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European Organization for Experimental Photogrammetric Research

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Joint OEEPE/ISPRS Workshop
– From 2D to 3D –
Establishment and maintenance of national core geospatial databases

OEEPE Commission 5 Workshop
Use of XML/GML

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Workshop

- FROM 2D TO 3D -
ESTABLISHMENT AND MAINTENANCE OF NATIONAL CORE GEOSPATIAL DATABASES

held at LGN (Landesvermessung + Geobasisinformation Niedersachsen), Hannover, Germany

8 – 10 October 2001

(with 3 figures and 1 appendix)

Report by Christian Heipke[1], Monika Sester[2], and Felicitas Willrich[1]
(1) Institute for Photogrammetry and GeoInformation, University of Hannover
(2) Institute for Cartography and Geoinformatics, University of Hannover

1. Workshop objectives

Core geospatial databases contain geographic information about legal boundaries, buildings, traffic, vegetation etc. which is essential in a large variety of applications. In most countries two-dimensional core geo-spatial databases have been established over the last years, they are maintained by National Mapping Agencies (NMA) and/or private companies. Current challenges include among others shorter revision cycles in order to improve the currency of the information, and the need for more detailed, in particular for three-dimensional information in order to meet the requirements of innovative applications.

The workshop has present the state-of-the-art and trends in the transition from two- to three-dimensional databases and its revision with special emphasise on questions related to European NMAs. The workshop topics are relevant for scientists, NMA employees as well as private providers and users of geo-spatial data. Topics to be discussed during the workshop included:

- Ways of transition from 2D to 3D core geo-spatial databases
- Applications of 3D core geospatial data
- Visualisation of 2D and 3D geospatial data
- Maintenance and revision of 2D and 3D core geo-spatial databases concepts, data sources, algorithms and systems
- Revision by means of imagery and collateral sources
- Requirements for core geo-spatial databases to better serve the user´s needs

Invited experts from research, administration, software developers and data users have covered these and related topics. In addition to the presentations, there were breakout sessions in which relevant issues and open questions were discussed in smaller groups and in more detail.

2. Organisation

The workshop was organised jointly by

- OEEPE Commission 2 'Image analysis and information content'
- OEEPE Commission 4 'Core geospatial databases',
- ISPRS Intercommission Working Group II/IV 'Systems for automated geospatial data production and update from imagery' and
- ISPRS Commission Working Group IV/3 'Data generalisation and data mining'.

The workshop was hosted by LGN Landesvermessung + Geobasisinformation Niedersachsen (State Survey and Geospatial Basic Information Lower Saxony), and the University of Hannover, Institute for Photogrammetry and GeoInformation (IPI) and Institute for Cartography and Geoinformatics (ikg) under the auspices of OEEPE and ISPRS.

3. Programme committee

Christian Heipke, IPI, University of Hannover
Ernst Jäger, LGN, Hannover
Erwin Kophstahl, LGN, Hannover
Felicitas Willrich, IPI, University of Hannover
Keith Murray, Ordnance Survey, Southampton
Monika Sester, ikg, University of Hannover

4. Workshop report

by Stephan Nebiker, FHBB Basel University of Applied Sciences, Switzerland

National mapping agencies and private geodata providers are experiencing an increasing demand for 3D geodata. They are consequently faced with the challenges of establishing regional or national geospatial databases and of defining new business models in order to finance the effort. The workshop on this topic was jointly organised by OEEPE Commissions 2 'Image analysis and information content' and 4 'Core geospatial databases', ISPRS Inter-Commission Working Group II/IV 'Systems for automated geospatial data production and update from imagery' and ISPRS Commission Working Group IV/3 'Data generalisation and data mining'.

The three-day workshop was held at LGN Landesvermessung + Geobasisinformation Niedersachsen (State Mapping Agency of Lower Saxony) and was jointly hosted by the Institutes of Photogrammetry and GeoInformation (IPI) and Cartography and Geoinformatics (ikg) of the University of Hanover and the LGN.

The meeting was attended by more than 60 participants from 12 different countries with a well-balanced participation from national and state mapping agencies, universities and private industry. Invited experts from research, administration, software developers and data users covered the aspects of user requirements, data acquisition, data management and visualisation, activities at NMAs, database revision and data integration in a total of six technical sessions. These sessions were interleaved with break-out sessions and a guided tour through LGN.

In his keynote address on '3D data: markets and business opportunities' Prof. André Frank reflected on the potential of geoinformation, on geodata markets and on factors responsible for the success or failure of a new technology. He critically pointed out that geodata markets are limited and highly specialised and that geodata itself is not the market driver. He used an inspiring example to show that the main growth can rather be expected from (3D) GI applications and products addressing specific, well defined problems.

In the first session on 'requirements and applications of 3D geospatial data', it became clear that most NMAs in Europe are currently occupied with establishing their 2D core databases. The third dimension is primarily addressed by providing more precise digital terrain models, an increasingly important issue, particularly in flat countries and coastal areas. In an interesting presentation on 3D car navigation, it was shown that Japan is leading the way in this field with first operational systems available on the market.

In the second session on 'acquisition of 3D geospatial data' several semi- and fully automatic approaches for 3D building extraction from aerial imagery, airborne laser scanning and SAR were presented. There was a consensus that the integration of different data sources will be the key towards a greater level of automation and a higher level of reliability. One presentation highlighted the benefits of a direct link between the photogrammetric system and a 3D-GIS.

The first session on the second day covered the topic of '3D geospatial databases and visualisation'. It included presentations of new 3D data models and of projects aiming at managing and visualising nation-wide landscape and city models. Several of the presentations emphasised the key role of multi-representation and levels of detail (LOD) in a 3D context. A life presentation of the dilas (Digital Landscape Server) project from Basel University of Applied Sciences demonstrated the feasibility of web-based management and visualisation of nation-wide 3D landscape models. A presentation of the Atlas of Switzerland highlighted the trends in interactive hypermedia cartography towards on-line contents and dynamic 3D visualisations.

In the following session several European mapping agencies presented their strategies and solutions for database revision and refinement. The Institut Cartogràphic de Catalunya reported on their ongoing move from a map-oriented data model to an object-based topographic databases (DLM) and on the difficulties involved which eventually led to a completely new acquisition using digital photogrammetry. In a paper by the Swiss Federal Office of Topography the vision of a national 3D TLM (topographic landscape model) was outlined together with its foreseeable impact on production procedures and with an interesting co-operation model including so-called reference partners.

The first session on the third day of the workshop was dedicated to concepts, algorithms and systems for geo-spatial database revision. Topics covered included architectures for the distributed data acquisition and update, the automated verification and updating of the topographic database ATKIS from imagery and a project in Israel for photogrammetric 3D updating of 2.5D maps. The workshop was concluded with a session on 'aspects of data integration: time, scale and geometric dimension'. The first presentations were focussed on multi-representation databases and the tasks of automatically deriving different representations and of automatically propagating changes in such frameworks.

The conclusions of the workshop can be summarised as follows:

- the establishment, maintenance and web-based visualisation of regional or national 3D core geo-spatial is technically feasible
- among the major technical challenges are the aspects of multi-representation, automatic generalisation of 3D objects and data models supporting the integration of 2D and 3D geodata
- key factors in making 3D geoinformation an economical success will be the identification of new 3D GI applications and business models for the mass markets
- future 3D applications will require the integration of outdoor and indoor data
- there is strong need for standardisation of 3D geodata

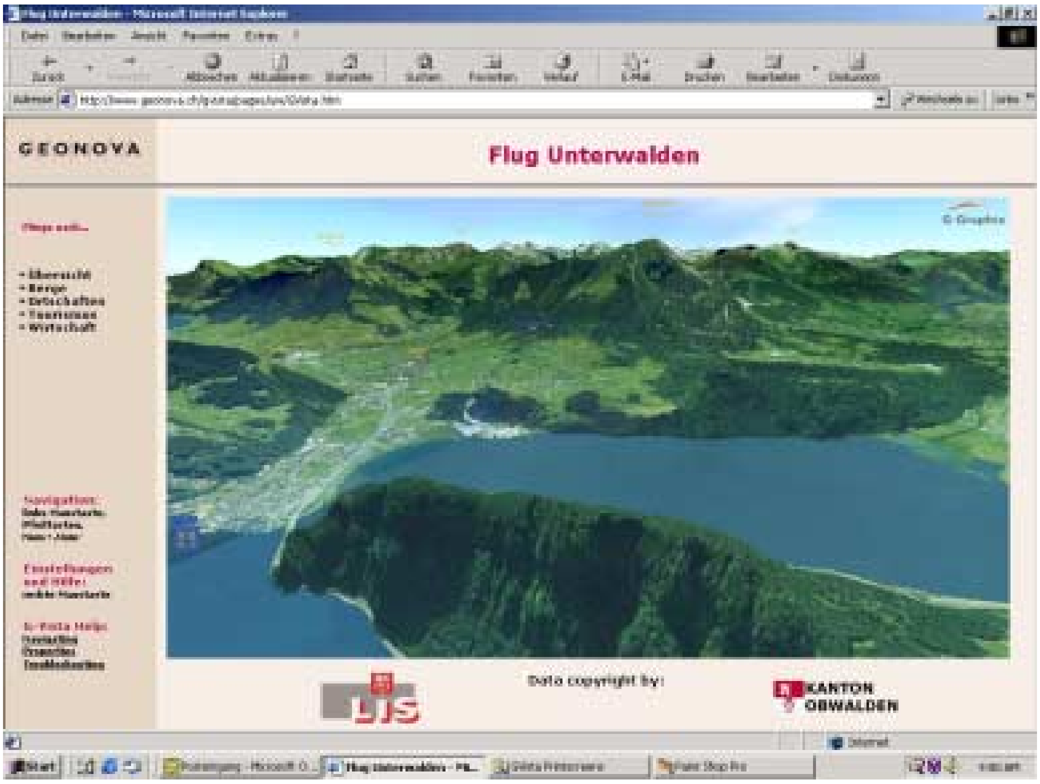


Fig. 1: Web-based visualisation of a nation-wide 3D landscape model of Switzerland (Copyright: GEONOVA AG, www.geonova.ch).

5. Final workshop programme

Monday, October 8, 2001

13:30 - 14:00 ***Workshop opening***
Ernst Jäger (LGN, Hannover), Introduction
Welcome addresses
Christian Heipke (University of Hannover), OEEPE Comm. II President
Ammatzia Peled (University of Haifa), ISPRS Council
Dietmar Grünreich (BKG, Frankfurt a. M.), EuroGeographics R&D Forum Chair

14:00-15.00 ***Key Note***
André Frank (Technical University Vienna)
New application areas: How to exploit 3D data as business

15:15 - 16:45 ***Session 1: Requirements and applications of 3D geo-spatial data***
Chair: Felicitas Willrich (University of Hannover)

Keith Murray (Ordnance Survey, Southampton)
Interacting with the topographic map of the future

Stephen T`Siobbel (Teleatlas, Gent)
3D and (car) navigation

Markus Müller (University of Stuttgart)
3D geo-spatial data requirements in environmental planning

17:00 - 18:30 ***Session 2: Acquisition of 3D geo-spatial data***
Chair: Keith Murray (Ordnance Survey, Southampton)

Norbert Haala (University of Stuttgart) and Claus Brenner (Robert Bosch GmbH, Hildesheim)
City model data acquisition from laser scanning

Eberhard Gülch (Inpho GmbH, Stuttgart)
Semi-automatic acquisition of topographic objects from digital imagery

Alix Marc (ISTAR, Sophia Antipolis)
3D geo-spatial data acquisition for telecom applications

Melanie Hayles (Laser Scan, Cambridge)
Integration of photogrammetry and 3D geo-spatial databases

Tuesday, October 9, 2001

9:00 - 10:30 ***Session 3: 3D geo-spatial databases and visualisation***
Chair: Peter Woodsford (LaserScan, Cambridge)

Lutz Plümer (University of Bonn)
3D geo-spatial data: models and topology

J. Bauer, A. Klaus, C. Zach, K. Karner, M. Gruber (TU Graz, Vexcel Imaging Graz)
Towards the hypermedia 3D urban database

Stephan Nebiker (FHBB, Basel)
dilas digital landscape server: management and 3D visualisation of large terrain data sets

Lorenz Hurni (ETH Zürich)
Atlas of Switzerland interactive

11:00 - 12:30 ***Session 4: Geo-spatial database revision and refinement at European NMAs***
Chair: Ernst Jäger (LGN, Hannover)

Friedrich Christoffers (LGN, Hannover)
ATKIS Authoritative Topographic-Cartographic Information System: Revision concept in Germany

Maria Pla, Santi Sànchez, Lluís Colomer (Institut Cartogràfic de Catalunya, Barcelona)
Updating topographic databases: the example of the Topographic Database of Catalonia at scale 1:5000

Stefan A. Voser (Federal Office of Topography, Wabern, Switzerland)
Towards the Topographic Landscape Model of Switzerland

13:30-14:30 ***Visit of LGN***

15:00 - 16:30 ***Breakout sessions:***

(1) The relevance of 3D geo-spatial data for National Mapping Agencies and user needs in 3D geodata and data revision
Convenor: Keith Murray (Ordnance Survey, Southampton)

(2) Revision of core geo-spatial data by imagery and collateral information
Convenor: Christian Heipke (University of Hannover)

(3) The role of cartography and 3D visualisation
Convenor: Monika Sester (University of Hannover)

17:00 - 18:00 ***Plenary session - findings of breakout sessions and discussion***

Wednesday, Oct. 10, 2001

9:00 - 10:30 ***Session 5: Concepts, algorithms and systems for geo-spatial database revision***
Chair: Christian Heipke (University of Hannover)

Peter Woodsford (LaserScan, Cambridge)
Architecture for distributed data acquisition and update

Felicitas Willrich (University of Hannover)
Automated ATKIS verification and updating from imagery

Ammatzia Peled (University of Haifa)
3D updating of a 2.5D map

Justin Simpson, Dan Edwards (USACE Technical Engineering Corps, Alexandria)
Integrating, maintaining, and augmenting multi-source data through feature linking[1]

11:00 - 12:30 ***Session 6: Aspects of data integration: time, scale and geometric dimension***
Chair: Monika Sester (University of Hannover)

Tiina Sarjakoski (Finnish Geodetic Institute, Masala)
Incremental generalisation in updating of geodata

Lars Harrie (Lund University)
Automatic propagation of updates

Thierry Badard (Institut Géographique National, Paris)
Propagating updates in multi-representations geographic databases

Ulrich Lenk (University of Hannover)
Strategies for integrating height information and 2D GIS data

12:30 *Workshop closing*
Christian Heipke (University of Hannover)

Appendix A is enclosed in the back cover as a compact disk and contains the overhead slides presented during the workshop as well as two specially prepared papers by Ulrich Lenk and Justin Simpson & Dan Edwards.

[1] Unfortunately, this talk had to be cancelled upon very short notice. The presentation material is available on the compact disk.

Figure 2: The workshop was held at the new LGN building in Hannover, Germany

Figure 3: Workshop participants attentively listening to the presentations

Integrating, Maintaining, and Augmenting Multi-source Data through Feature Linking

Dan Edwards and Justin Simpson
Topographic Engineering Center[1]

1 Introduction. The passage from spatial information in two dimensions (2D) to three dimensions (3D) necessitates many changes. At the level of the data model, it is important to realize that geometry, topology and objects require new treatment. The traditional functions of a geographical information system (GIS) will have to be redesigned and rewritten to accommodate the 3D data model. The direction of these changes will be guided by the emerging 3D applications, some of which have been discussed at this workshop.

The collection, integration and validation of 3D geospatial information will change as well. Collecting data from aerial photographs will not completely populate a 3D GIS. Stereo photogrammetry, at best, can model a 3D representation of the earth as a 2D shell covering the terrain. It can not capture, for example, the interior of a building. Collecting 3D data requires sources other than aerial photographs, and the data from these sources will have to be integrated into a comprehensive entity.

The passage from 2D to 3D data will force users to consider data from multiple sources. Our experience has been that multi-source data over the same geographical area will be disparate, both spatially and thematically. Consequently, multi-source data can disrupt the internal consistency of a national database. At the local level, how does one reconcile the differences between data from multiple sources? Our point of view is that without further information or source imagery, we can not say which data, if any, are correct.

Multi-source data needs special tools to manage, automatically, the disparities that are endemic to such data. This paper concerns one particular facet of the collection, integration, and validation of 3D geospatial data: two managerial tools that are useful in integrating data from multiple sources. We shall discuss some of the problems that arise and give our solution, called “linking”, where disparities can be preserved yet integrated automatically. We shall discuss a second tool, called “Best Map” in which linked data can be viewed as a unified whole. We shall then outline possible extensions of linking.

Our work, to date, has been entirely limited to disparities that arise in 2D multi-source data. The problems, which we shall be discussing, are a characteristic of multi-source data, regardless of the underlying dimensions. Given the relative difficulty in extracting accurate z-values, compared to x and y, we feel that the locational disparities will increase, rather than decrease, as one passes from 2D to 3D.

[1] The work described here reflects work over a number of years and across several programs. Intergraph Corporation has written prototype linking software. Intergraph and Swiftsure Spatial Systems Inc. have written prototype best map software. These software developments have helped us test and refine the ideas presented here.

2 What is Linking?

When vector data from two sources are overlaid, the vector representations of the terrain do not agree. The disparity can be due to scale, resolution, compilation standards, source accuracy, registration, sensor characteristics, currency, seasonality, atmospheric conditions, or errors. Whatever the case, the data do not agree and the user is unsure which data best represents the terrain. See figure 1.

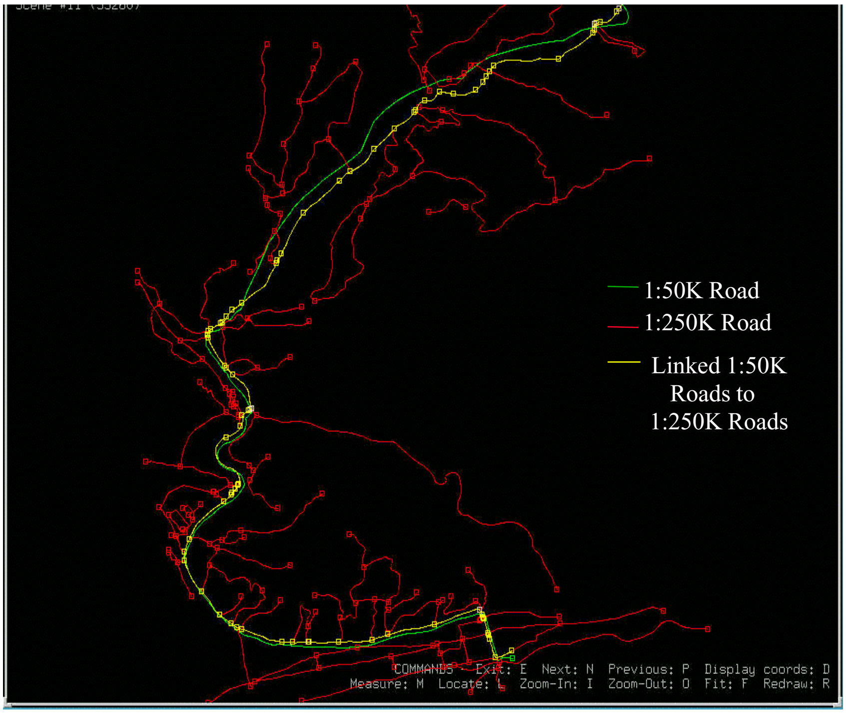


Figure 1

Linking is an automated process that forms a correspondence between feature elements in two overlapping vector data sets; these feature elements must correspond both spatially and thematically. Linking does not attempt to eliminate differences. Linking simply identifies two representations of the same element on the terrain without judging which representation is better. A fundamental tenet is that we do not know the truth, in the absence of further evidence.

For example, higher resolution data cannot automatically be assumed to "better data" than lower resolution information. Figures 2 and 3 illustrate this point. Figure 2 contains a heterogeneous collection of features loaded from different sources. In this example, an urban area is covered by road feature data from two sources, one of a higher resolution and detail than the other. The background is an image of a reference map. Some of the information available on the 1:50,000 scale source (blue) is unique and not available on the 1:250,000 scale source (yellow). But the reverse is also true in a nearby region of these same collective datasets (Figure 3). The assumption that one dataset is better than the other is obviously not correct. The discrepancies may be due to different collection specifications, temporal disparity, sensor differences, or obscuration in the source imagery. Comprehensive "truth" is not attained from a single source. Use of a pluralistic system addresses this problem by providing the ability to integrate and assemble, by linking, different versions of information available to describe a geographic area. Data are stored "as-is", as received from the provider, preserving separate spatial and semantic detail. Use of a pluralistic database and linking tools integrates features from disparate sources. From a data perspective, this resulting integrated view has many geometric features. Each feature represents the "best" version of the spatial component available in the pluralistic database. User applications can then be run on these integrated “best” elements.

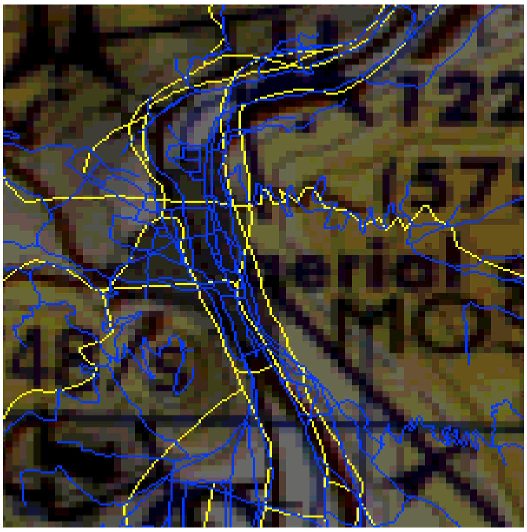


Figure 2

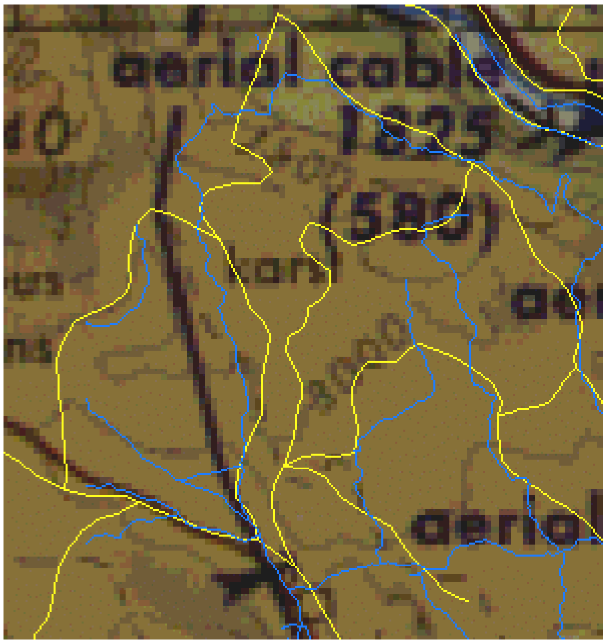


Figure 3

Nevertheless, linking generates new information when linked data elements reinforce, augment, or contradict each other. Linked data elements represent two analysts' views of the same entity. When viewed in the context of the collection specifications, two independent interpretations can provide a spectrum of information, ranging from mutually reinforcing to contradictory. The new information provides a more realistic confidence in the feature elements.

Although linking is a non-destructive process that preserves the original data sets, linking facilitates the assembly of a unified view of the terrain that represents the intelligent fusion of the disparate information. (See Section 5.) Since any number of data sets can be linked, one can assemble an integrated view of all available data over an area of interest.

Feature elements can represent points, linear entities, or areal entities, and the linking correspondence is not constrained by dimensionality. For example, an areal river in one source can be linked to a linear river in another source. A point bridge can be linked to a linear or areal bridge. An areal city can be linked to a point city. The entities in one source that correspond to entities in another source can be single feature elements or groups of feature elements.

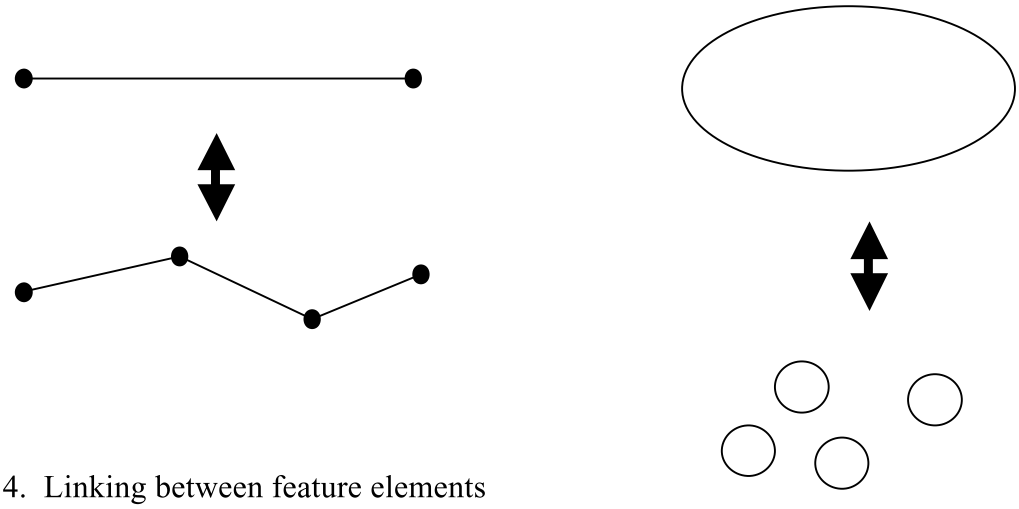


Figure 4. Linking between feature elements

It would be possible to use our 2D linking is to link an urban vector map to wire-frame building models. Using terrain rules, derive a vector representation of either the base or the top of the buildings. Project this vector representation to Z=0, and link this 2D representation of buildings to the urban vector map. Transfer attributes from the urban vector map to the 2D and 3D vector representation of buildings, and thereby to the wireframe building models. We must emphasize that we have not assembled all of the tools needed to do this, but we feel that the individual tools are in place at this time.

3 Benefits from Linking

The previous section on the reasons to link provides a background against which we can appreciate the benefits of linking. In this section we shall discuss the following benefits that result from linking:

Potential use of all available information
Automated use of future information
Dealing with an uncertain reality
Linking is not destructive
Creation of knowledge
Opportunity to compare sources.

3.1 Potential to Use All Available Information

As discussed above, no one source contains the perfect representation of the terrain for all applications. This pluralistic reality suggests that a goal of mapping is to integrate the unique advantages of data from various sources. Commercial data, used outside of the mapping community, may have rich thematic content that can enhance data of a higher spatial fidelity. As the commercial importance of geospatial data increases, all of tomorrow's data sets, both commercial and governmental, could become a rich collective source of information for the mapping community.

3.2 Automated Use of Future Information

New vector data can by linked to existing data – automatically integrating new vector information with the old. Minor discrepancies are resolved and only significant differences are highlighted so that human intervention is invoked only when problems are indeed major. This integration of new data through linking avoids conflation and its inherent pitfalls. (See Section 3.4.) Moreover, linking greatly reduces the need for human editing and the resulting destruction of information.

3.3 Dealing With an Uncertain Reality – We Do Not Know the Truth

We do not know the truth – at least when comparing disparate maps. When maps differ, massive human intervention is needed to explain the differences, and sometimes even human intervention does not suffice. Even with the aid of stereo imagery and multi spectral data it can be difficult to resolve differences between maps.

We have seen examples where low-resolution data contained roads that were not present in higher resolution data. Lower resolution data can be collected with a richer set of attribution than higher resolution data. High-resolution data can be poorly controlled, giving it uncertain spatial accuracy. The most current information can contain errors, making it less reliable than older data.

Such issues as scale, resolution, spatial accuracy, currency, and thematic accuracy are important aids to be considered when resolving differences between maps. However, it is risky to decide that one feature is correct while another is incorrect based upon automated criteria.

3.4 Not Destructive

Since we do not know the truth, we are reluctant to destroy one of two conflicting data sets, in favor of the other. Linking preserves the original data sets. Linking simply identifies corresponding terrain elements in two data sets without making a judgment that one element is to be preserved and the other deleted. Linking strengthens our confidence in the underlying data, when they agree; it provides a forum for comparison, when they are similar; and it notifies us when they disagree.

A separate tool, Best Map, produces an integrated view of the linked data at a point of time. This view is not intended to replace the original data.

3.5 Creation of Knowledge

Linking yields new knowledge – knowledge that things in different data sets are the same, which reinforces the validity of both. However, linking can result in additional knowledge. Linking data sets can result in a synthesis that is greater than the sum of the component parts.

For example, a set of high-resolution roads that are linked to a low-resolution road is endowed with an additional attribute: that it is a candidate for a major road. Attributes can be transferred from one road to the linked road in another. As we shall see in the discussion of Best Map, linking two road networks provides additional knowledge of how to integrate the networks – of how to pass from one network to the other.

3.6 Opportunity to Compare Sources – Strength in numbers

Linking is a comparison of data and that comparison can strengthen or weaken our confidence in the underlying data. Map information is pluralistic – we do not know the truth, but we can alter our certainty through linking.

4 Pluralism

Overlapping vector data provides independent views of the same underlying physical reality – views that are sometimes incongruous or sometimes reinforcing. Among these multiple views, we do not know which view, if any, is correct or even best. The nature of map data is pluralistic.

Linked feature elements are constrained by the linking algorithm to be similar both in space and in a core set of thematic attribute values. In this section we shall examine how linking can alter our perception of this pluralistic state of affairs, both inside and outside of the core areas of agreement. The following table suggests the kinds of relationships that can arise in linked information.

Table 1: Relationships in Information Pluralism

	Identity	**Similarity**	**Augmentation**	**Contradiction**
Spatial Pluralism	Identical spatial coordinates	Equivalent spatial representation (linked)	Additional spatial detail	Conflicting spatial information
Thematic Pluralism	Identical semantics (feature code & attributes)	Equivalent semantic representation (Thesaurus)	Additional semantic detail	Semantic disagreement

4.1 Thematic Pluralism

In this section we compare the thematic content of objects that are spatially similar or identical, as established through linking. Before data sets are linked the user defines core sets of attribution in each data set that must match before features are linked. Since the linking software does not consider attributes outside of this core, these non-core attributes may or may not agree for linked features. For example, “road” should link to “highway” but other attribution may agree, disagree, or provide additional and unique information. We shall examine the relationships that can exist between linked features and their attributes whose values were not constrained by linking.

4.1.1 Thematic Identity

This provides strong corroboration that the attribution is valid. One would expect spatial differences to be small with the discrepancies being due to scale, resolution, generalization, registration and the like. The technology to derive accurate spatial information is in place. In contrast, supplying attributes to objects in imagery is an imprecise craft, making identical thematic agreement a happy event.

4.1.2 Thematic Similarity

Thematic similarity increases confidence when, for example, a road, whose transportation use is “road” in the schema of Source 1, links to a road, whose transportation use is “highway” in the schema of Source 2.

Comparing similar attributes within a schema to similar attributes in different schema can increase or decrease uncertainty, depending upon the context. Translation between schemas can be so imprecise that a meaningful comparison of features is difficult. For example, a vegetation feature in Source1 can have the attribute “without trees” while the
same feature in Source 2 could be labeled “paddy”. These two descriptions are hardly an inspiring confirmation; possibly, the attributes are as close as the two specifications allow. This is a case in which one feature could inherit the attribution of the other, in the sense that the feature without trees is possibly a paddy and that the paddy is possibly without trees.

An example of decreased certainty arises when a forest with predominant tree height of 10-15 meters is linked to a forest with predominant tree height of 15-20 meters. In the absence of other evidence, such as temporality or accuracy, the certainty or each attribute decreases while we become more certain that the predominant height is between 10 and 20 meters.

4.1.3 Thematic Augmentation

If linked features have some identical or similar attribute values, then the unique attributes of one can be transferred as possible attributes of the other, making the fullest use of information from both sources. This is particularly useful when one source contains much richer thematic detail than the other.

Linking also provides the opportunity to augment the data with new knowledge – knowledge not explicitly present in either source. For example, if a 1:50000 road is linked to a 1:10000 road, then the higher resolution road is endowed with the additional attribute that is possibly a major road. Using this new information is discussed below in the section on Best Path.

4.1.4 Thematic Contradiction

The eyebrow of uncertainty is raised when linked features have attributes that are contradictory. Linking has identified a conflict that needs resolution – either by a human or by another linked source. In practice, thematic contradiction uncovered by linking has proved to be an important tool in automated error detection. If timely resolution is impossible at least the user is given a warning to use the data with care.

4.2 Spatial Pluralism

Linked objects are constrained by the linking algorithm to be spatially similar. Moreover, in the basic model, we expect that a base feature be linked to secondary feature elements. Nevertheless, comparing the spatial content of linked objects can provide new information.

4.2.1 Spatial identity

Given the difficulty that a single operator experiences in placing the cursor twice on the same location, it is unlikely that two feature elements have identical vertices. If two feature elements have identical vertices, the coincidence would be so striking to suggest that the feature elements have a common digital origin. If all the vertices of one feature element are present in a second linked feature element then there is a strong possibility that the first feature element is a generalization of the second.

Spatial identity, coupled with agreement of core attributes is a strong indication that the feature elements represent the same entity and have a common genesis.

4.2.2 Spatial similarity

This is the case where objects are spatially similar while agreeing on a core set of thematic attributes. This is the sense of agreement that the linking software is designed to uncover. To say that linked objects are spatially similar is simply to say that they are linked.

The linking of two objects provides a confirmation that the positioning and core attributes are correct, within the constraints of both the product accuracies and of their respective schemas. In addition, new information can arise from attribute transfer where attributes from one object are transferred to the other.

4.2.3 Spatial augmentation

Transferring spatial information from one source to another can violate the internal consistency of the recipient data set. Ideally, spatial transfer of data is best done manually using editing tools in a photogrammetric environment. However, such spatial transfer represents a temptation that linking is designed to diminish, not increase. We link so that we do not have to manually adjudicate differences between data sets.

While spatial augmentation has its perils, it can have benefits as well. For example, consider a low-resolution road network that is linked to a high-resolution road network. The linked high-resolution roads represent a view of the low-resolution roads at a higher resolution. The linked high-resolution roads can be generalized to obtain another view of the low-resolution network. It is quite possible that the generalized roads violate the internal consistency of the high-resolution data.

4.2.4 Spatial contradiction

A spatial contradiction arises when a base feature element can not be linked. This is a strong indication that something is wrong, either in our expectation, in the data, or in the linking algorithm. Human intervention is needed to resolve this contradiction – possibly with the aid of additional information or imagery.

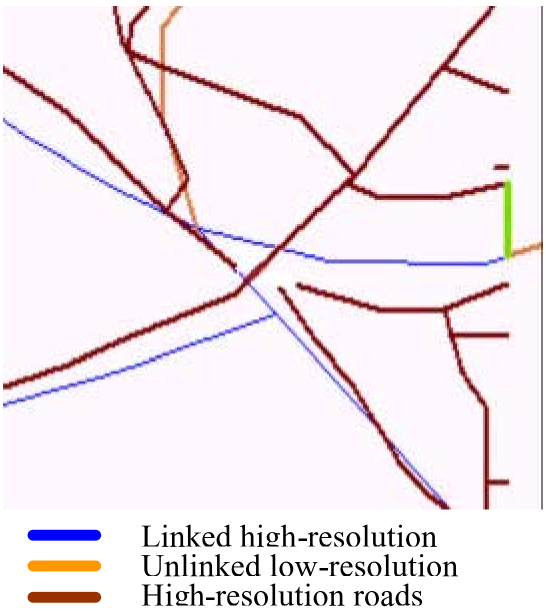


Figure 5

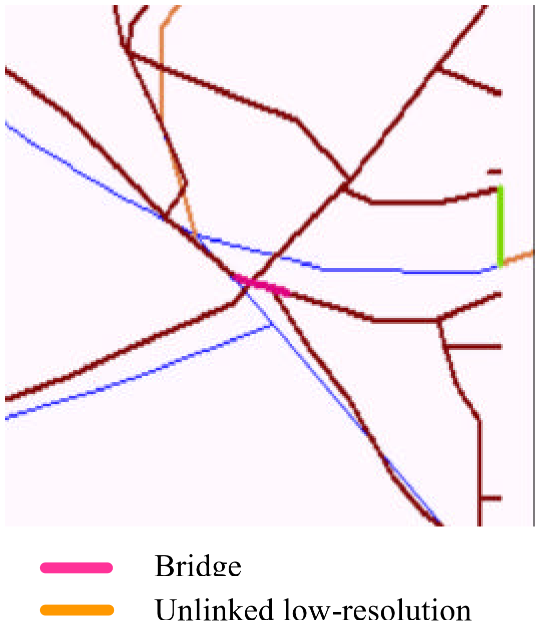


Figure 6

Figures 5 and 6 illustrate spatial contradictions that were uncovered by linking. In Figure 5 the blue high-resolution roads should link to low-resolution roads, but linking fails in the center area due to a gap in the high-resolution data. Figure 6 shows that the gap in the high-resolution data is a bridge. Roads in the low-resolution data are represented as both roads and bridges in the high-resolution data. Linking roads to roads produces a linking failure, while linking roads to roads plus bridges succeeds.

The unlinked low-resolution road at the top of Figures 5 and 6 is another example of a spatial contradiction. It seems that this road should have linked to a high-resolution road. Perhaps this failure is due to a topological problem in the high-resolution data, or to the features being too far apart, or to a flaw in the linking software.

The high-resolution roads exhibit curious behavior near the center of Figure 6, where the unlinked low-resolution road joins the linked low-resolution road (blue). Which resolution, high or low, better represents reality? Without further information or source data, we do not know.

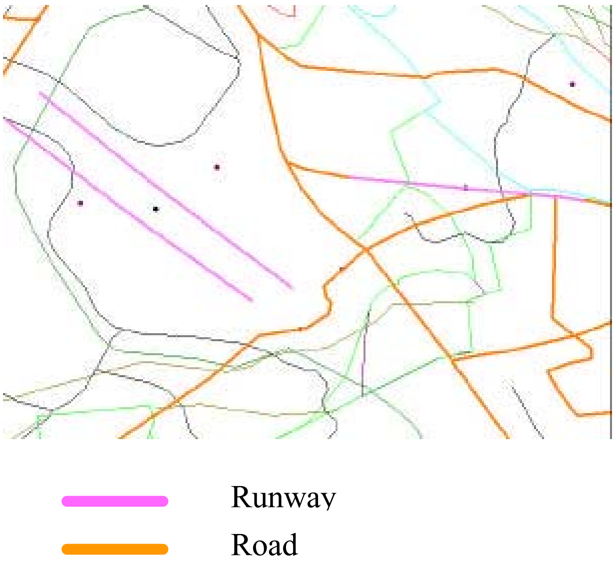


Figure 7

Figure 7 illustrates a similar problem. The road network contains a gap because a road has been mislabeled as a runway. Here linking would fail since one does not expect that roads in one source will be represented as runways in a second source (not shown).

5 Best Map

Linking establishes a correspondence between feature elements across two data sets. The Best Map is an application that enables one to view two linked data sets, assembling them in an intelligent manner into a unified representation, capable of supporting digital spatial analysis. As we shall see, the Best Map application neither destroys the original data nor the links. The output of the Best Map software can be either stored or deleted, as the user wishes, without affecting the integrity of the source data.

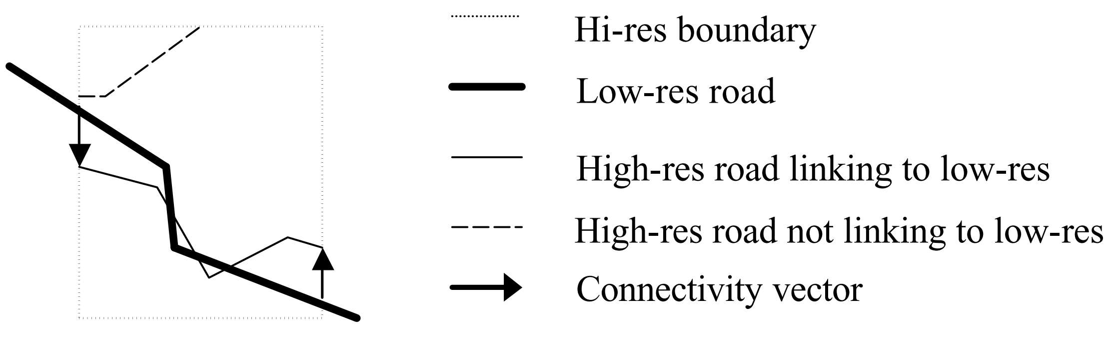
5.1 Current implementation of linear Best Map

Since the larger issues are still under investigation, this discussion of Best Map centers on software developed independently by Swiftsure and Intergraph, under the direction of TEC. These applications are designed for the case of a low-resolution road network linking to a high-resolution road network. We are still investigating the representation of area, point, or other linear data sets. The rules of similar-scale Best Map are still under investigation, as well.

5.1.1 Spatial rules

In constructing the best representation of the data this software uses spatial and thematic rules. The spatial rules are summarized:
1 in high-resolution areas, the high-resolution data take precedence
2 in outside high-resolution areas, the low-resolution data are the best
3 place connectivity vectors at the boundary
4 retain unlinked low-resolution features that penetrate the high-resolution area.

Include all high-resolution roads in the Best Map. Outside the area of high-resolution, the low-resolution data are best, by default. Along the boundary between these data sets, place connectivity vectors to join a low-resolution road to the high-resolution road to which it links. These connectivity vectors join base and secondary roads that are linked in the interior of the high-resolution area – not simply joining roads that are closest at the secondary boundary. This insures connectivity of major roads. Linking is based upon the behavior of the base and secondary roads within the secondary area, rather than upon the nearest neighbor at the boundary. See Figure 8.



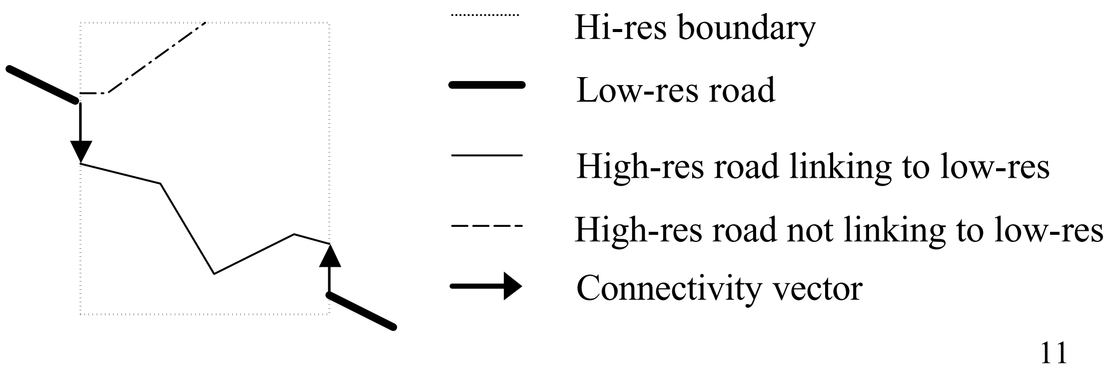


Figure 8 Construction of Best Map

5.1.2 Thematic rules – Common Schema Formation

Quite possibly, no one schema will encompass the attributes of two linked data sets. Mapping these schemas into an existing schema usually results in a loss of information. Creating a new schema results in non-standard information. The schema of the Best Map is, notionally, the union of the schemas of the source data sets, called the common schema. This non-standard schema is unique to the Best Map, but it has the advantage that no information is lost. This is based on the principles, described above, of thematic similarity and augmentation.

In forming the common schema, a base feature class serves as a core feature class in the common schema. The common schema feature class has all the attributes of the core feature class plus the attributes of all the secondary features classes that are permitted to link to the core feature class. Common attributes, if any, among these core and secondary features classes are used only once in the common schema.

In addition, there are new attributes in the common schema feature class. There is a new attribute indicating that the Best Map feature coincides spatially with a secondary feature element that is linked to a base feature element. Another new attribute indicates that a low-resolution road is unlinked. The connectivity vectors form a feature class in the common schema.

6 Best Path

Best Path is a practical application of linking and Best Map. A person might want to travel from a rural area, mapped at a low resolution, to an urban area, mapped at a high resolution. These maps can be linked and a unified Best Map created, enabling a Best Path to be calculated.

The first step is to obtain one continuous, unifying map that combines differing scales, differing attributes and differing spatial representations. This was discussed in the section on Best Map. The second step is to traverse the Best Map, making use of its unique qualities. This is the Best Path application whose first version was developed by Dr. Dianne Richardson of the Canada Centre for Remote Sensing, under a contract with Swiftsure Spatial Systems Inc. Helonics Inc. and Intergraph developed later versions of this software.

As with many applications that traverse networks, after the user selects starting and ending points, the software computes a Best Path between them based upon such things as distance, geometry, and the attributes of the roads. This software is able to give preference to the high-resolution roads that link to low-resolution roads by using the new attribute of "linked" that is added by the Best Map application. Consequently, the software can be biased toward main roads in high-resolution areas as avenues of entry or exit.

Best Map is one example of the many types of spatial analysis that can be performed on a multi-source Best Map. Since connectivity and spatial relationships have been preserved during the formulation of Best Map, any processing tool of spatial analysis can operate on both multi-source data and single source data.

7 Summary

Sources of spatial information – whether sensors, maps, or other – vary widely. The spatial information itself differs in scale, accuracy, and representation. There are varied uses and applications of spatial information. All of these inevitably call for multiple datasets, rather than a single monolithic database.

We believe that the solution to maintaining a national core geospatial database is to exploit the similarity, redundancy, and uniqueness in multiple datasets, and, in the process, de-conflicting them. Research in feature linking involves developing a set of tools that enable these capabilities. Research in Best Map involves developing a set of tools that can quickly extract the best data from multiple datasets and assemble this into a coherent, topological, augmented picture for a given application and for a given instant in time. To date, our results are exploratory and tentative. More research is needed.

Strategies for integrating height information and 2D GIS data*

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Abstract

An overview of different approaches to establish 2.5D data models for geographic information systems (GIS) and nation-wide spatial data bases will be given. The restriction to 2.5D models is made to provide compatibility with existing 2D GIS data sets and the 2.5D *digital terrain models (DTM)* available from the national mapping agencies. In particular, an approach based on *polynomial surface objects* being a generalization of the established *height step objects* as well as procedures using *triangulated irregular networks (TIN)* are explained in detail. The data model derived from the latter is also known under the technical term of *simplicial complexes* or *2.5D-GIS-TIN* for the special case of 2.5D approaches.

A comparison of the two methods yields that TIN based approaches provide several advantages in contradistinction to polynomial surface objects. Integrated 2.5D-GIS-TIN require less computing effort during the step of integration. Data reduction may be conducted with available methods in which the resulting accuracy of the integrated model is controlled efficiently. 2.5D-GIS-TIN fit into existing approaches of geodata capturing, higher dimensional data modelling (3D and even 4D) and management as well as analysis and visualization. Polynomial surface objects do not provide all of these favourable properties in the same manner.

1 Introduction

1.1 Terminology

One main focus of current *geographic information systems (GIS)* research is the extension of traditional 2D data structures to incorporate height information (GOODCHILD, 1997), thus, to integrate *digital terrain models (DTM)* or products derived from them into GIS. These sloppy words already lead to the first

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clarification that is required. Several authors discussed the integration of DTM into GIS (e. g. WEIBEL, 1993; PFANNENSTEIN & REINHARDT, 1993; FRITSCH & PFANNENSTEIN, 1992; REINHARDT, 1991; MAYER, 1991; EBNER ET AL., 1990) and really meant the incorporation of DTM functionality or DTM products into an existing 2D GI software system while probably providing special data structures for them. It is not the intention of the present author to provide yet another paper on this way of integration which is on the one hand commonly available in certain (not only commercial) GIS software packages and on the other hand even considered as the 2D+1D approach in GIS data modeling (e. g. BILL & FRITSCH, 1994). The focus of this research is on *integrated 2.5D GIS data structures* which leads to landscape objects integrated or enriched in some way with height information.

The restriction of this research to 2.5D models has several reasons. Firstly, real 3D models are already discussed by numerous authors who work on 3D city models. Details of these approaches may hence be found there. Secondly, the existing national core geospatial data bases are mainly 2.5D, i. e. they provide a unique height value for a position in the horizontal plane in contradistinction to real 3D applications where a multitude of height values may exists at each position. It is one major intention of this article to discuss procedures which use as input the existing data sets. This will allow for upward compatibility of the existing data sets with new methods and thus will save investments that have been made.

Approaches of integrated modeling may be distinguished into different categories. A well known classification is given by FRITSCH (1996, 1990). He distinguishes approaches of integration into three cases:

1. height attributing: simply providing a z coordinate to each node whereas it is commonly accepted that this kind of integration does not meet the requirements of integrated modeling;

2. terrain information systems: this approach is basically the mentioned integration of DTM functionality and maybe special data structures into a GI software system and thus not integrated modeling;

3. ”total integration” (2.5D, 3D): these are approaches which will lead to models fulfilling the requirements of integrated modeling, and therefore the main focus of this paper is on 2.5D modeling (see above).

1.2 Overview of existing 2.5D approaches

A closer look to literature shows that there have been conceptionel approaches for the integration of height information and 2D GIS data at least since the late 1970s. Indeed, one approach may be traced back to the roots of a well known concept in digital terrain modeling, the *triangulated irregular network* (*TIN*, PEUCKER ET AL., 1976). Although these authors state that they would feel that a combination of a TIN and a polygon system would incorporate the advantages of both concepts, by knowledge of the present author it does not seem that there have been substantial developments in that direction, at least at that time. Later in the 1990s there were some authors who conducted research to combine 2D GIS data structure with a TIN. The approach of combining DTM-TIN with 2D GIS data is treated in Section 2.

Besides these investigations based on TINs, the latter as well as other approaches have been discussed conceptionally by BUZIEK (1993). One approach is based on the so-called *hybrid DTM* which are basically gridded DTM enriched with skeleton lines (breaklines, ridgelines etc.) to depict the relief in a morphological sound way. Grid cells affected by skeleton lines are triangulated locally to incoporate the lines into the DTM (e. g. KRAUS, 2000; BUZIEK ET AL., 1992). In the integrated model based on hybrid DTM, cells affected by 2D GIS geometry are triangulated locally while computing intersection points of grid lines with the 2D geometry. Grid cells and triangles are linked in some way to landscape objects and hence, height information may be analyzed object-based. Restricting this approach to solely triangles leads to the integrated model based on TIN and due to this circumstance, in this paper only the latter approach is treated in more detail (Section 2).

The last case mentioned in BUZIEK (1993) is the integration based on *polynomial surface objects*. BUZIEK (1993) discussed it conceptionally while providing hints how to built landscape objects to contain polynomial height information within their boundaries. This approach (as well as the one based on TIN) was investigated in detail by the present author (LENK, 2001). A summary of the most important aspects of polynomial surface objects will be given in Section 3.

2 Integration of DTM-TIN and 2D GIS data

The basic idea of integrating DTM-TIN and 2D GIS data has already been mentioned by PEUCKER ET AL. (1976). Since then various authors have worked on this topic. As an important property of an integration process, KLÖTZER (1997) stipulated that the shape of the DTM-TIN should not be altered while adding nodes and edges of the 2D GIS data to it.

It is presumed that the reader is familiar with DELAUNAY-triangulations and digital terrain modeling based on TINs. Introductory reading on this topic may be found in standard text books on GIS (e. g. LONGLEY ET AL., 1999) or computational geometry (e. g. O'ROURKE, 1998; DE BERG ET AL., 1997). A survey on triangulations is provided by BERN & EPPSTEIN (1995). One particular algorithm necessary for the following explanations is the incremental insertion of vertices into an existing TIN (e. g. DE BERG ET AL., 1997; DEVILLERS, 1997; EGENHOFER ET AL., 1989; GUIBAS & STOLFI, 1985; DEVIJVER & DEKESEL, 1982). Locations of insertion of spatially independent points of different data sets may be in existing triangles as well as on their respective edges (a point may thus also fall onto an existing point). The major difference in runtime behaviour of incremental algorithms is given by the various spatial access methods to find the location of insertion in the TIN as the actual area influenced by the insertion procedure remains the same for all. It forms a star-shaped polygon around the location of the point (e. g. DEVIJVER & DEKESEL, 1982). Spatial access methods in TINs are treated in particular by DEVILLERS ET AL. (2001) and DEVILLERS (1997) as well as the references in there.

Firstly, technical terms related to simplicial complexes will be introduced and the conceptual model of the approach will be explained in more detail. Afterwards, the existing computational approaches as well as new developments by LENK (2001) are introduced and discussed with respect to their efficiency and resulting data volume.

2.1 Simplicial Complexes

In each dimension, there is a minimal object, called *simplex*. Figure 1 shows the *0-simplex*, which is a point/node; the *1-simplex*, which is an edge; as well as the *2-simplex*, which is a triangle. Each n-

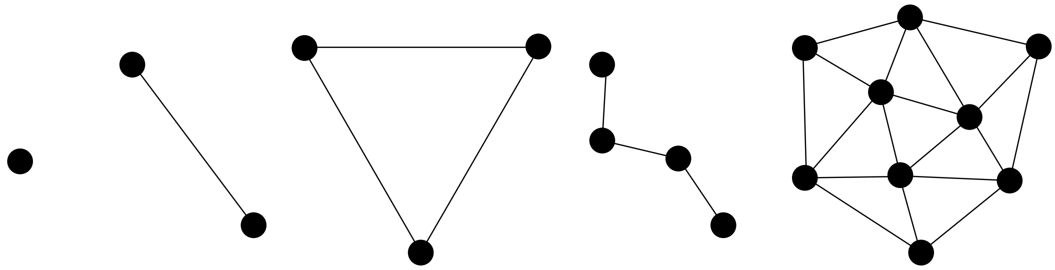

Figure 1: Examples for simplexes und simplicial complexes.

simplex consists of $(n+1)$ geometrically independent simplexes of dimension $(n-1)$. A *facet* or *face* of a simplex is every simplex which is part of the first (thus higher dimensional) simplex. A *0-face* of a *2-simplex* is each of its 0-simplexes, i. e. point of its corners, and an edge of a triangle is a *1-face*. A *simplicial complex* is a finite set of simplexes satisfying the following properties (cf. WORBOYS, 1995):

1. A face of a simplex in a simplicial complex is also in the simplicial complex.

2. The intersection of two simplexes in a simplicial complex is either empty or also part of the simplicial complex.

An example for 2-simplicial complexes are TIN. Simplicial complexes may be easily extended to higher dimensions, i. e. 3D modeling etc. Further introductory readings on simplicial complexes may be found in text books on topology (e. g. JÄNICH, 1995). WORBOYS (1995) discusses general GIS aspects of simplicial complexes, BREUNIG (2000, 1996) as well as PILOUK (1996) worked on 3-simplicial complexes, i. e. modeling 3D objects in space whereas EGENHOFER ET AL. (1989) discuss the use of 2-simplicial complexes for 2D GIS.

2.2 Conceptual data model

The conceptual data model of an integrated 2.5D-GIS-TIN model may be illustrated by Figure 2. A surface feature, i. e. an area object, is decomposed into a set of triangles and is hence represented by a 2-simplicial complex whereas a linear feature is represented by a 1-simplicial complex, i. e. it consists of a set of arcs. Similarly, a point feature will be represented by a node.

2.3 Existing procedures to create the integrated model

2.3.1 The method of PILOUK (1996)

PILOUK (1996; see also PILOUK & TEMPFLI, 1994a; 1994b; 1993) bases his work on the *single-value vector map (SVVM)* and the *formal data structure (FDS)* of MOLENAAR (1989). Hints are given to extend the approach to *multi-value vector maps (MVVM)* (PILOUK & KUFONIYI, 1994; cf. KUFONIYI, 1995). The approach is also referenced by KRAUS (2000; 1995) and FRITSCH (1996).

PILOUK (1996) introduces the concept to model space by *simplicial networks*. 3D bodies are built by 3-simplexes (tetrahedrons) and area objects or surfaces in space consist of 2-simplexes (see Sec. 2.1).

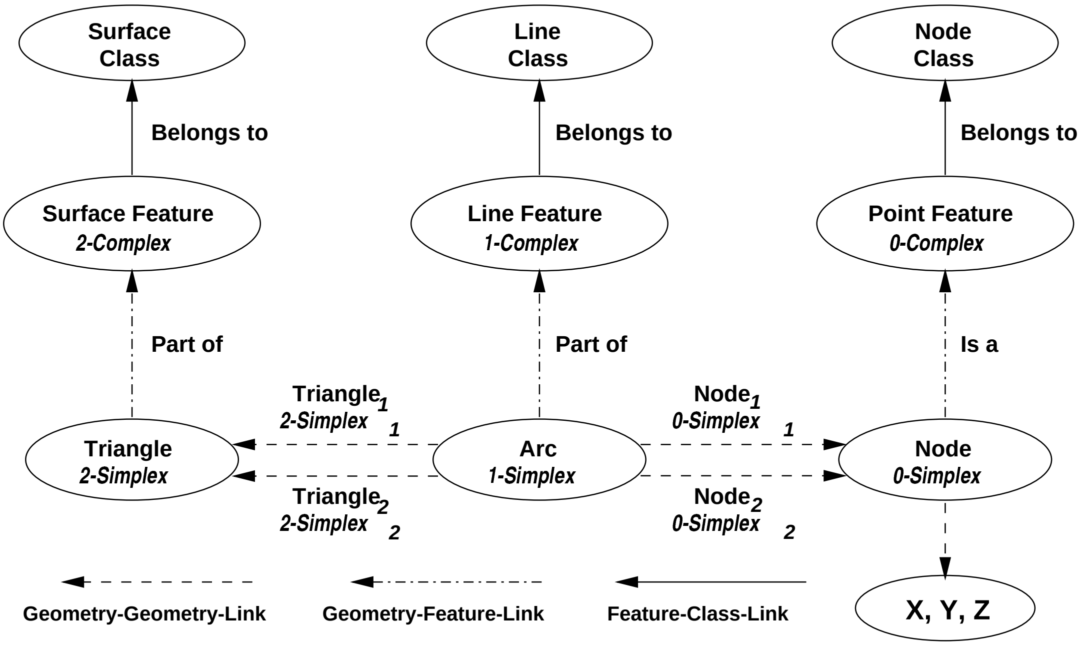

Figure 2: 2.5D-GIS-TIN data model (adapted from PILOUK, 1996).

In the following only the part dealing with 2.5D models, i. e. 2-simplixes, will be considered. The procedure of PILOUK (1996) to establish an integrated 2.5D model is as follows (taken from PILOUK, 1996):

1. Structure the 2D data of determinate spatial objects according to SVVM or MVVM; these are called 2D FDS data.

2. Obtain terrain relief data in the form of a grid or TIN.

3. Introduce the height component for each node of the 2D FDS data that have only the planimetric component by means of interpolation, using the DTM data set.

4. Convert the DTM to TIN if it is in the form of a grid. Redundant data with respect to relief representation may be eliminated to reduce the volume of data.

5. Combine the nodes that are vertices of TIN with the nodes of the 2D FDS data.

6. Embed all features into TIN by performing constrained triangulation, using terrain features as constraints. The result is recorded as the 2.5D unified data structure ... (which is basically a 2.5D model of the landscape, comment by the present author).

2.3.2 The approach of KLÖTZER (1997) and EGENHOFER ET AL. (1989)

The approaches of KLÖTZER (1997, see also the research of GRÖGER, 2000, and PLÜMER & GRÖGER, 1997, 1996) and EGENHOFER ET AL. (1989) are quite similar, hence they are treated together in this subsection. It should be emphasized that the intention of EGENHOFER ET AL. (1989) was not the derivation of an integrated data model to combine 2D GIS and DTM-TIN, however extending their approach to 2.5D and interpolating heights linearly for points to be inserted into an existing DTM-TIN will fulfill the requirements of shape invariance during the integration process.

One major contribution of KLÖTZER[1] (1997) to the topic of integrating 2D GIS data and TIN has already been stated above: the shape of the surface modeled by the TIN should not change during the integration process. Generally speaking, KLÖTZER (1997) firstly inserts all nodes of the 2D GIS data into the TIN and then splits existing edges of the 2D GIS data at locations where the geometry is intersected by the so far existing TIN. In detail, KLÖTZER (1997) describes his approach as follows:

1. Insert all points and nodes of the 2D GIS data into the DTM-TIN by incremental DELAUNAY-triangulation. The DELAUNAY-criterion is re-established after inserting the points and vertices(!).

2. Add the edges of 2D data to the TIN by splitting them at the intersection points with the edges of the so far existing TIN and add the intersection points without swapping TIN edges. Hence, in this part of the procedure the shape of the surface will not be altered (further).

Unfortunately, the first step will lead to minor alterations of the shape of the original DTM-TIN at the end points of the 2D GIS data edges. However, if swapping of edges is suppressed at this stage of the algorithm, the procedure is a valid method that will fulfil the requirement of shape invariance. In the following discussion this procedure will hence be referenced as the *revised* approach of KLÖTZER (1997).

The approach of EGENHOFER ET AL. (1989) differs from KLÖTZER (1997) only in the sequence of insertion of the 2D data points. Whereas the revised approach of KLÖTZER (1997) adds all points at the beginning of his procedure, EGENHOFER ET AL. (1989) will process data edge based. To embed a 2D data edge into a TIN, firstly its end points are inserted and afterwards intersection points are computed and added the to 2-simplicial complex. A complete polygon is inserted into the TIN by adding its edges sequentially.

2.3.3 The procedure by ABDELGUERFI ET AL. (1997)

Another procedure of integrating 2D GIS data and TIN is described by ABDELGUERFI ET AL. (1997). Their work is conducted on the background that the so far existing *vector-product-format (VPF)* does not meet the requirements of the modeling and simulation community of the US forces anymore. They therefore introduce the so-called *extended-vector-format (EVPF)*. For each area object a local TIN is computed and the heights to be determined are interpolated linearly in the existing surface. The actual procedure is as follows: “The process regions with a polygon with absolute x, y boundary coordinates. After determining which triangles contain these points, the polygon is overlaid by dividing it into one or more child polygons based on the elevation TIN edges. Once the child polygons are defined they are triangulated...“ (ABDELGUERFI ET AL., 1997). To triangulate the child polygons a procedure described in O’ROURKE (1998) is adapted.

[1]The approach of KLÖTZER (1997) was presented by KLÖTZER, F. & PLÜMER, L., as *Homogene Verknüpfung des digitalen Geländemodells mit ATKIS-DLM-Daten* at the 34th meeting of the working group ”Automation in der Kartographie (AGA)”, which took place on the 7./8. October 1997 at the Technical University of Dresden, Germany. Unfortunately no contribution of the authors to the conference proceedings is available. Reference is hence given to the diploma thesis of KLÖTZER which was kindly provided by Gerhard Gröger, currently with the Institute for Cartography and Geoinformation, University of Bonn, Germany.

2.3.4 Discussion of the existing approaches

A closer look to the existing procedures to compute an integrated 2D-GIS-DTM-TIN reveals that generally they are capable of preserving the shape of the existing DTM-TIN, the only exception being the approach by PILOUK (1996). Inserting the line segments of 2D geometry as constraints into a DTM-TIN will change the shape of its surface considerably as one might easily see by the following example: imagine a road crossing a ridge line. By applying the approach of PILOUK (1996), the ridge line will not exist in an integrated model anymore as it has to be replaced by some other triangles to establish the local triangles to include the line segment of the road. Other examples may be easily derived. As a consequence, the algorithmic approach of PILOUK (1996) to integrate 2D GIS geometry into a DTM-TIN has to be rejected if the shape of the DTM-TIN has to be preserved. The revised procedure of KLÖTZER (1997), the approach of EGENHOFER ET AL. (1989) as well as the method by ABDELGUERFI ET AL. (1997) do not suffer from problems of changing the shape of the surface of the DTM-TIN, however they ignore certain special geometric constellations that might occur and may as well be improved algorithmically. These aspects will be treated in the following.

Special geometric constellations: A special situation that might occur when merging 2D GIS data and DTM-TIN is that there are points at geometrically identical positions in the plane in both data sets. Points of the 2D GIS data may also fall onto existing edges in the DTM-TIN and as a consequence, there might be edges in both data sets that are partially collinear. The insertion of points onto existing edges is a standard operation in computational geometry (e. g. DE BERG ET AL., 1997) that is taken into account explicitly by EGENHOFER ET AL. (1989), and even identical points are considered by the authors, however KLÖTZER (1997) ignors the latter situation. Seemingly he claims that the input data sets are geometrically independent which is the common case in computational geometry when triangulating point sets. Due to the independent capture of 2D GIS and DTM data the spatial independence of both data sets generally cannot be assumed. The partial collinearity of edges is neglected in both references. With respect to these special geometric cases the procedure of ABDELGUERFI ET AL. (1997) relies heavily on the implementation of the map overlay used to overlay the triangles containing the polygon points with the polygon itsself. If the overlay algorithm does not consider these constellations faulty results may be achieved.

Discussion of the algorithmic approaches: Analyzing the algorithmic background of the procedures shows that they all neglect existing topological relations in both input data sets. For example, KLÖTZER (1997) firstly inserts *all* points of the 2D data set into the TIN. Therefore, he seemingly uses a spatial access method to find the location of insertion for *each* point without considering the inherent line topology in the 2D data set. EGENHOFER ET AL. (1989) firstly insert the start point of an edge and secondly its end point before computing intersection points with the so far existing edges of the TIN. The approach of ABDELGUERFI ET AL. (1997) is algorithmically completely different as again their approach relies on the map overlay process. To conduct a map overlay in an efficient way, some sorting of input data has to be performed before computing the actual overlay itsself. A possible sorting order for line segments is along one coordinate to compute the overlay afterwards with an output sensitive plane sweep algorithm (e. g. DE BERG ET AL., 1997). Hence, sorting all existing edges will commonly not use the existing topology of the input data sets.

Locating the respective triangle (or edge) for insertion of the first point (or a respective point where the 2D data point may fall on) will provide a location in the spatial proximity of the second point of a line. Hence, applying the strategy of *walking in a triangulation* that utilizes the topology of a TIN to navigate in the latter (e. g. DEVILLERS ET AL., 2001) should speed up the procedure substantially. Similarly, one may find all successing locations of insertion of points for a linear geometry. The approach of starting a topogogical walk in a triangulation with a predetermined triangle is also called the *jump-and-walk* strategy (e. g. VAN KREVELD, 1997). Hence, implementing an algorithm that traverses all geometries of a 2D GIS data set and steps along the points of the geometries while walking simultaneously in the TIN exploits the topologies of both input data sets advantageously. Additionally, no special presorting of geometric primitives has to be conducted.

2.4 A new way to compute the integrated model

From the above considerations a new method to integrate existing piecewise linear geometries into a TIN has been developed (cf. LENK, 2001). It fully exploits existing topologies of input data and works similar to the *jump-and-walk* strategy. The algorithm ”sews like a sewing-machine” the 2D data into the TIN while traversing the latter along the 2D data.

2.4.1 Algorithmic background

The basic principle of the algorithm is illustrated by Figure 3. The area of a triangle and its adjacent neighbours as well as its incident edges and points may be distinguished into distinct geometric locations. The basic primitive for this operation is the determinant computed by an oriented edge of the triangle and the point to be tested. The determinant will provide by its sign information whether the point lies to the left or right of the respective edge and in addition, it will deliver the area (multiplied by 2, hence Area2; cf. O’ROURKE, 1998) of the triangle given by the edge and the point. Therefore, if Area2 equals zero, the test point must be collinear with the edge, however it is yet not known whether it lies between the end points of the base edge or somewhere else one the line formed by the end points of the edge.

Combining all the three determinants computed from the test point and the edges of a triangle provides information whether the point lies on an edge or a point of the triangle. If the location of the point is outside the triangle, the combination will deliver an adjacent triangle which will serve as input for the next determinant test (see Fig. 3). Using this strategy, one may navigate in a TIN to a destination given by its coordinates in the plane.

Modifiying this approach will provide a procedure that integrates 2D data into a TIN while navigating along the 2D data in the TIN. Figure 3 may be re-drawn in the way given in Figure 4. By knowing an incident triangle the horizon around a point may be divided into distinct sectors represented by its incident edges and other geometric locations. The basic primitive for this operation again is the signed determinant. The respective determinants computed by the edges of the incident triangles and the end point of the current line segment to be integrated into the TIN will provide information whether next point is located:

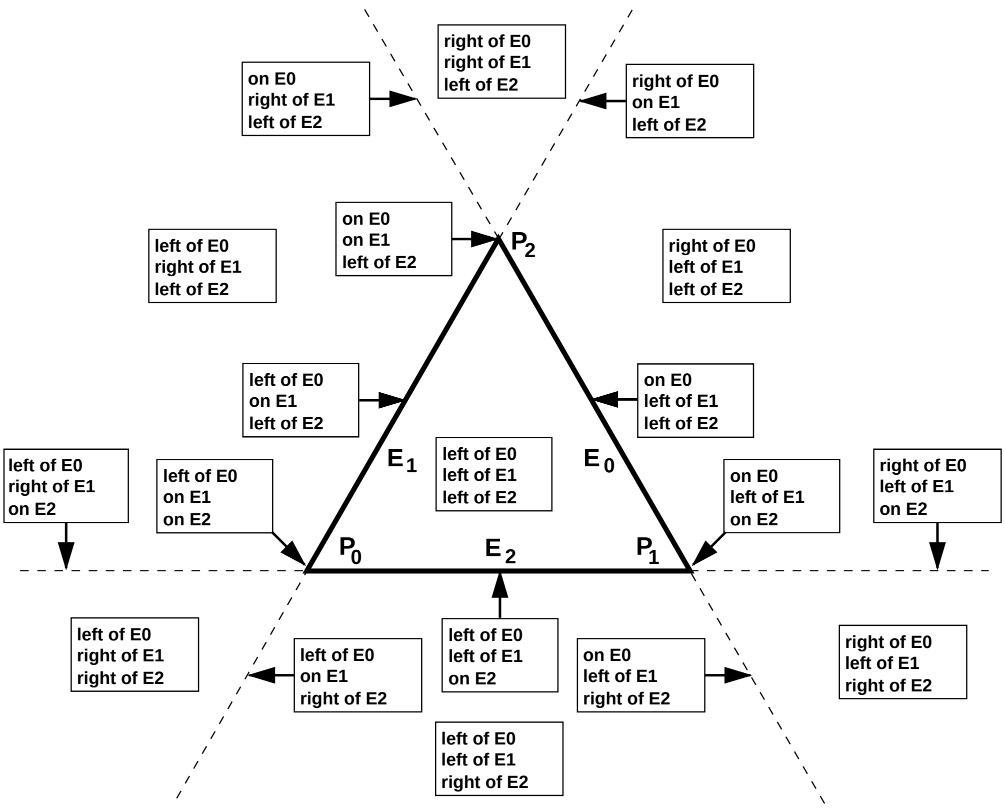

Figure 3: Dividing the horizontal plane around a triangle into decision areas.

1. in the triangle itsself (case 1), so the point is simply added to the TIN and the procedure continues with the next point of the geometry;

2. on an incident edge of the last point (case 2a/b), hence the current line segment is partially collinear with existing edges;

3. on adjacent points of the points (case 3a/b), i. e. the next point of the current segment is identical to an existing point in the TIN;

4. on the prolongation of the incident edges of the point (case 4a/b), i. e. the current line segment will be split by the adjacent point as the incident edge is partially collinear to the line segment;

5. in the sector of an adjacent triangle (case 5a/b), the search will continue with a triangle whose index is determined by use of the topology of the TIN;

6. on the edge opposite the point (case 6), i. e. the point lies on the edge;

7. beyond the edge opposite the point (case 7), consequently, the current line segment will be split by the opposite edge and an intersection point must be computed;

8. to the back of the current point (case 8a/b/c), the search continues with an adjacent triangle;

9. on the current point, i. e. they are geometrically identical (case 9).

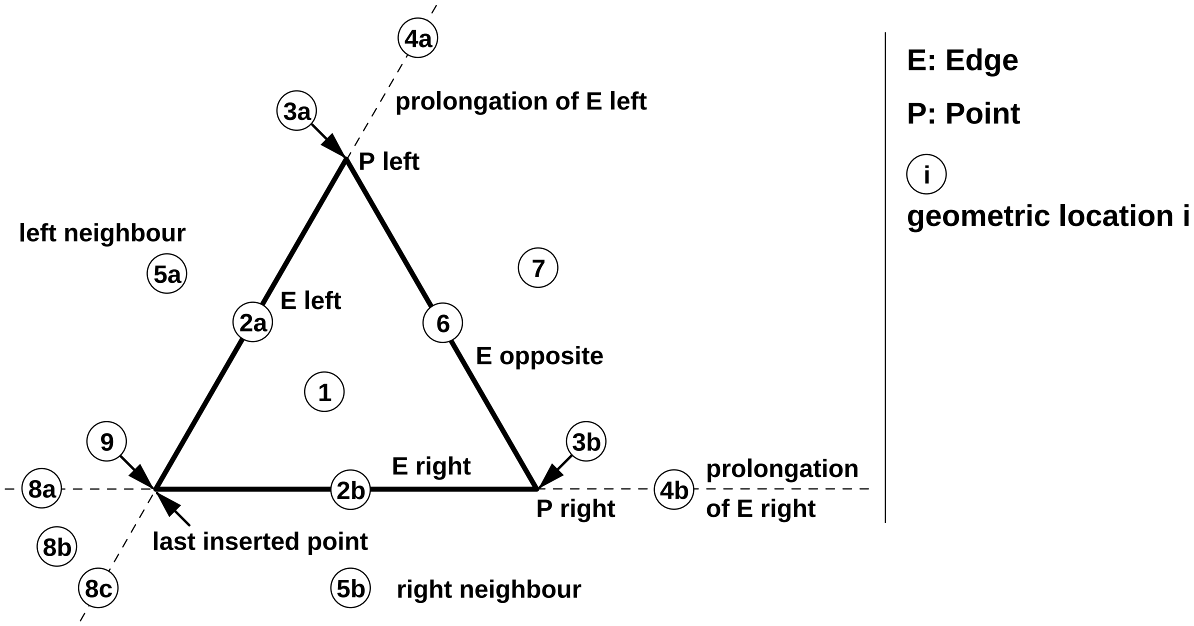

Figure 4: Radial-topological search around a point.

On the basis of these events all geometries may be integrated into the mesh by traversing the container object holding the respective 2D geometries. As the basic operation in this algorithm is the radial sweep combined with a topological walk along the 2D geometry and in the TIN, the algorithm is termed the *radial-topological algorithm*. The advantage of this procedure is that it considers the partial collinearity of edges of both input data sets explicitly as respective edges are split by points already existing.

2.4.2 Geometric analysis of the approach

The explanations in Section 2.4.1 dealt solely with an individual triangle incident to the current point being processed. It is now the aim to investigate how the algorithm works with a number of successive points of a 2D geometry in a triangle of the DTM-TIN. A possible situation is given in Figure 5. A geometry entering the triangle from North-East has some breakpoints given by the points 2 and 4 inside the triangle. In the integrated model the 2D geometry is represented by points with the numbers 1, 2, 3, 4, 5 and 6 where the numbering of the points indicates the sequence of their respective insertion (the sequence may be evaluated by use of Figure 4). Point 1 and point 6 are intersection points with existing edges of the original DTM-TIN and are hence necessary for the tesselation of the horizontal plane into area objects in the integrated model. Only points 3 and 5 do not contribute additional information either to the tesselation of the plane (as they lie collinearly on edges of the 2D geometry) nor do they add information to the description of the surface shape of the original DTM-TIN (as their heights were interpolated linearly in the original DTM-TIN-triangle). Therefore, points 3 and 5 are *redundant data* in the integrated model.

As a result from this investigation, the radial-topological algorithm leads to redundant data if intersection points are computed between the geometry to be added into the DTM-TIN and edges that have been added to the integrated TIN beforehand. With respect to the set up of national core geospatial data

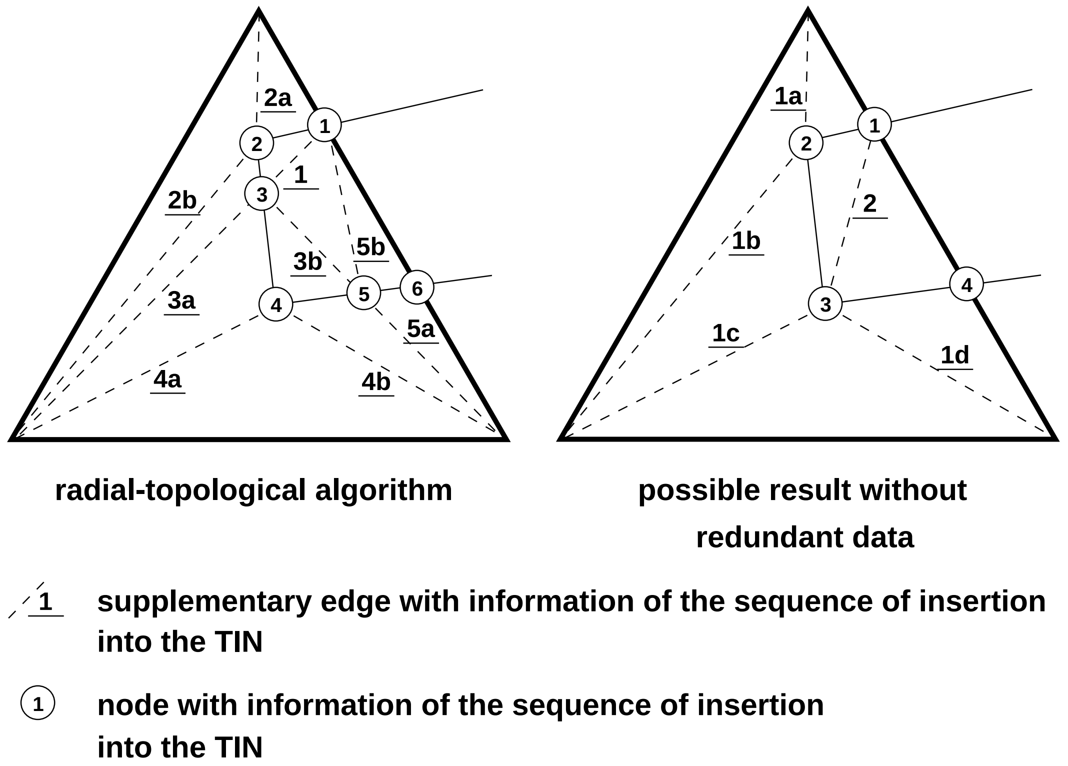

Figure 5: Geometric analysis of the results of the radial-topological algorithm.

bases and their large data volume the generation of redundant data should be avoided. The high amount of data produced by an integration process has also been indicated e. g. by EGENHOFER ET AL. (1989).

2.5 The data model with minimal number of nodes

From the investigations above one may conclude that intersection points added during the integration are only valid if and only if they are intersection points between edges of the 2D GIS data set and edges of the DTM-TIN. This relation has been considered in the integrated data model which is now presented (Fig. 6). The DTM-TIN and the 2D GIS data must treated as independent input data sets in the resulting integrated model, the 2.5D-GIS-TIN. A point of the 2D GIS data may fall onto an existing edges of the DTM-TIN or on an already existing point of the TIN. Hence, edges of the 2D data may be partially collinear with existing edges of the DTM-TIN. A map (which may not be compared to a traditional analogue map; cf. PLÜMER & GRÖGER, 1997; 1996) is decomposed into one or more faces, and each face consists of one or more triangles.

Examples of integrated models in LENK (2001) showed that the redundant data volume computed by the radial-topological algorithm may be more than 50 %. As a consequence, it is highly recommended either to avoid or to delete redundant data.

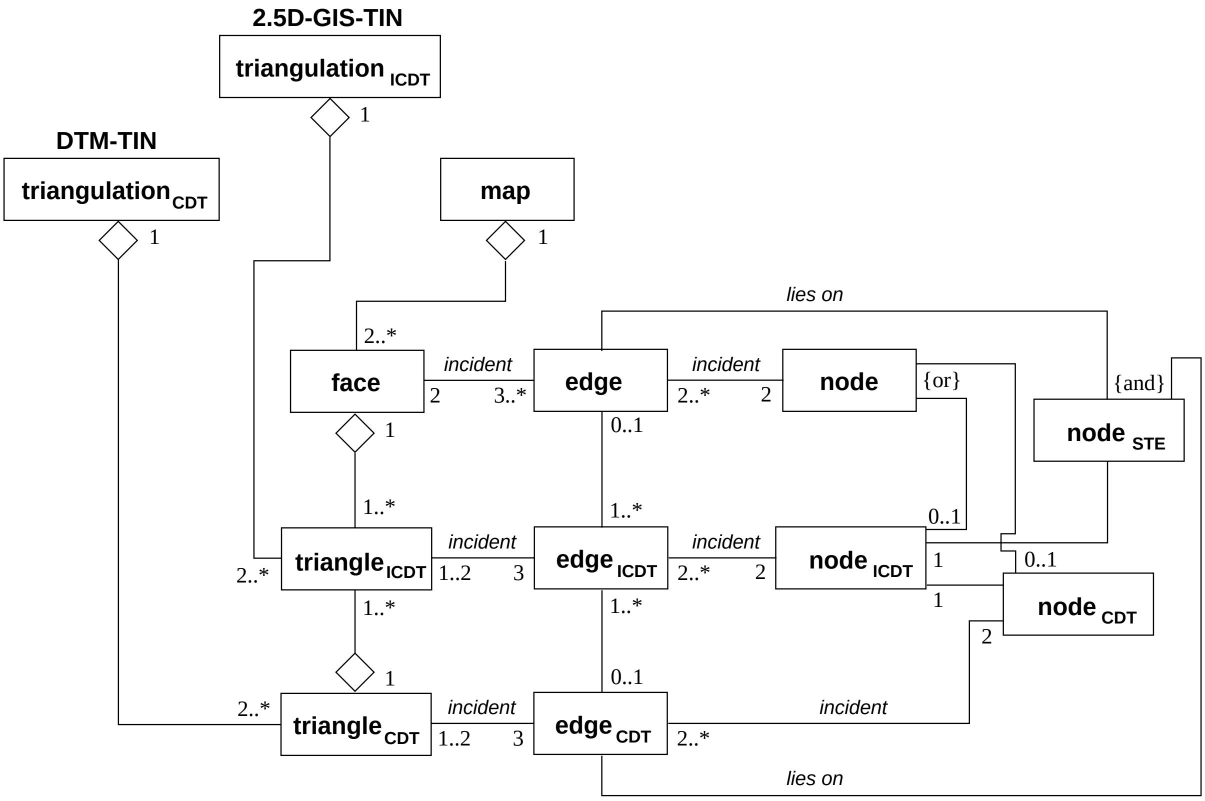

Figure 6: Integrated data model with minimal number of nodes as unified modeling language diagram.

2.6 Algorithms to compute the integrated model with minimal number of nodes

A possible algorithm to compute the integrated data model with minimal number of nodes is given by the procedure of ABDELFUERFI ET AL. (1997). One must keep in mind that this approach relies heavily on the implementation of the map overlay and additionally, the approach suffers from algorithmic disadvantages as a presorting of data has to be conducted prior to an efficient computation of the map overlay.

The algorithmic advantages of the radial-topological algorithm have been explained above. It is obviously to investigate whether it is possible to modify the algorithm in a way that the creation of redundant data is avoided. If an algorithm to compute the data model with minimal number of nodes has to be developed, it is necessary to decide whether the algorithm should compute the model directly or if alterations should be applied to an intermediate integrated model.

In order to avoid redundant data in the integrated model directly using the radial-topological algorithm, it is necessary to insert the first points of the geometry temporarily until it leaves the starting DTM-TIN triangle. At this stage it must be checked whether redundant data was generated inside the triangle. If this is the case, re-triangulation has to be conducted while suppressing redundant data. An indirect approach may be to compute a temporary integrated model and to delete redundant data afterwards.

A procedure for the latter case is indicated in Figure 7. To delete a redundant node in the intermediate

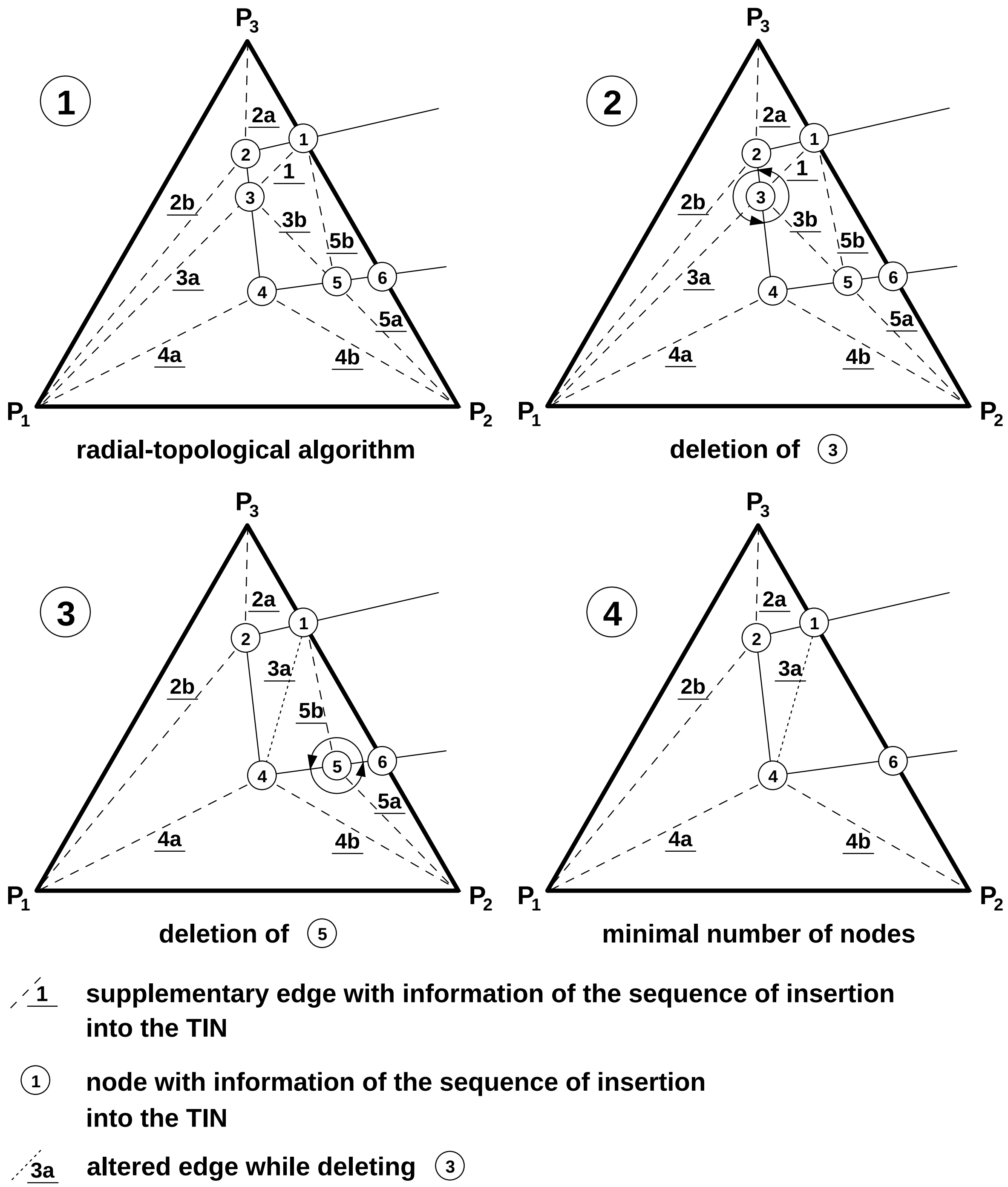

Figure 7: Deletion of redundant data in Figure 5.

Type of data	Threshold $[m]$	Nodes abs.	Nodes [%] of full data set
full 12.5-m-Grid	0	25921	100
simplified DTM-TIN	1	1103	4.3
simplified DTM-TIN	3	265	1.0
full 2D data set	0	1608	100
simplified 2D data set	1	947	58.9
simplified 2D data set	3	620	38.6

Table 1: Amount of nodes in (simplified) input data sets for test area Leine.

integrated model one may simply sweep radially around the respective point to buffer incident and adjacent primitives and perform polygon triangulation afterwards (e. g. O'ROURKE, 1998; DE BERG ET AL., 1997). Redundant nodes have to be marked as such during the initial step of integration or detected by other procedures while checking for redundant data. The disadvantage of this approach is the additional computational effort for firstly inserting and afterwards deleting redundant data, furthermore, the temporary storage required for the complete intermediate integrated model is hence higher than for the resulting model.

Further investigation of the resulting data volume in TIN-based integrated models revealed that data reduction should be conducted as well by simplifying input data. Triangulating the gridded DTM adaptively provides the highest potential in data reduction whereas simplification of the 2D data may also be considered. One well known procedure for line simplification is the algorithm by DOUGLAS & PEUCKER (1973), others are summarized e. g. by WEIBEL (1997). Adaptive triangulations are treated by LENK & KRUSE (2001), GARLAND & HECKBERT (1995) and HELLER (1990) and others.

Figure 8 shows two examples of input data sets as well as two integrated models for a test area (the Leine floodplain) south of Hannover. The Leine running south along the base of a small mountain may be easily identified. The eastern part of the area shows the floodplain with low relief energy.

One integrated model is based on the triangulated grid (gridwidth 50 m) while the other was computed using the adaptively triangulated grid (initial gridwidth 12.5 m, threshold 1 m). A deeper insight to numerical results with respect to data volume is given in Tables 1 and 2. It should be noted that data quality of DTM data was stated with 1 m by the respective national mapping agency, the respective value for horizontal accuracy of 2D data is 3 m. Therefore, applying a threshold of 1 m for simplification to both data sets does not deteriorate the general accuracy of the integrated model in comparison to its full input data. The second step of simplification (3 m) was computed to show the result according to the specified accuracy of the 2D input data set. Comparable results are obtained for other areas in dependence of their morphology and density of 2D data geometry. It is clearly visible that applying data reduction algorithms to input data sets leads to significantly smaller amount of nodes in the integrated models (up to 95 % data reduction) and that adaptive triangulation contributes the major part in data simplification.

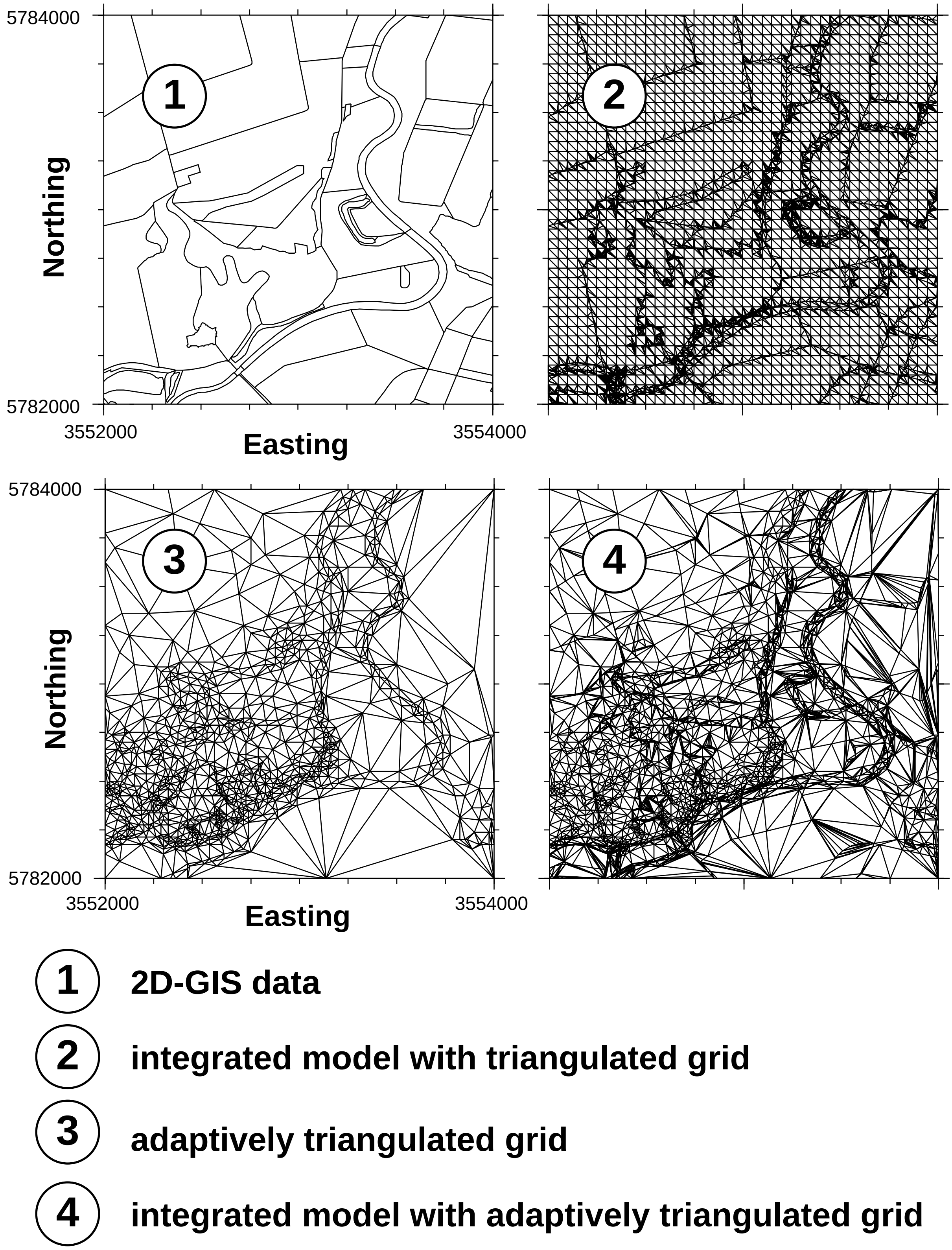

Figure 8: 2D GIS data, simplified DTM-TIN (threshold 1 m) and integrated models on the basis of simplified 2D data (threshold 1 m) while using a triangulated grid as well as the simplified DTM-TIN for test area Leine south of Hannover, Germany.

Type of input data	Threshold $[m]$	Nodes abs.	Nodes [%] of full data set
full 12.5-m-Grid as TIN and full 2D data	0	34166	100
simplified DTM-TIN and 2D data	1	3143	9.2
simplified DTM-TIN and 2D data	3	1314	3.8

Table 2: Amount of nodes in integrated data models with simplified input data sets.

3 Polynomial Surface Objects

After introducing the variant of integrating 2D GIS data and height information via TINs, it is now the aim to provide an alternative approach to the topic at hand.

Polynomial surface objects may be considered as a generalization of the well known height step objects which are commonly used to combine 2D GIS data with height information. Height step objects may be easily derived on the basis of precomputed contour lines. Unfortunately, height step objects yield only a very rough approximation of the terrain relief as they suffer from the ”wedding cake effect” illustrated in Figure 9. It is due to the discretization of the continuous relief by the contours.

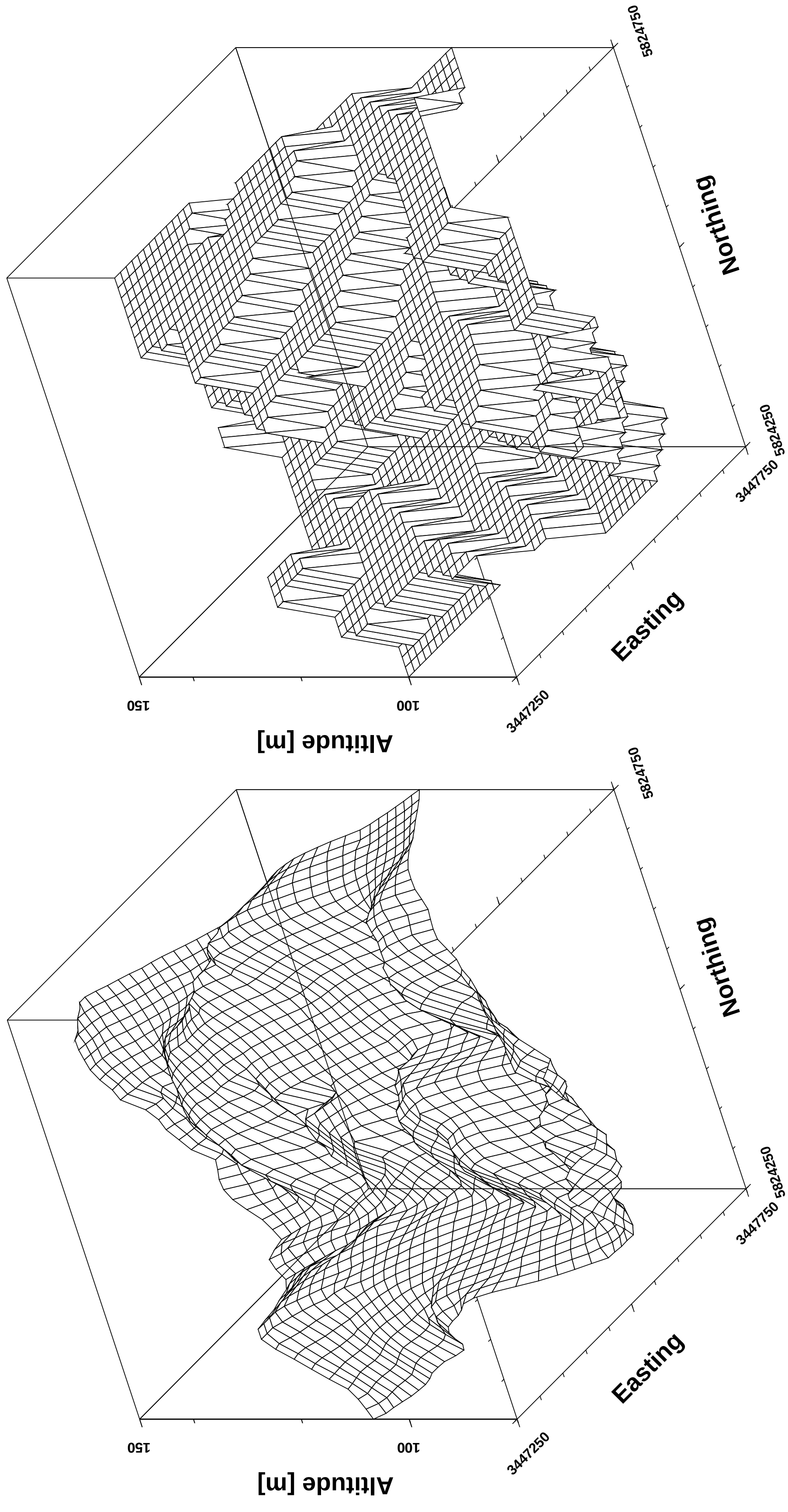

Figure 9: Grid points computed from heights step objects and original grid.

The constant height value for each height step object may also be interpreted as a polynomial of degree zero, i. e. a horizontal plane for each object. Thus, it seems obvious to extend this approach to polynomials of higher degrees or more generally to establish area objects for which mathematical functions are determined individually. This will lead to a better approximation of the surface. The respective coefficients of the functions are then stored as attributes to the objects, and an integration of this kind of height information with 2D GIS data may be achieved by map overlays similar to the approach with height step objects. Such an approach comprises of three major aspects:

1. There have to be existing area objects for which the polynomials are computed, or the objects have to be built during the process of computation.
2. For each individual polynomial surface object, the degree of its associated polynomial has to be fixed or determined.
3. The coefficients of the polynomials have to be computed itsself. During this process some sort of quality control has to be established.

Approaches of polynomial surface approximation are also discussed by JONES (1997; see also KIDNER ET AL., 1990), although his discussion is motivated by the search for alternative DTM data structures and not introduced as an extension of the mentioned height step objects. Two procedures related to polynomial approximation are discussed by JONES (1997). The first one approximates relief data by polynomial patches which are computed for square shaped patches in regular grids. To achieve a required accuracy, the degree of each polynomial is increased until a threshold value has been reached. Due to technical limitations in providing polynomials with very high degrees this approach does not seem to be promising for the integration of height information with 2D GIS data if a certain accuracy is required in relief approximation. Even more, this would lead to 2D data superimposed by a grid pattern. Another approach described by JONES (1997) tries to overcome these problems by applying a hierarchical data structure, i. e. a quadtree in case the required accuracy is not achieved by the implemented degree of polynomials (see also CHEN & TOBLER, 1986). This however requires that the DTM data used as input has to be available in a way that quadtree decomposition may be conducted, i. e. the size of the DTM data has to be in a square shape and the number of the points along a side has to be a power of 2 (thus 2^n). As this restriction seems to be a very limiting factor for practical applications, this approach as well as the one based on regular patches do not seem to be appropriate for the integration of polynomial height information with 2D GIS data. A major advantage of these approaches however is that the boundaries of the objects do not have to be computed as they are implicitly given by the data structure (see step 1). As a consequence, alternative ways to tesselate the relief into discrete objects as a basis for polynomial surface objects have to be found.

An investigation of the existing approaches from geomorphology and hydrology to tesselate the plane into discrete objects (e. g. classification of relief parameters, the *Pfaltz*-graph, watersheds) revealed that on the one hand some of them suffer from conceptual problems, on the other hand there are also associated with computational and algorithmic problems while extracting them automatically from existing DTMs. As a consequence, a new method was developed to extract polynomial surface objects from DTM. The procedure was explained conceptually for irregular point sets on the basis of

VORONOI-diagramms and DELAUNAY-triangulations, and the actual implementation was conducted for gridded DTM due to the substantial algorithmic simplification. It is based on a region growing algorithm (e. g. HARALICK & SHAPIRO, 1993) in combination with least squares adjustments (e. g. KOCH, 1999) for the actual computation of the polynomial coefficients. Details regarding the system of linear equations and its solution to determine the polynomial coefficients may be found in LENK (2001) and PRESS ET AL. (1996) and will not be discussed in the following.

For each object, firstly a starting cell of the region growing process has to be determined. To provide the possibility that the object may grow in all directions, it is reasonable that this starting grid point should have a maximal neighbourhood of free grid points. Furthermore, it should be located in an area with low relief energy in order that the object may grow rapidly with polynomials of low degree before switching to polynomials of higher degrees. The latter require more observations and hence, the growing process could terminate at an early stage leading to a huge amount of objects with low degrees if these aspects are not considered. As these aspects cannot be considered simultaneously a combination of both of them has to be used. The free starting points are classified by their neighbourhoods available and for each neighbourhood class the potential starting point with the minimal standard deviation of a mean height computed from the neighbourhood and itsself is selected. From the two maximal neighbourhoods available the one with the minimal standard deviation is selected.

The next step in the region growing process is to include a point from the neighbourhood of the object into the respective object. This step is iterated until there is either no point available in the respective neighbourhood anymore, a maximum error threshold in approximation of the relief inside of the existing object is reached, and/or the maximum of implemented polynomial degrees is already used by the object and it cannot be switched to a polynomial of higher degree. The latter is a technical aspect rather than a conceptual restriction.

While it is of vital importance that the threshold of maximum approximation error is taken into account for the selection of the next point to be included into an object, it is also necessary to avoid grid points which are connected only by a corner with the other points of the object. Therefore, the buffer used for selection has to be based on the 4-neighbourhood of its points rather than on the 8-neighbourhood. In addition, it is necessary to avoid long hose-like objects as they lead to a very bad approximation of the relief between the grid points due to the properties of polynomials of higher degrees. Hence it is desirable achieve *compact objects* (cf. e. g. WAHL, 1989). Compactness may be described by Equation 1:

$$K = \frac{U^2}{4\pi A}, \tag{1}$$

where U the circumference of an object and A its area. The smaller the compactness K, the more compact an object will be. However, due to the tesselation of the plane by the regular pattern of grid cells the compactness given in Equation 1 does not seem appropriate to be used for the selection of points from the buffer of an object. Figure 10 illustrates that it seems better to use the number of points of the object itsself contained in the 8-neighbourhood of the point to be tested. From the upper object the two lower objects may be derived by region growing. Both will have a compactness of $K = \frac{16}{3\pi}$. The circle containing the right object however will have a diameter of $\sqrt{8}\ d$ whereas the respective circle of the left object shows a diameter of $\sqrt{10}\ d$. Without going into more details the right object must therefore be more compact than the left one because of $\sqrt{8} < \sqrt{10}$.

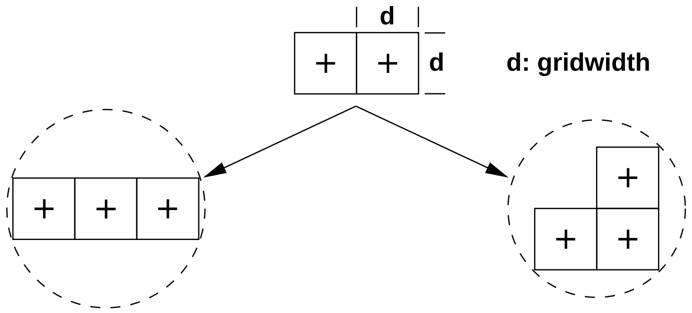

Figure 10: Object with similar compactness and differing circumcircle diameters.

As the maximum approximation error and the compactness of an object cannot be considered simultaneously (likewise the selection of a starting point for an object), a combination of both must be used for the selection process. Several combinations are possible and treated in detail by LENK (2001). As an empirical result, the selection of the next point to be included is based on the following properties:

1. the points are classified according to the amount of points of the respective object in the 8-neighbourhood of the test points;

2. from the two classes with the highest neighbourhood indicator the one with the smallest residual resulting by an inclusion into the object is taken.

Using these properties for object extraction lead in various test areas to almost circular shapes for the objects and thus to a very high compactness.

After extracting all possible objects from a DTM it may happen that some grid points will not be included into an object due to the requirement of a certain threshold value for the maximum approximation error allowed. One way to fill these gaps is to add a point to the respective neighbouring object for which it will cause the smallest approximation error. As a consequence, the maximum approximation error for the object given by the threshold value of the initial extraction will commonly not be valid anymore. This is a major disadvantage of the approach of object extraction in comparison to the quadtree based procedure of CHEN & TOBLER (1986). Another strategy is to simply add the point to the object without including it as observation.

One particular problem associated with polynomial surface objects is given by the discontinuities on their boundaries. For height step objects, the discontinuities equal the height step with which the contour lines used for the creation of the objects were computed. The use of polynomials of higher degrees lets the discontinuities increase to considerable magnitudes which cannot be accepted if height values located between grid points have to be computed from the polynomials. LENK (2001) discusses several approaches to remedy this effect including local object based adjustments as well as global adjustments modeling dependencies between the polynomials of adjacent objects. As a result, the best approach to reduce the discontinuities on the boundaries efficiently is to compute a buffer of the object after its extraction and to include these points as additional observations into the final least squares process to determine the coefficients of the respective polynomial. This moves the exponential growth of a polynomial into the area of adjacent objects where the respective polynomial is not used for height computation anymore (i. e. the polynomials of the adjacent objects are used in that areas). However, it must be emphasized that this procedure will not eliminate the discontinuities on the boundaries, rather it reduces them to magnitudes comparable to the residuals of the observations. Besides this fact regarding the discontinuities, including additional observations into an object will commonly lead to a worser approximation of the grid points inside the objects (see above).

The final step in computing the coefficients of the polynomials is the iteration of the local adjustments while increasing the degrees of local polynomials. In each iteration step the adjacent objects of the geometry with the highest discontinuity are re-adjusted. This may be conducted in case the discontinuties on a geometry do not fulfill a certain threshold values and the degrees of the polynomials have yet not reached the implemented maximum. A procedure without a threshold iterates until both adjacent objects show the maximum degree. As the discontinuities are not introduced themselves into the adjustment, the overall discontinuity may increase by this procedure. In this case the modeling showing the optimal discontinuity should be taken.

Figures 11 and 12 show an example of polynomial surface objects extracted in the hilly moraine area of Figure 9. Figure 11 depicts the area after all objects have been extracted and Figure 12 shows the same objects after buffering the objects to minimize the effect of discontinuities at the boundaries of the objects. Please not that Figure 9 is based on a 12.5-m-grid whereas the models in Figures 11 and 12 have a gridwith of 2.5 m to emphasize the discontinuities of adjacent objects. The discontinuities are easily identified and the effect of buffering to reduce the latter is clearly visible. A small object situated almost in the center of the area is approximated by a horizontal (or obligue tending to be horizontal) plane in Figure 11. In Figure 12, this object approximates the relief clearly with an obligue plane.

Table 3 shows numerical results that have been obtained from data sets situated in areas of different relief types. To provide information on mean accuracy as well as absolute accuracy, the maximal ($max.$) residuals (R) of the observations as well as root mean square residuals (rms) are given. Similar values for discontinuities (D) were computed based on a discretization as discontinuities are continuous functions. Additionally, the average discontinuity is used as a mean value because discontinuities are unsigned values.

test area (# objects)	after filling initial gaps		after adjustment including buffers		after iteration of adjustment	
-	max. $\|R_{overall}\|$ (rms)	max. D (mean)	max. $\|R_{grid}\|$ (rms)	max. D (mean)	max. $\|R_{grid}\|$ (rms)	max. D (mean)
Damme (197)	7.52 (0.35)	22.23 (1.63)	3.07 (0.47)	4.57 (0.60)	3.07 (0.48)	2.84 (0.58)
Ebergötzen (357)	17.73 (0.46)	52.08 (2.94)	9.38 (0.67)	8.57 (1.07)	6.72 (0.65)	4.18 (0.85)
Leine (140)	15.94 (0.35)	+ (+)	31.63 (3.91)	27.48 (2.00)	- (-)	- (-)
Saar (720)	+ (+)	+ (+)	13.19 (0.65)	15.13 (1.15)	13.19 (0.64)	11.79 (1.12)

Table 3: Numerical results for extracted polynomial surface objects.

The results show that the extraction of polynomial surface objects based on the above procedure is feasable with an absolute accuracy of a few metres, the mean accuracy is commonly better than one metre. Similar results have been obtained for discontinuties. The considerable higher values for the Leine area are due to numerical problems generally associated with approximating polynomials. Boxes showing a + indicate values with extrem magnitudes. These are due to the exponential growth of approximating polynomials in the proximity of their boundaries, i. e. their outer areas. Further detailed analysis of the results is given in LENK (2001).

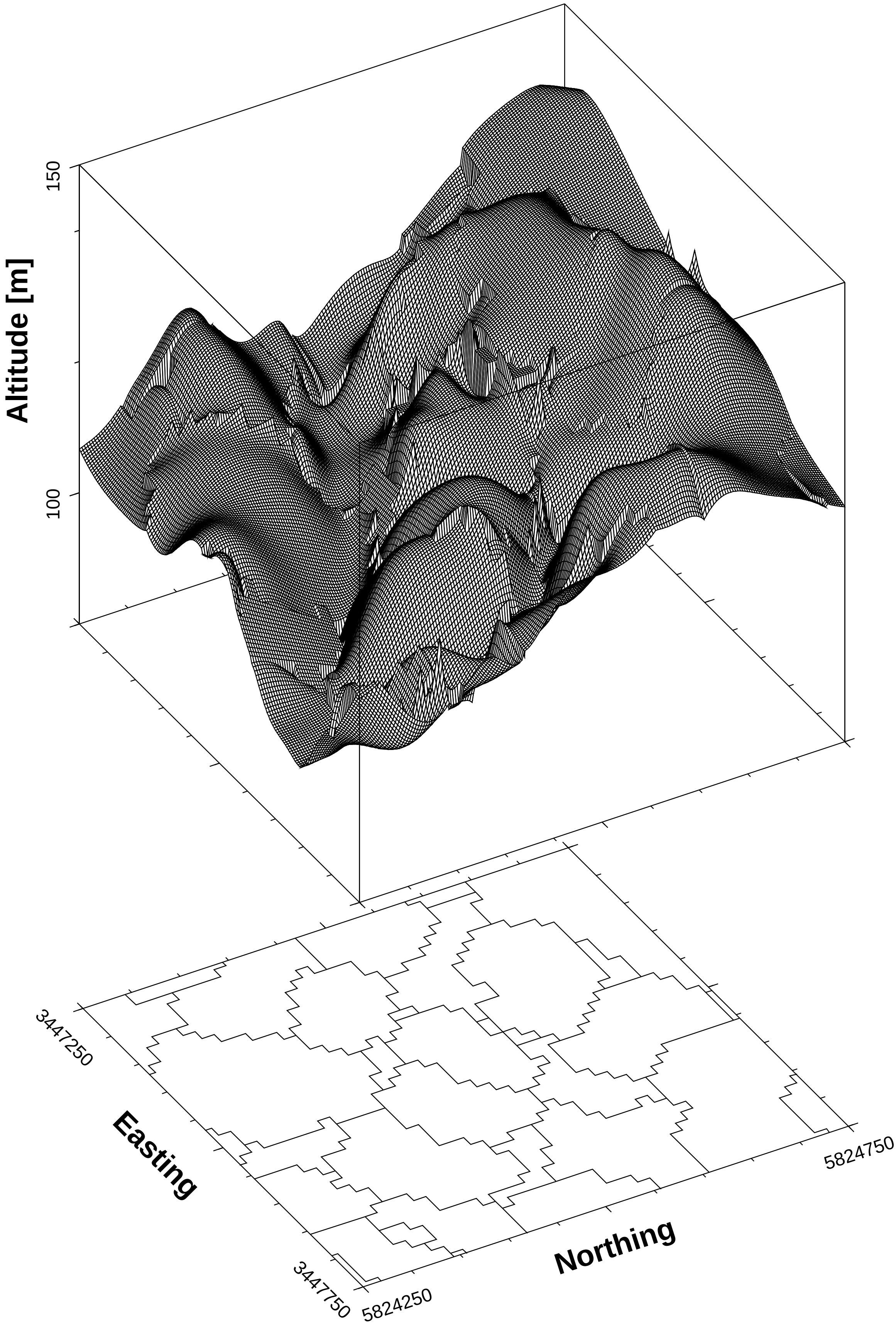

Figure 11: Surface built by polynomial surface objects before buffering.

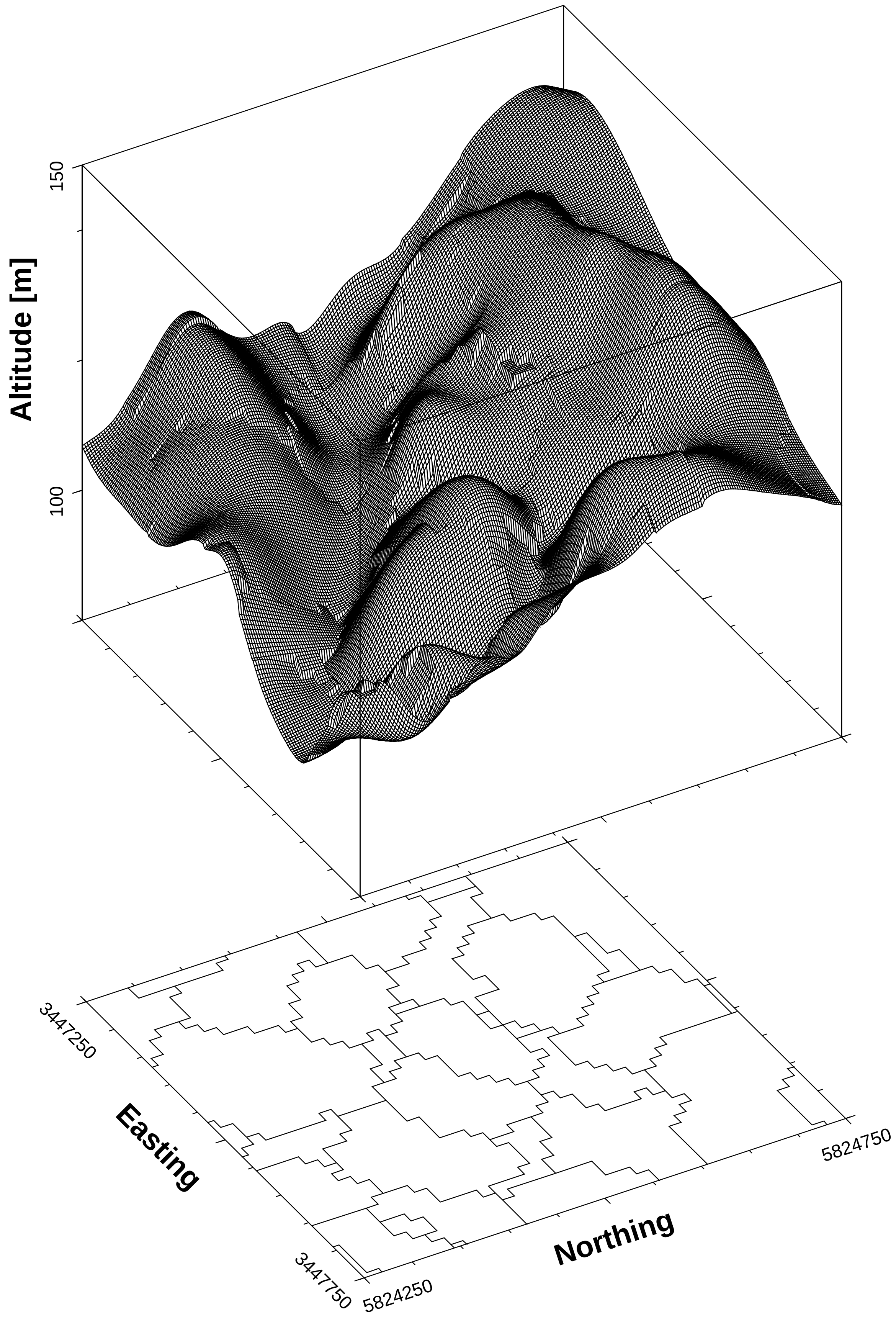

Figure 12: Surface built by polynomial surface objects after buffering.

4 Comparison of the two strategies

An assessment of the suitibility of a specific data model to fulfill the requirements for a certain task at hand must always be conducted on the basis of the respective system specifications. It is not the aim of this article to develop a procedure or a general catalogue of features with which data models may be compared to each other or it may be checked whether they meet certain specifications. Instead, a small and not necessarily complete list of properties or features is used to highlight some differences between the data models. For the definite decision in a specific project, these elaborations may then serve as initial assessment which have to be extended in more detail under the current requirements. The topics treated here include

1. compatibility of the approaches with existing data sets;
2. compatibility with existing approaches in geospatial (and temporal) data modeling;
3. compatibility of the approaches with existing GIS software packages;
4. domains of the models and their usability for the determination of height information for the different geometric primitives node, edge and polygon;
5. geometric model quality and possibilities to control quality;
6. numerical effort while computing the models;
7. analysis and spatial queries of the models;
8. data volume;
9. visualization of the models.

Keeping in mind that the four major tasks of GIS are the capture, management, analysis and visualization of spatial data, these tasks are treated under the items 1 and 6 (data capture), 7 (analysis and management) and 9 (visualization).

Compatibility of the introduced variants of 2.5D geospatial data models with existing data sets was one of the major prerequisites for their development. Both procedures use input data as provided by the national mapping agencies.

The usability of existing data sets as input is closely related with compatibility with existing geodata models and the usability of existing GIS software. Polynomial surface objects are compatible with simple geodata models which comprise of a geometric part (the polygon) and some attributes for linking the polynomial coefficients with them. Therefore, polynomial surface objects may be stored in standard geodata bases if they can handle the required numerical accuracy of the attributes. To compute heights from this kind of surface modeling, simple procedure evaluating the coefficients have to be implemented whereas creating polynomial surface objects requires further expertise. Furthermore, as software to extract polynomial surface objects and to compute their respective coefficients only research prototypes are available.

Compatibility of simplicial complexes with existing geodata models and GIS software is provided under certain restrictions. Simplicial complexes may be stored in geodata bases if they are capable of processing complexes objects which consist of several geometric parts. Otherwise they must be stored as TINs where each TIN triangle is linked with the full attribute data sets of the respective parent object. This as well as other special non-spatial solutions described by PILOUK (1996) are hence only compromises. 2-simplicial complexes are compatible with higher dimensional data models as the theoretic background may be easily extended to 3D and even 4D approaches. Examples for 3D are described by PILOUK (1996), both extensions are treated by BREUNIG (2000). Hence, the proposed procedure of integration on the basis of triangulations provides also safety for investments been made for the creation of the so far existing national core geospatial data bases if a migration to 3D is considered in a long term development of the data sets.

In case a larger area is represented by polynomial surface objects the heights computed on boundaries are not unique due to the discontinuities and therefore, the domain of polynomial surface objecs is restricted to the interior of their bounding polygons. As a consequence, the usability of polynomial surface objects to determine heights for geometric primitives is also restricted. In contradistinction, heights interpolated in a 2.5D-TIN are unique and their domain is the complete horizontal plane.

Quality of terrain modeling in TIN is influenced completely by quality of input data as no approximation is conducted. In case simplification of input data is applied, this may be efficiently controlled by threshold values. At the current stage of research and development this is not the case for polynomial surface objects extracted by the described procedure as the computation of the polynomial cofficients is based on least squares processes and additional observations are added after the initial extraction to achieve a complete coverage of the plane by polynomial surface objects. The quality of the model can therefore hardly be controlled entirely. In case the extraction procedure is altered in the way that grid points not included in objects after the initial extraction are treated as individual objects, the quality is described by the threshold. Consequently the respective coefficients of the objects are not based on least squares process as they are horizontal planes.

The numerical effort to compute polynomial surface objects is ruled by the least squares process where linear algebra routines are used to determine the respective coefficients. Commonly, procedures like matrix multiplication and solutions of systems of linear equations are cubic processes ($O(n^3)$, e. g. PRESS ET AL., 1996). Algorithms for DELAUNAY-triangulations may be implemented as $O(n\ log\ n)$ processes with moderate effort, and even the insertion of additional points has $O(n^2)$ in worst case. Consequently, the numerical effort for computing an integrated model is considerably smaller for TIN-based approaches.

As the TIN is a well-researched data model in terrain modeling, there do exist a lot of algorithms to analyze this data structure. The problem associated with polynomial surface objects is that height information is stored as functions which have to be evaluated analytically in order to conduct further analysis. Not only does this circumstance include an additional computational effort in analysis but also requires special procedures to be developed for analysis as so far, algorithms to analyze polynomial surface objects have rarely been the focus of GIS related research. This implicit storing of height information also limits 2.5D spatial access. Inside the objects the surface may reach local maximums and minimums which have to be detected analytically to use them for spatial access. 2.5D-GIS-TIN may be easily accessed spatially as they describe objects with discrete points.

The resulting data volume of polynomial surface objects can hardly be estimated. The general problem involved is that the extraction is based on treshold values which may vary for special applications, hence they are not objective. In contradistinction, the integration based on triangulation leads to a large data volume (cf. e. g. EGENHOFER ET AL., 1989). The latter however may be reduced, i. e. controlled efficiently.

Visualization of TINs is a standard procedure and consequently, no problems are antissipated in case a TIN has to be visualized. Indeed, ABDELGUERFI ET AL. (1997) state that the integration based on triangulations may advantageously be used for object based visualization using some sort of look-up-table for object-dependend colouring of polygons. As stated above, polynomial surface objects require special techniques, even for visualization, as some sort of discretrization has to be conducted. This leads to a tesselation of the surface which may serve as the basis for further processing.

5 Conclusions and further outlook

As a consequence from the above comparison of the two approaches it is concluded that for general purposes, the integration based on triangulations is superior to polynomial surface objects. 2D-GIS-DTM-TIN fit into existing approaches of geodata capturing, higher dimensional data modelling (3D and even 4D) and management as well as analysis and visualization. Polynomial surface objects do not provide all of these favourable properties in the same manner. This however does not include that in special cases, the latter may be the preferred method to choose.

Further research in 2.5D-GIS-TIN should address the necessary check of geometric and semantic consistency of the input data sets. Extending the model to higher dimensions (3D and 4D) using other/additional data sources as well as application oriented specific models (e. g. a specific surface model for car navigation similar to the approach of CHEN ET AL., 2000) are also promising topics for further research and development.

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6 References

DE BERG, M., VAN KREVELD, M., OVERMARS, M. & SCHWARZKOPF, O., 1997: *Computational Geometry - Algorithms and Applications*. Springer Verlag, Berlin, Heidelberg.

BERN, M. & EPPSTEIN, D., 1995: *Mesh Generation and Optimal Triangulation.* In: DU & HWANG, 1995, 47-123.

BILL, R. & FRITSCH, D., 1994: *Grundlagen der Geo-Informationssysteme, Bd. 1., Hardware, Software und Daten.* Wichmann Verlag, Heidelberg.

BUZIEK, G., 1993: *Considerations on Integration of DTM in GIS.* In: *Proceedings of Eurocarto XI,* Kiruna, 165-176.

BUZIEK, G., GRÜNREICH, D. & KRUSE, I., 1992: *Stand und Entwicklung der digitalen Landschaftsmodellierung mit dem Topographischen Auswertesystem der Universität Hannover (TASH).* Vermessung, Photogrammetrie, Kulturtechnik 90(2): 84-88.

CHEN, J., SUN, M. & ZHOU, Q., 2000: *Expression and Visualization of Cloverleaf Junction in a 3-Dimensional City Model.* GeoInformatica 4(4):375-386.

CHEN, Z.-T. & TOBLER, W., 1986: *Quadtree Representations of Digital Terrain.* In: *Proc. Auto-Carto London, Volume 1, Sept. 14-19th,* London, 475-484.

DEVIJVER, P. A. & DEKESEL, M., 1982: *Insert and delete algorithms for maintaining dynamic Delaunay triangulations.* Pattern Recognition Letters 1(2):73-77.

DEVILLERS, O., 1997: *Improved Incremental Randomized Delaunay Triangulation.* Institut National de Recherche en Informatique et en Automatique (INRIA), Rapport de recherche no 3298.

DEVILLERS, O., PION, S. & TEILLAND, M., 2001: *Walking in a Triangulation.* Institut National de Recherche en Informatique et en Automatique (INRIA), Rapport de recherche no 4120.

DOUGLAS, D. H. & PEUCKER, T. K., 1973: *Algorithms for the reduction of the number of points required to represent a line or its caricature.* The Canadian Cartographer 10(2):112-122.

DU, D. Z. & HWANG, F. K. (EDS.), 1995: *Computing in Euclidean Geometry (2nd Edition).* Lecture Notes Series on Computing, Vol. 4, World Scientific, Singapore, New Jersey, London, Hong Kong.

EBNER, H., HÖSSLER, R., & WÜRLÄNDER, R., 1990: *Integration von digitalen Geländemodellen in Geoinformationssysteme - Konzept und Realisierung.* Nachrichten aus dem Karten- und Vermessungswesen, Reihe I, Heft 51, 71-76.

EGENHOFER, M. J., FRANK, A. U. & JACKSON, J. P., 1989: *A Topological Data Model for Spatial Databases.* In: *Proceedings First Symposium SSD'89*, Santa Barbara, California, USA, 17.-18.07.1989, 271-286.

FORESMAN, T. W. (ED.), 1997: *The History of Geographic Information Systems: Perspectives from the Pioneers.* Prentice-Hall, Upper Saddle River, New Jersey.

FRITSCH, D., 1996: *Three-Dimensional Geographic Information Systems - Status and Prospects.* International Archives of Photogrammetry and Remote Sensing, Vol. XXXI, Part B3, Vienna, Austria, 215-221.

FRITSCH, D. & HOBBIE, D. (EDS.), 1995: *Photogrammetrische Woche '95.* Herbert Wichmann, Heidelberg.

FRITSCH, D. & PFANNENSTEIN, A., 1992: *Conceptual Models for Efficient DTM Integration into GIS.* In: *Proceedings EGIS'92, Third European Conference and Exhibition on Geographical Information Systems*, Munich, Germany, 23.-26.03.1992, 701-710.

GARLAND, M. & HECKBERT, P. S., 1995: *Fast Polygonal Approximation of Terrains and Height Fields.* Technical Report CMU-CS-95-181, School of Computer Science, Carnegie Mellon University, Pittsburg.

GOODCHILD, M. F., 1997: *What Next? Reflections from the Middle of the Growth Curve.* In: FORESMAN, 1997, 369-381.

GRÖGER, G., 2000: *Modellierung raumbezogener Objekte und Datenintegrität in GIS.* Herbert Wichmann Verlag, Heidelberg.

GUIBAS, L. & STOLFI, J., 1985: *Primitives for the Manipulation of General Subdivisions and the Computation of Voronoi Diagrams.* ACM Transactions on Graphics 4(2): 74-123.

HARALICK, R. M. & SHAPIRO, L. G., 1993: *Computer and Robot Vision. Vol. II.* Addison-Wesley, Reading, Massachusetts.

HELLER, M., 1990: *Triangulation algorithms for adaptive terrain modeling.* In: *Proc. 4th Int. Symp. on Spatial Data Handling, Volume 1, 163-174,* Zürich.

JÄNICH, K., 1995: *Topology.*

Springer Verlag, Berlin, Heidelberg.

JONES, C., 1997: *Geographical Information Systems and Computer Cartography.* Addison Wesley Longman, Reading, Massachusetts.

KIDNER, D. B., JONES, C. B., KNIGHT, D. G. & SMITH, D. H., 1990: *Digital terrain models for radio path profiles.* In: *Proc. 4th Int. Symp. on Spatial Data Handling, Volume 1, 240-249,* Zürich.

KLÖTZER, F., 1997: *Integration von triangulierten digitalen Geländemodellen und Landkarten.* Diploma thesis, unpublished, Institute of Computer Science III, Rheinische Friedrich-Wilhelms-Universität, Bonn.

KRAUS, K., 2000: *Photogrammetrie, Bd. 3, Topographische Informationssysteme.* Dümmler Verlag, Köln.

KRAUS, K., 1995: *From Digital Elevation Model to Topographic Information System.* In: FRITSCH & HOBBIE, 1995:277-285.

VAN KREVELD, M., 1997: *Digital Elevation Models and TIN Algorithms.* In: VAN KREVELD ET AL., 1997, 37-78.

VAN KREVELD, M., NIEVERGELT, J., ROOS, TH. & WIDMAYER, P. (EDS.), 1997: *Algorithmic Foundations of Geographic Information Systems.* Lecture Notes in Computer Science 1340, Springer, Berlin, Heidelberg.

KUFONIYI, O., 1995: *Spatial coincidence modelling, automated database updating and data consistency in vector GIS.* PhD Thesis, Wageningen Agricultural University, The Netherlands.

LENK, U., 2001: *- 2.5D-GIS und Geobasisdaten - Integration von Höheninformation und Digitalen Situationsmodellen.* Wissenschaftliche Arbeiten der Fachrichtung Vermessungswesen der Universität Hannover. Doctoral thesis, University of Hannover, Germany, to appear.

LENK, U. & KRUSE, I., 2001: *Multibeam data processing: Data Reduction, Adaptive Triangular Meshing and Comments to Brouns et al. (2001, THJ 101).* The Hydrographic Journal, to appear.

LONGLEY, P. A., GOODCHILD, M. I. MAGUIRE, D. J. & RHIND, D. W. (EDS.), 1999: *Geographical Information Systems, Vol. 1., Principles and Technical Issues.* John Wiley & Sons, Inc., New York, Chichester.

MAYER, H., 1991: *Integration von digitalen Geländemodellen in hybride graphische Systeme.* In: SCHILCHER, 1991, 119-125.

MOLENAAR, M., 1989: *Single valued vector maps - a concept in GIS.* GIS 2(1): 770-781.

O'ROURKE, J., 1998: *Computational Geometry in C. 2nd Edition.* Cambridge University Press, Cambridge, New York.

PEUCKER, T. K., FOWLER, R. J., LITTLE, J. J. & MARK, D. M., 1976: *Digital Representation of Three-Dimensional Surfaces by Triangulated Irregular Networks (TIN) (Revised).* Technical Report Nr. 10, Simon Fraser University, Burnaby, British Columbia, Canada & Office of Naval Research, Geography Programs, Arlington, Virginia, USA.

PFANNENSTEIN, A. & REINHARDT, W., 1993: *Data Analysis in Geographical Information Systems in Combination with integrated Digital Terrain Models.* In: *Proceedings EGIS'93, Fourth European Conference and Exhibition on Geographical Information Systems*, Genova, Italy, 23.03.-01.04.1993, 1341-1349.

PILOUK, M., 1996: *Integrated Modelling for 3D GIS.* PhD Thesis, ITC Publication Series No. 40, Enschede, The Netherlands.

PILOUK, M. & KUFONIYI, O., 1994: *A relational data structure for integrated DTM and multitheme GIS.* International Archives of Photogrammetry and Remote Sensing, Commision III, Vol. 30, Part 3/2, Munich, Germany, 670-677.

PILOUK, M. & TEMPFLI, K., 1994a: *Integrating DTM and GIS using a relational data structure.* In: *Proceedings GIS'94*, Vol. 1, Vancouver, Canada, 163-169.

PILOUK, M. & TEMPFLI, K., 1994b: *An object oriented approach to the unified data structure of DTM and GIS.* International Archives of Photogrammetry and Remote Sensing, Vol. XXX, Part 4, Athens, Georgia, USA, 672-679.

PILOUK, M. & TEMPFLI, K., 1993: *An integrated DTM-GIS data structure: a relational approach.* In: *Proceedings 11th International Symposium on Computer Assisted Cartography (AUTOCARTO 11)*, 30.10.-01.11.93, Minneapolis, Minnesota, USA, 278-287.

PLÜMER, L. & GRÖGER, G., 1997: *Achieving Integrity in Geographic Information Systems - Maps and Nested Maps.* GeoInformatica 1(4): 345-367.

PLÜMER, L. & GRÖGER, G., 1996: *Nested Maps - a Formal, Provable Correct Object Model for Spatial Aggregates.* In: *Proceedings 4th ACM Workshop on Advances in GIS (ACM Press),* Rockville, Maryland, November 15-16: 77-84.

PRESS, W. H., TEUCHOLSKY, S. A., VETTERLING, W. T. & FLANNERY, B. P., 1996: *Numerical Recipes in C.* Second Edition, Cambridge University Press, Cambridge.

REINHARDT, W., 1991: *Zur Integration von digitalen Geländemodellen in Geo-Informationssysteme.* In: SCHILCHER, 1991, 107-118.

SCHILCHER, M. (ed.), 1991: *Geo-Informatik - Anwendungen, Erfahrungen, Tendenzen.* Siemens Nixdorf Informationssysteme AG, Berlin, München.

WEIBEL, R., 1993: *On the Integration of Digital Terrain and Surface Modeling into Geographic Information Systems.* In: *Proceedings 11th International Symposium on Computer Assisted Cartography (AUTOCARTO 11),* 30.10.-01.11.93, Minneapolis, Minnesota, USA, 257-266.

WAHL, F. M., 1989: *Digitale Bildsignalverarbeitung.* Springer Verlag, Berlin, Heidelberg, New York.

WEIBEL, R., 1997: *Generalization of Spatial Data: Principles and Selected Algorithms.* In: VAN KREVELD ET AL., 1997, 99-152.

WORBOYS, M. F., 1995: *GIS - A Computing Perspective.* Taylor & Francis, London, Philadelphia.

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1 *Trombetti, C.:* „Activité de la Commission A de l'OEEPE de 1960 à 1964" – *Cunietti, M.:* „Activité de la Commission B de l'OEEPE pendant la période septembre 1960 –j anvier 1964" – *Förstner, R.:* „Rapport sur les travaux et les résultats de la Commission C de l'OEEPE (1960–1964)" – *Neumaier, K.:* „Rapport de la Commission E pour Lisbonne" – *Weele, A. J. v. d.:* „Report of Commission F." – Frankfurt a. M. 1964, 50 pages with 7 tables and 9 annexes.

2 *Neumaier, K.:* „Essais d'interprétation de »Bedford« et de »Waterbury«. Rapport commun établi par les Centres de la Commission E de l'OEEPE ayant participé aux tests" – „The Interpretation Tests of »Bedford« and »Waterbury«. Common Report Established by all Participating Centres of Commission E of OEEPE" – „Essais de restitution »Bloc Suisse«. Rapport commun établi par les Centres de la Commission E de l'OEEPE ayant participé aux tests" – „Test »Schweizer Block«. Joint Report of all Centres of Commission E of OEEPE." – Frankfurt a. M. 1966, 60 pages with 44 annexes.

3 *Cunietti, M.:* „Emploi des blocs de bandes pour la cartographie à grande échelle – Résultats des recherches expérimentales organisées par la Commission B de l'O.E.E.P.E. au cours de la période 1959–1966" – „Use of Strips Connected to Blocks for Large Scale Mapping – Results of Experimental Research Organized by Commission B of the O.E.E.P.E. from 1959 through 1966." – Frankfurt a. M. 1968, 157 pages with 50 figures and 24 tables.

4 *Förstner, R.:* „Sur la précision de mesures photogrammétriques de coordonnées en terrain montagneux. Rapport sur les résultats de l'essai de Reichenbach de la Commission C de l'OEEPE" – „The Accuracy of Photogrammetric Co-ordinate Measurements in Mountainous Terrain. Report on the Results of the Reichenbach Test Commission C of the OEEPE." – Frankfurt a. M. 1968, Part I: 145 pages with 9 figures; Part II: 23 pages with 65 tables.

5 *Trombetti, C.:* „Les recherches expérimentales exécutées sur de longues bandes par la Commission A de l'OEEPE." – Frankfurt a. M. 1972, 41 pages with 1 figure, 2 tables, 96 annexes and 19 plates.

6 *Neumaier, K.:* „Essai d'interprétation. Rapports des Centres de la Commission E de l'OEEPE." – Frankfurt a. M. 1972, 38 pages with 12 tables and 5 annexes.

7 *Wiser, P.:* „Etude expérimentale de l'aérotiangulation semi-analytique. Rapport sur l'essai »Gramastetten«." – Frankfurt a. M. 1972, 36 pages with 6 figures and 8 tables.

8 „Proceedings of the OEEPE Symposium on Experimental Research on Accuracy of Aerial Triangulation (Results of Oberschwaben Tests)" *Ackermann, F.:* „On Statistical Investigation into the Accuracy of Aerial Triangulation. The Test Project Oberschwaben" – „Recherches statistiques sur la précision de l'aérotriangulation. Le champ d'essai Oberschwaben" – *Belzner, H.:* „The Planning. Establishing and Flying of the Test Field Oberschwaben" – *Stark, E.:* Testblock Oberschwaben, Programme I. Results of Strip Adjustments" – *Ackermann, F.:* „Testblock Oberschwaben, Program I. Results of Block-Adjustment by Independent Models" – *Ebner, H.:* Comparison of Different Methods of Block Adjustment" – *Wiser, P.:* „Propositions pour le traitement des erreurs non-accidentelles" – *Camps, F.:* „Résultats obtenus dans le cadre du project Oberschwaben 2A" – *Cunietti, M.;*

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9 *Beck, W.:* „The Production of Topographic Maps at 1 : 10,000 by Photogrammetric Methods. – With statistical evaluations, reproductions, style sheet and sample fragments by Landesvermessungsamt Baden-Württemberg Stuttgart." – Frankfurt a. M. 1976, 89 pages with 10 figures, 20 tables and 20 annexes.

10 „Résultats complémentaires de l'essai d'«Oberriet» of the Commission C de l'OEEPE – Further Results of the Photogrammetric Tests of «Oberriet» of the Commission C of the OEEPE"

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