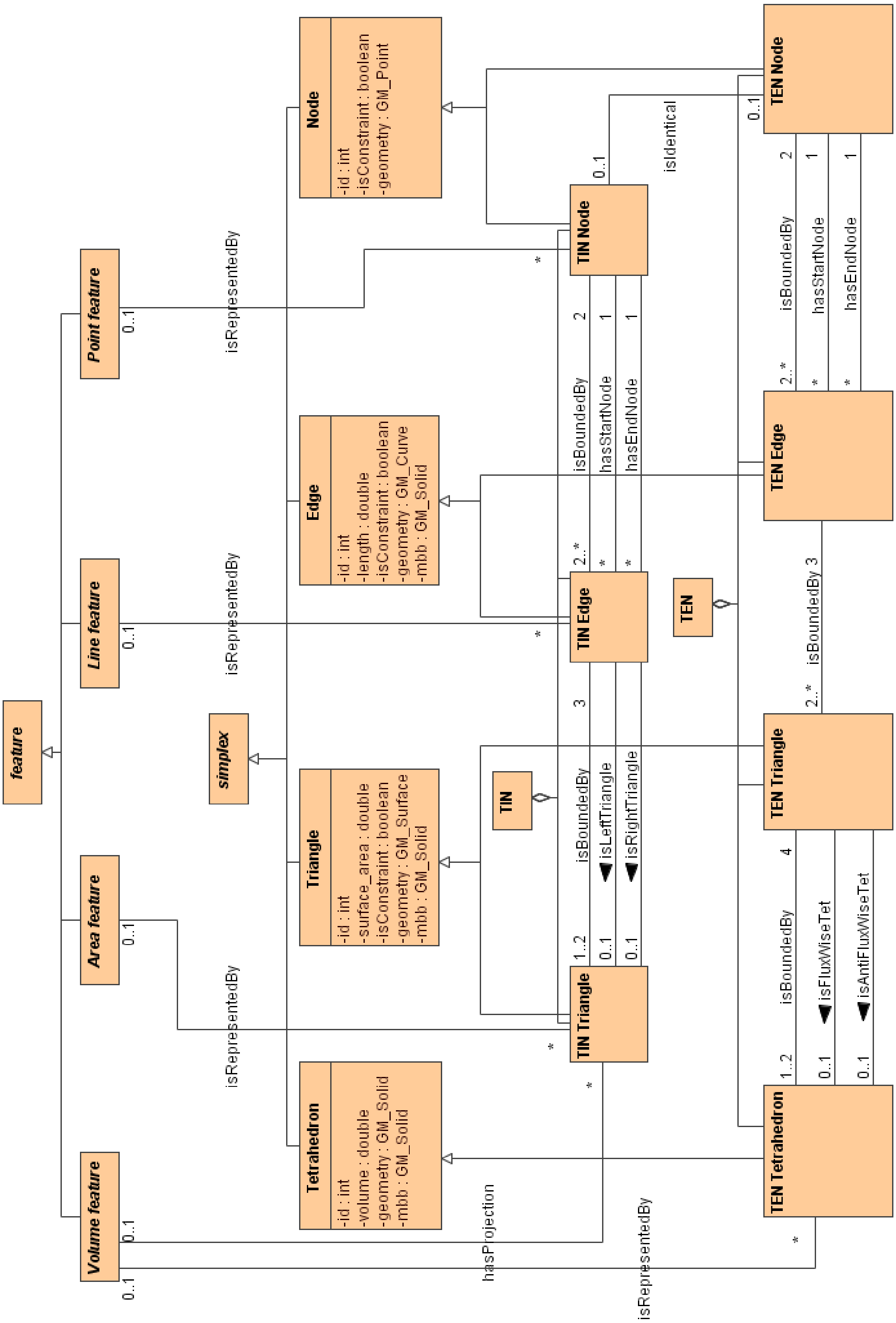

Figure 3.2 UML class diagram of the feature based TIN/TEN model

As this combined data structure might be experienced as a complex structure by the average user, special attention will be given to the 'interface'. Updating should be possible by adding or removing topographic features (in 2D: points, polylines, polygons, in 3D: polyhedrons), which will internally be processed as the addition or removal of constraints (now modelled as an attribute of the simplexes) in the TIN/TEN data structure. The basic principle is that the user needs not to be aware of the underlying TIN/TEN architecture. Data retrieval should result in plain topographic features, thus 'masking' the internal triangle/tetrahedron decomposition. This idea is illustrated in figure 3.3.

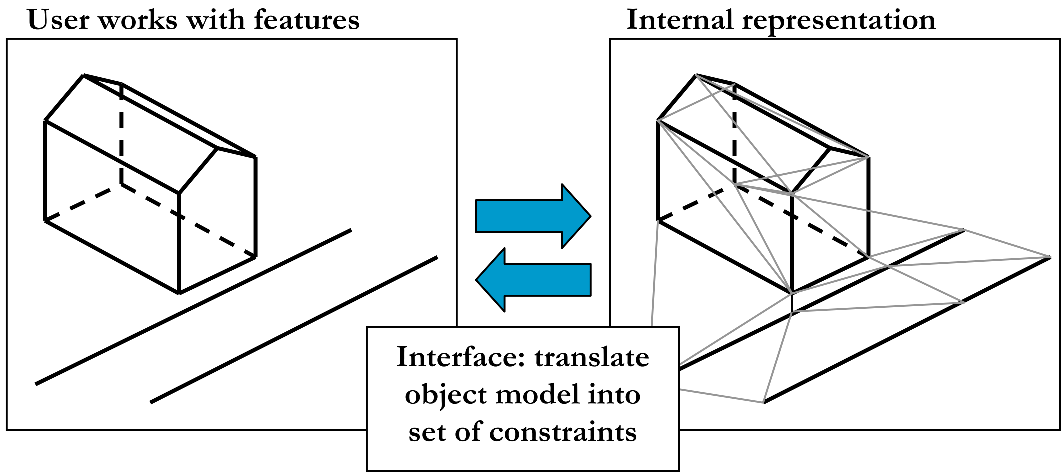

Figure 3.3 **An efficient interface translates polygons and polyhedrons into sets of constraints in the internal feature-based TIN/TEN architecture**

3.3 Context of this research

This project is part of a larger research project in the field of 3D Topography, which covers the entire geo-information process on 3D data, from data collection (with the emphasis on retrieving 3D models from aerial or terrestrial laser scanning data), through modelling and analysis (in an explicit data structure) to visualization and interaction (with emphasis on virtual reality interaction). This research is submitted for funding [5] in the Bsik Programme Space for Geo-Information by a consortium of research partners. At this moment the proposed allocation of research is as follows:

- the research in the field of data collection will be carried out by ITC Enschede, department of Earth Observation Science (amongst others by prof.dr.ir. George Vosselman and a PhD-student),
- the research in the field of data modelling and analysis will be carried out by Delft University of Technology, OTB, section GIS Technology (amongst others by prof.dr.ir. Peter van Oosterom, ir. Edward Verbree and the author, ir. Friso Penninga),
- the research in the field of visualization and interaction will be carried out by Delft university of Technology, faculty Electrical Engineering, Mathematics & Computer Science, section Computer Graphics and Human-Computer Interaction (amongst others by prof.dr.ir. Erik Jansen and a post-doc/PhD-student).

Besides these research groups the consortium also consists of TD Kadaster and AGI, as they produce almost all relevant data sets. The consortium is likely to grow with some industry partners, of which Oracle is definite. Also ProRail, responsible for the maintenance of the Dutch railway network, is likely to join the research consortium.

As this PhD research is closely related to the PhD research of Edward Verbree [8], some topics will be a joint research effort. Generally speaking most topographic feature model / application related issues are part of the author's research and most data structure issues are part of Edward Verbree's research.

3.4 Research tracks

In an attempt to split up the research in manageable parts four different tracks have been identified:

- Theoretical TIN/TEN Track:
  This track will focus on the logical design of the data model, input/output functions and data formats *(joint research effort Edward Verbree and Friso Penninga)*.
- Topographic Track:
  This track will focus on the design and prototyping of a method to create a 3D topographic model by combining current 2D topographic products with 3D topographic and height data sets. Some results in this area are available from earlier research of Edward Verbree [9] *(research effort Friso Penninga)*.
- Technology Track:
  This track will focus on the implementation in a geo-DBMS environment of data structures and algorithms as designed in the Theoretical Track, the creation of input/output functions and design of true 3D analyses *(joint research effort of Edward Verbree and Friso Penninga)*.
- Advanced TIN/TEN Track
  This track will focus on issues like modelling temporal aspects in the TIN/TEN model, creating and testing different spatial indexing techniques, multi-scale representations, multi-representation, etc. *(research effort Edward Verbree)*.

3.4.1 Theoretical TIN/TEN Track

Main objective of this track is the logical design of an integrated TIN/TEN model. Topographic features will be stored as constraints in this model. The 2.5D TIN will hold all 2.5D features (point features, line features, area features). The basic principle is that the user will be handling only these features, its underlying 2.5D TIN architecture will not be visible. Real 3D volume features, like buildings and construction works, will be modelled as separate TEN models. Connecting the 3D TEN models to the 2.5D TIN model will be another research topic in this track. One option is to use the base triangles from the TIN as constraints in the TEN (or the other way around), thus ensuring a direct 1:1 relationship between boundary faces of the TEN models and faces in the TIN surface. Another option is to store the footprint of volume features in the TIN.

Another design question will be the way to store topological relationships. In our approach, the feature based TIN/TEN modelling, both feature topology and TIN/TEN topology is needed. Feature topology describes the relations between the topographic features, such as 'this house is built in water', whereas TIN/TEN topology describes relationships such as triangle/tetrahedron adjacency.

Closely related to the subject of topology lies the subject of validation. During updates of the topography it is important to maintain both a valid TIN/TEN data structure and a valid feature model. This means that during updates the model still has to satisfy all constraints, both TIN/TEN constraints and business constraints. TIN/TEN constraints might be for instance Delaunay constraints, such as the empty circumcircle property. Working with constraints in TINs and TENs might complicate fulfilling Delaunay criteria. Attention has to be paid to the question whether one wants to work with a constrained, conformal or refined constrained TIN/TEN, see also [7]. In a nutshell one can say that TIN/TEN constraints deal with the data structure and determine the TIN's/TEN's characteristics.

The business constraints refer to the classification of features, thus enabling a semantic validation of user updates. One might want for instance to disable the possibility to place a point feature of class 'tree' inside an area feature of class 'water' or trigger a confirmation request as soon as one tries to place an area feature of class 'house' inside an area feature of class 'water'. By using logical constraints (or feature constraints) one enables on-the-fly validation in order to maintain data integrity.

Another important theoretical design question is the design of the interface specifications: how is the 'interface' between features and the feature-based TIN/TEN model in the DBMS possible? As mentioned earlier the objective is to hide the internal TIN/TEN architecture from the user by the design of input/output functions based on topographic features (points, polylines, polygons, polyhedrons) only. The used data formats will be part of the research, but at this time it is likely to work with the DBMS API and/or SQL to retrieve the data from the DBMS and with XML in combination with GML 3 and/or X3D and/or native GIS-formats and/or native CAD-formats to export the data.

3.4.2 Topographic Track

Developing a method to create a 3D topographic model by combining existing 2D topographic data sets with 3D topographic data and 2.5D height data is the main goal of this track. First the existing topographic and height products and their specifications have to be studied. Based on this results the product specifications of topographic data sets have to be converted from 2D into 3D. As a next step research has to be carried out to answer the question whether the creation of additional explicit 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 or that the implicit presence of this height features in the terrain surface TIN is sufficient. During this research several sources for the creation of additional features can be looked at:

- current TOP10 (converting map symbols into features),
- DTB (boundaries (polylines) of banks and inclines are available and can be converted into polygon features, for strips alongside rivers and highways only),
- unfiltered AHN (automatic break line/feature detection),
- railroad data (for strips alongside railroads only).

As all hard topographic features (like buildings, viaducts) are converted into 0D-3D features in 3D space, the question arises how to model the space in between hard topographic features. It has to be determined later whether it is necessary to model for instance the air between the terrain surface and an underlying tunnel in order to support certain spatial analyses. On terrain surface level it will be useful to model terrain surface heights in the 2.5D TIN. In the current topographic products these surfaces have no height component, although for instance the TOP10 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 and a method to select these height points from the AHN. Several techniques can be examined (amongst others the one introduced in [7]), such as slope based filtering 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).

As the 2.5D topographic constrained TIN is created, the volumes can be modelled as TENs and added to TIN. This might be carried out in a two-step approach, starting with easy convex objects and later with more complicated concave objects. An important product design question to answer will be 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 trick introduced in paragraph 2.4.1 where buildings were 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. In figure 3.4 this is illustrated. The house is being built partially in the dike. If one wants to calculate the house's volume, for instance for tax purposes, the shaded part is relevant, but not part of the TIN model.

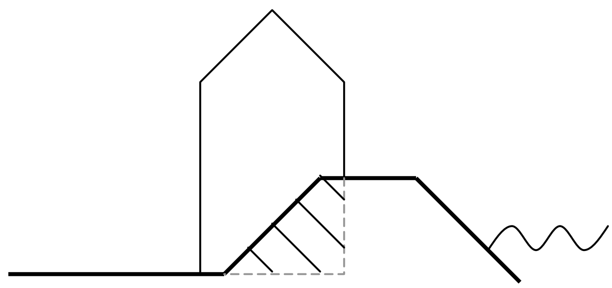

Figure 3.4 Cross section of a house built partially in a dike

Related to this design decision, especially in 3D cases, is the more general question where features stop (depends on the feature definition), i.e. where are the boundaries. Identifying boundaries of some hard topographic features like buildings is easy, but other features' boundaries are less obvious. It has to be decided for instance whether to model a road as a line feature or as an area feature. Boundaries of three dimensional features like hills, dikes, valleys, mountains and viaducts are difficult to define.

3.4.3 Technology Track

This track will focus on the implementation of the conceptual and logical data model design in a DBMS environment. The TIN/TEN data structure will be implemented in a spatial database. Functions for building and updating the model have to be created, as well as Input/Output functions. A schematic lay-out is given in figure 3.5. At this moment the combination of Oracle Spatial and Java is the intended development platform. We intend to make our implementation available as open source software. As mentioned earlier the Input/Output of the model will be in the form of topographic features (point, polyline, polygon, polyhedron constraints). A range of formats has to be tested, starting with SQL and the DBMS API to retrieve data and formats like XML with GML3 or X3D, native GIS-formats and native CAD-formats for the output. The usage of native formats is related to the functionality offered by these software packages (products of Bentley, ESRI, etc.).

The data structure as we have in mind at this moment (see UML class diagram in figure 3.2) is relatively straight-forward. The TIN is composed of TIN triangles, which are bounded by TIN edges, which are bounded by TIN nodes. It was decided to use separate data types for e.g. TIN edges and TEN edges, because (despite the identical attributes) of the difference in relationships between edges and triangles in TINs and TENs. Besides nodes, edges and triangles a TEN also contains tetrahedrons. The TIN and TENs are integrated by the IsIdentical-relationship between the TIN and TEN node.

Features are composed of several simplexes. Point, line and area features are represented by a set of TIN nodes, TIN edges and TIN triangles. Volume features are represented by tetrahedrons, although each volume feature has also its projection represented in TIN triangles. It has to be underlined that this approach might change over time, due to advancing knowledge or practical implications.

At this moment we aim to implement triangulation and tetrahedronization algorithms in a DBMS environment, but at first existing external software might be used. Closely related are the update algorithms: adding or removing features (where moving features can be considered as a combined removing-adding operation) has to be translated into adding or removing constraints in the TIN/TEN data structure. The implementation of the tetrahedronization algorithm might be performed in two steps, starting with an easy algorithm for convex features, followed by a more complex approach for tetrahedronizing complex, concave features.

Within these algorithms validation of both the data structure and the feature model play an important role, as the suggested approach offers an on-the-fly semantic validation which is an extremely important functionality in data management. Maintaining data integrity is facilitated by such a functionality.

Another part of this track will be the realization of true 3D analyses, as this is the most important addition to current 2.5D models and drapings. A large range of possibilities exists: 3D buffers, 3D overlay, cross country movement planning, line-of-sight, antenna coverage analysis, cut-and-fill computations, 3D airplane and communication corridor planning, etc. Also less complex operations have to be implemented, for instance DBMS operators like return edge length, return face area, return tetrahedron volume. Based on combining an using these basic operators feature operators like return feature length, feature area and feature volume have to be developed.

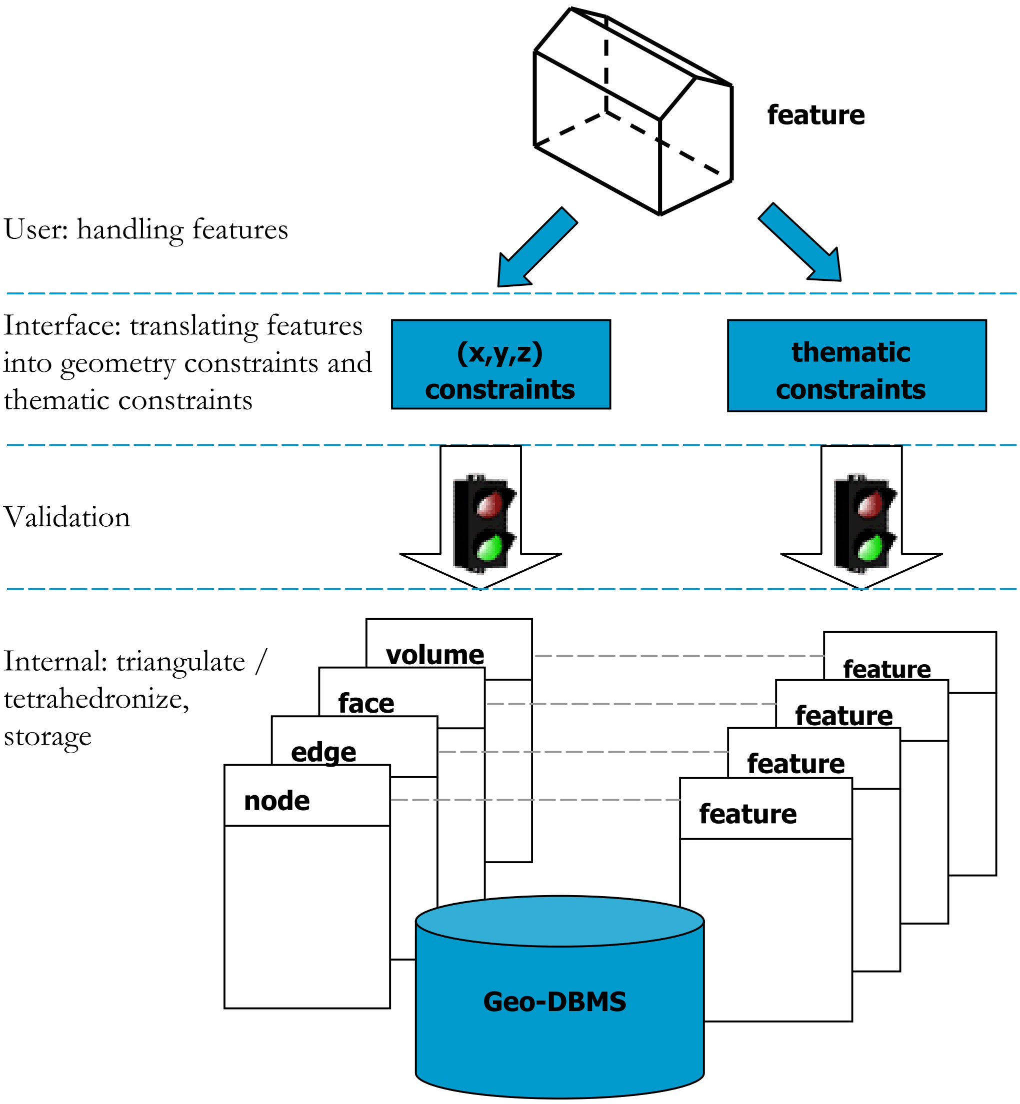

Figure 3.5 Schematic lay-out of implementation of integrated TIN/TEN model

3.4.4 Advanced TIN/TEN Track

As the author is not involved in this track, this description will only give an indication of the type of the research topics in this track. The advanced TIN/TEN Track will further extend or improve the functionality of the TIN/TEN model.

Research topics are for instance improving TIN algorithms (as current algorithms optimize Delaunay criteria in 2D instead of 3D) and spatial indexing of TINs/TENs. Modelling temporal aspects (both history and future design) within a TIN/TEN model is another topic, including a rollback in order to get the situation at a certain time. The application of multi-scale representations and multi-representations in the model and algorithms is also part of the research.

3.5 Research questions

In an attempt to summarize the research issues stated in the previous paragraphs some research questions are formulated. The main question of this PhD research will be:

How can a 3D topographic terrain representation be realized in a feature-based integrated TIN/TEN model?

Within the research a lot of research subquestions can be formulated. The following list is an indication, but the research will not be limited to these questions.

Theoretical TIN/TEN Track:
How should the data model of the feature-based TIN/TEN model be designed?
How should the connection between the TEN models and the TIN be established?
How should the relationship between features and the simplexes be established?
How should topology be handled in the feature-based TIN/TEN data structure?
How should feature topology be handled in the model?
How can other feature constraints be handled?
How should the interface with the user, i.e. converting feature geometries (in XML/GML3 or X3D) into TIN/TEN constraints and vice versa, be designed?

The conceptual models will be made using UML (Unified Modelling Language) and OCL (Object Constraint Language).

Topographic Track:
How can a 2D topographic data set be extended into 3D?
How should the different topographic features be defined (including boundaries) and which geometrical primitive has to be used for these features?
Which features should be modelled in 2.5D and which in 3D?
Which additional height features are necessary (or none and if any, how can the boundaries be defined)?
Which data sources can be used to derive height data?
How should significant height points be selected?
How can one determine the number of required height points?

Technology Track:
How can the data model be implemented in a (Geo-)DBMS?
How should the add feature function be implemented?
How should the remove feature function implemented?
How can the data be retrieved (SQL)?
In which formats should the data be returned?

How should the triangulation algorithm function?
How should the tetrahedronization algorithm function?
Which existing products can be learned from as 'best practices'?
How can the validation of the TIN/TEN constraints be performed?
How can the validation of the feature constraints be performed?
Which and how can 3D analyses and functions be implemented?

This last question covers a large research part and has to be rephrased into more detail in a later stage. Although not included in my research, a short overview of subjects in the advanced TIN/TEN Track:

Advanced TIN/TEN Track:

- Validation of the STIN (Surface TIN) method [10]. Usually TINs are created by applying Delaunay criteria in 2D, this method includes the third dimension in calculating the optimal triangulation.
- 2.5D TIN modelling as the intermediate from 2D surface TIN models to 3D solid TEN models.
- Spatial indexing of TIN/TEN models
- Dynamic editing of TIN/TEN models
- TIN/TEN models to perform GIS operations: buffering and overlays

3.6 Limiting conditions

In order to define the scope of this project as clear as possible the research is limited in several ways:

- Intended scale level: 1:500 – 1:25,000 with related resolution and accuracy. This means that large and midscale topographic data sets can be subject of research, such as the GBKN, TOP10NL, DTBs and railroad data sets.
- Despite its potential growing use (for example in the disaster management area) indoor topography is excluded from this research.
- Subsurface features like tunnels and parking garages are included in the research.
- Data collection and creation of models from these data is excluded from this research, so for instance models of buildings are considered as available input. The research part of George Vosselman and others (see paragraph 3.3) will supply these models.
- Visualisation / virtual reality is excluded from this research. This research part will be carried out by Erik Jansen and others (see paragraph 3.3).
- Main focus of the model is enabling computations, analyses and validation (data management), not visualization

4 Planning

As the research will have an iterative character between several development steps and research activities of the different tracks will mix, this time schedule contains only a rough indication of time consumption. As this PhD research started officially on April 1st 2004, the available time is as follows:

Year	Number of available months
2004	9
2005	12
2006	12
2007	12
2008	3

Table 4.1 Available time per year

It has to be pointed out that of this time at least 75% is available for the research, the other 25% is used for amongst others training, meetings, supervising students and other research projects. The planning is as follows:

2004

Background literature	3 months
Writing research plan	2 months
Topographic height representation	
Including visits to TD Kadaster, RWS AGI	4 months

2005 / 2006 / 2007

Converting product specifications of topographic data set from 2D to 3D
Determining need for additional 3D (height) features
Comparing different sources for height data

Implementing triangulation algorithm within the DBMS
Implementing tetrahedronization algorithm within the DBMS
Creating update functions (SQL interface to edit data in data structure)
Creating Input/Output functions of features in GML 3/X3D (internally with SQL / DBMS API, externally in open formats (maybe in OpenFlight format, from game industry)

Connecting TENs with TINs
Determine number of required height points and method to select these height points
Creating and using topology (both in TIN/TEN model as feature topology)
Visit to other university / research institute (about 1 month)
Visit to Oracle
Implementing 3D analyses

Writing dissertation

2008

Improving dissertation and defending ceremony

During this period the following publication goals are set:

- Each year a progress report will be made for TD Kadaster and RWS AGI
- Each year two conference papers
- Each year two Dutch publications (Geo-Info, VI Matrix, …)
- In total two or three journal papers

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