GIS – The Third Dimension

Wolfgang Förstner
Institut für Photogrammetrie, Universität Bonn
Nußallee 15, D-53115 Bonn
e-mail: wf@ipb.uni-bonn.de

Abstract

The paper wants to discuss the problem areas in establishing 3D-GISs. Among the many applications it restricts to the 3D-modelling of cities. Acquisition methods for 3D-data and examples for the use of such 3D-models are presented. Finaly, a 2D-representation for 3D-objects with vertical walls but without passages is proposed which may be used for storing buildings and which may form a link to CAD-systems.

1 Motivation

Currently available Geoinformation Systems (GISs) provide tools for managing 2-dimensional (2D) data. The third dimension can only be stored as attribute. Digital Elevation Models (DEMs) serve to represent the 3-dimensional (3D) structure of the terrain. This situation is motivated by the primary applications as e. g. in cadastre or medium scale planning and the broad use of GISs in geography, integrating remote sensing data into the analyses.

For an increasing number of applications a 2D representation is not sufficient. This especially holds for geology, for architectural design or for large scale urban planning, where the complexity of the objects results from their rich 3D spatial structure. E. g. city models may contain buildings, roads including bridges or tunnels, subways, sewer of gas pipe networks or just the vegetation. All this information up to now can only be stored in 2D layers, which might be sufficient for some applications, however, in general this representation appears to be inadequate in the long run, as clearly is suggested by Fig. 1[1].

This paper wants to discuss the problem areas in establishing 3D GISs. Among the many applications it restricts to the 3D-modelling of cities. Acquisition methods for 3D-data and examples for the use of such 3D-models are presented. Finaly, a 2D-representation for 3D-objects with vertical walls but without passages is proposed which may be used for storing buildings and which may form a link to CAD-systems.

2 Problem Areas

There are variuous reasons why the third dimension is not really present in GISs. Costs and time are only one aspect, limitations result both from practice and from theory.

2.1 Costs

Costs for setting up a GIS are largely influenced by the data acquisition, estimates reach 80 % to 95 % of the total costs. The costs for data acquisition highly depend on the degree of attributation necessary. Acquiring the 3D-geometry of buildings (cf. section 3) e. g. may cost in the range between 500.– DM to 3000.– DM per km^2, if one restricts the resolution to 1–2 m at the object, not including a link to the city map, e. g. for having access to the buildings via the street name. Increasing the level of detail of the acquired data, and linking the data to existing information, e. g. base maps, may easily increase costs by a factor 5 or 10. This explains the hesitation of many

---

[1] by courtesy of A. Hoffmann, pixel size 1 m

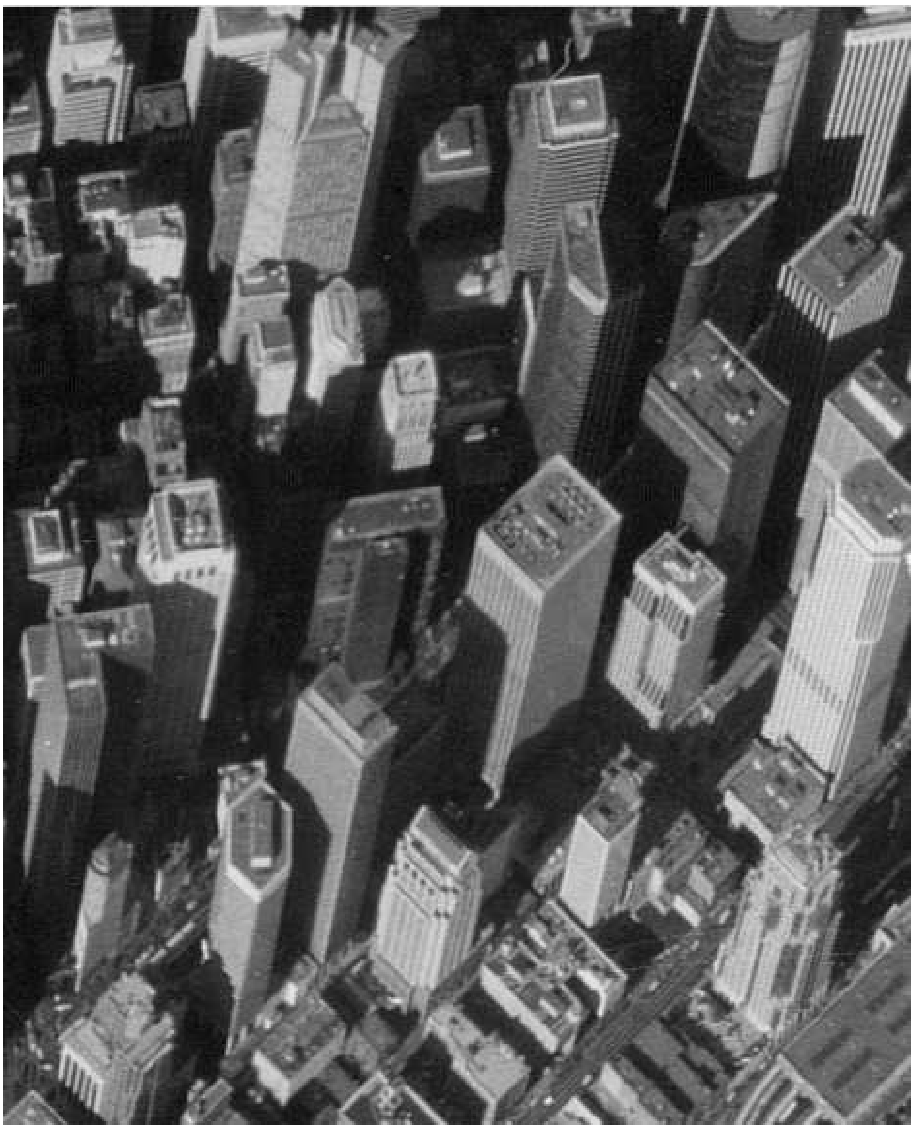

Fig. 1: A section of an aerial image over San Francisco, pixel size 1 m

institutions to start to acquire such data and is one of the main motivation for universities to develop automatic acquisition tools. Though any degree of automation would help. According to F. Leberl [Gruber *et al.* 1995] factors of 10 to 40 in efficiency need to be envisaged by automation to reach acceptance by cities.

2.2 Time

On the other hand the pressure on geodesists as the professional group being responsible for the provision of these data is high. The telecommunication companies need 3D-data for the planning of transmitter stations today. Currency, completeness and homogeneity of the data are of higher importance than accuracy, when compared to cadastrial plans. These urgent requirements may trigger a discussion on the value of *3D-structures*, especially buildings *as topographic objects.* It does not seem reasonable or acceptable for survey agencies to wait with the acquisition of 3D-data until the cadastrial base maps are complete in order to have only one representation of a building in the data bases. It may be neccessary to accept multiple representations in spatial data bases, here for buildings as objects with legal *and* topographic aspects.

2.3 User Specifications

A severe difficulty in building up 3D-datasets is the lack of clear user specifications. There seems to be an egg and chicken problem: the present difficulties in acquiring 3D-data results in the lack of user specifications as they are not aware that such data can be acquired. On the other hand, the lack of user specifications limits the motivation to push the development of techniques for data acquisition. However, even if the potential applications would be clear, the diversity of the requirements with respect to the 3D-data would become obvious, an experience made with 2D-data already. The OEEPE (Organisation Européenne d'Études Photogrammetriques Experimentales) is starting a test on 3D-City Models for establishing a link between the producers of 3D-data in urban areas and the users of such data in order to find out the needs of the market and to provide basic information on photogrammetric technology.

2.4 Scientific Basis

The theory for handling 2D-objects in spatial information systems is quite far advanced (cf. [Molenaar 1989]). This especially holds for the analysis of the connectivity (topology) of spatial objects which is essential for efficient retrieval (cf. [Egenhofer *et al.* 1989], [Egenhofer *et al.* 1994]). These concepts partly have found application in GISs. The difficulty of defining topological relations in 3D has hindered a fast development of 3D-data models for GISs. Recent developments explicitely adress this problem (cf. [Breunig *et al.* 1994], [Pilouk *et al.* 1994]).

On the other hand CAD-Systems since a long time provide efficient ways of managing 3D-data. However, there is dichotomy between GIS and CAD-Systems: While GISs are meant to provide a large number and variety of analysis tools, to enable access via composed thematic atributes and via geometry and – as mentioned above – are mainly 2D, CAD-systems are meant to support construction of complex objects based on standardized primitives and to support version control for being able to backtrack to previous situations and support full 3D (though there are 2D-CAD-Systems). An integration of the concepts of both technologies appears to be difficult. Intermediate solutions, where only for certain cases a link between both types of systems is required, seem to be neccessary (cf. an example in section 4).

3 Acquisition Methods and Use of 3D-Models

3.1 Acquisition Methods

Acquisition of 3D-data need to distinguish objects visible from space, objects only visible from the ground and objects below ground. Most efficients techniques are those which can rely on images, intensity images of range images, and at the same time can cover large areas. Thus only objects visible from space can be expected to be acquired with acceptable cost benefit. Objects only visible from the ground as passages, but also fassades, and of course tunnels, subways etc. require a high acquisition effort, unless special techniques are available for supporting highly automatic data acquisition.

For acquiring buildings, vegetation and streets a number of techniques are available:

1. *Photogrammetry* in this context is based on aerial photographs. It allows to derive 3D-information with high accuracy and efficiency. All mentioned objects can be acquired. Classical techniques are based on the evaluation of the analogue film by a human operator. Digitized images give rise to automation, especially automatic derivation of high resolution DEM's (cf. [Krzystek 1991]) which may be analysed with respect to building structures (cf. [Weidner and Förstner 1995]). Semi-automatic procedures (cf. [Lang and Schickler 1993]) are already competetive with classical techniques and have the potential of highly increased efficiency.
2. *Laser Profiling* [Lindenberger 1993] immediately leads to a high-resolution DEM, which also can be analysed with respect to buildings. Costs are getting comparative to photogrammetric techniques. An integration of both techniques appears to be promising and will be available in a few years.

   Figure 2 shows a rendering of a 3D-model derived by laser profiling[2].

---

[2] by courtesy of TopScan

3. *Remote Sensing* relies on digital satellite imagery. Currently available data with pixel sizes of 10 m (SPOT) or larger do not show the required resolution. However, it is to be expected that in one ore two years satellite data with a resolution of 1 m will be available [Fritz 1995]. Figure 1 is a subsection of a digitized aerial photo with a pixel size of appr. 1 m, giving an impression of the resolution to be expected from such space imagery.

3.2 Use of 3D-Models

3D-models represent an image of the 3D-world, being a past, a present or a future world. We therefore may distinguish different types of applications.

Past Worlds. 3D-models may be derived from old images or films, e. g. for the reconstruction of buildings, interiors, cars or full scenes which may even not be accessible anymore. Such reconstructions may be used for the analysis of changes in settlement, architecture or behaviour.

Present World. 3D-models may serve as a replacement of the current world. Travel bureaus could use such models for advertisements, estate agents could provide active catalogues, where users can walk through their expected property. Hotels or fairs could provide interactive guides for visitors. *3D-Kiosks* could offer all type of information using multimedia tools, e. g. city-tours. Architects need 3D-models of the current state as a basis for planning. In case of drastic changes of the environment the present situation could be archived.

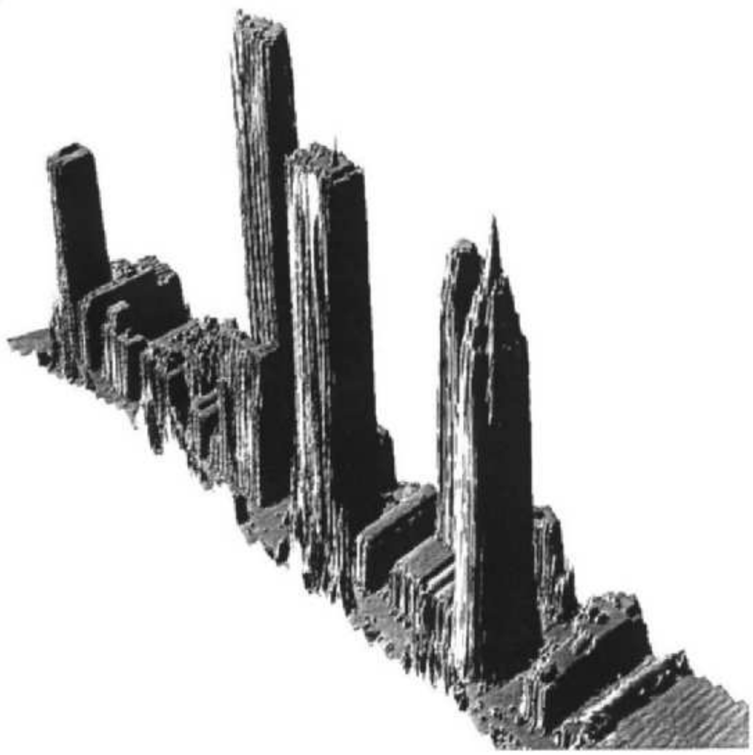

Fig. 2: Rendering of a 3D-model of a part of Toronto acquired with the system TopScan. The ground resolution is appr. 2 m. The height accuracy is in the order of 0.2 m.

Future Worlds. 3D-modelling of future worlds is the domain of planning of any kind via simulations. City planning certainly is one of the most complex markets, telecommunication – as mentioned above – the most growing one. Environmental monitoring is a permanent task, using present and future 3D-models for analysis. Large scale applications are building information systems.

Virtual Reality. Virtual reality essentially relies on 3D-models. Its application domains are wide: Simulators are used for education and training of all type of vehicles: air planes, cars but also trains. The game industry is increasingly using 3D-models. City models as a byproduct e. g. could be used to support games like *Mr. X*, where game rules could depend on the town, thus being different for London and for Tokyo. Films could be produced on the background of old scenery complemented with new (ficticious) furniture.

There seems no real limitation in using 3D-models, providing a strong motivation not only to develop tools for data acquisition and management, but actually to build up 3D-information systems, as the number of users can be expected to be large.

4 A 2D-data Model for Representing Buildings

This section is more technical and presents a 2D-data model for representing buildings.
It is motivated by the following facts:

- Buildings are truly 3D-objects, which cannot be stored in a 2D-GIS appropriately.
- The development of truly 3D-GIS will take time, due to the complexity of 3D-data structures and the overwhelming amount of 2D-queries in practical applications, even in simulations requiring 3D-data, which actually often can do with 2 1/2 D data.
- The visualisation of buildings for planning may be a motivation to acquire building data, but requires vertical walls together with the reflectance properties to be explicitly storable in a GIS.
- A 2D-data model serving 2 1/2 D representations *and* building visualisation may be useful, as it can be realized within available GIS.

The idea for the new representation is the following:

- We impose the restriction that buildings are composed of a set of not necessarily planar surfaces having normals with non-negative z-component. Thus no overhanging faces are allowed. This ensures a unique projection of the surface structure into a 2D-map.
- As a consequence, the projection of a 3D-face is either a 2D-face showing the same side as the 3D-face when looking from above, or a 1D-line, which is the extreme case with the z-component of the normal being 0. The projection of a 3D-line is either a 2D-line or a point.
- The data structure can use any 2D-representation. The surface can be represented as a 2D-vector map according to MOLENAAR ([Molenaar 1989]) with 0D-points, 1D-lines and 2D-faces, all being open sets and their mutual relations.

The coding of the *planar* elements in the vector map, indicated by the prime ' (in Fig. 3) or the superscript $^{(2)}$, is the following:

- Interpretation of 2D-faces $\mathcal{F}^{(2)}$ of the 2D-map.

  3D-faces $\mathcal{F}^{(3)}$: These are open 2D-sets embedded in $\mathbb{R}^3$, i. e. mappings $\mathbb{R}^2 \to \mathbb{R}^3$ given by a function $z = f(x,y)$ which is valid within the open set $\mathcal{F}^{(2)}$.

  Examples are DEM's for representing the topographic surface, flat or sloped roofs or roofs of any shape occuring e. g. at congress halls. Only *one* 3D-surface above one 2D-face is allowed.

  Face $\mathcal{F}_1'$ in Fig. 3 represents the sloped roof $\mathcal{F}_1$.
- Interpretation of 1D-lines $\mathcal{L}^{(2)}$ of the 2D-map.

  Here are two possibilities:

  - *3D-Lines* $\mathcal{L}^{(3)}$:

    These are open 1D-sets embedded in $\mathbb{R}^3$, i. e. mappings $\mathbb{R}^1 \to \mathbb{R}^3$ given by a function $\boldsymbol{p}^{(3)} = \boldsymbol{p}^{(3)}(t)$ with $\boldsymbol{p}^{(3)} = (x,y,z)^T$, with the restriction the mapping $(x,y) = (x,y)(t)$ to be unique, i. e. nonoverlapping.

    Examples are any type of break lines occuring in DEM's or roof surfaces, provided the slope at both sides of the line is finite.

    Line $\mathcal{L}_2'$ in Fig. 3 is of type n (normal) representing the single horizontal line $\mathcal{L}_2$.

  - *vertical 3D-faces* $\mathcal{F}^{(3)}$:

    These are three open sets: The 2D-face and the lower and upper border line.

    The 2d-face is an open 2D-set embedded in $\mathbb{R}^3$, i. e. a mapping $\mathbb{R}^2 \to \mathbb{R}^3$ given by the function $\boldsymbol{p}^{(2)} = p^{(2)}(u)$ specifying the ground line of the vertical surface with $\boldsymbol{p}^{(2)} = (x, y)^T$. Two functions $z_- = z_-(u)$ and $z_+ = z_+(u)$ specify the lower and upper boundary of the vertical face. The mapping is assumed to be unique, i. e. nonoverlapping. The z-values are assumed to follow $z_-(u) \leq z_+(u)$.

    Examples are vertical walls of buildings, which in case of a building with flat roof yields a linear function $(x, y) = (au + b, cu + d)$ specifying the position of the wall, and two constants $z_- = h_0$ and $z_+ = h_1$ specifying the lower and upper border of the wall. But also buildings with round vertical walls can be represented.

    Line $\mathcal{L}_1'$ in Fig. 3 is of type v (vertical) and represents the triple $(\mathcal{L}_1^-, \mathcal{F}(\mathcal{L}_1), \mathcal{L}_1^+)$.

- Interpretation of 0D-points $\mathcal{P}^{(2)}$ of the 2D-map.

  Here again are two possibilities:

  - *3D-point* $\mathcal{P}^{(3)}$: This is trivial (cf. points $\mathcal{P}_6'$ to $\mathcal{P}_9'$).
  - *vertical 3D-line* $\mathcal{L}^{(3)}$:

    These again are three open sets: the vertical line segment represented by the point $\boldsymbol{p}^{(2)} = (x, y)$ and the two end points, specified by z_- and z_+.

    Prominent examples are vertical edges occuring at corners of buildings, but also vertical poles.

    Point $\mathcal{P}_5'$ in Fig. 3 being of type v, shows such a pole, and represents the triple $(\mathcal{P}_5^-, \mathcal{L}(\mathcal{P}_5), \mathcal{P}_5^+)$. Observe, that if the pole would sit at one of the corners of the building, say $\mathcal{P}_4$ the representation of the map-point would be a list of more than 3 3D-elements, e. g. $(\mathcal{P}_4^0, \mathcal{L}^0(\mathcal{P}_4), \mathcal{P}_4^1, \mathcal{L}^1(\mathcal{P}_4), \mathcal{P}_4^2)$.

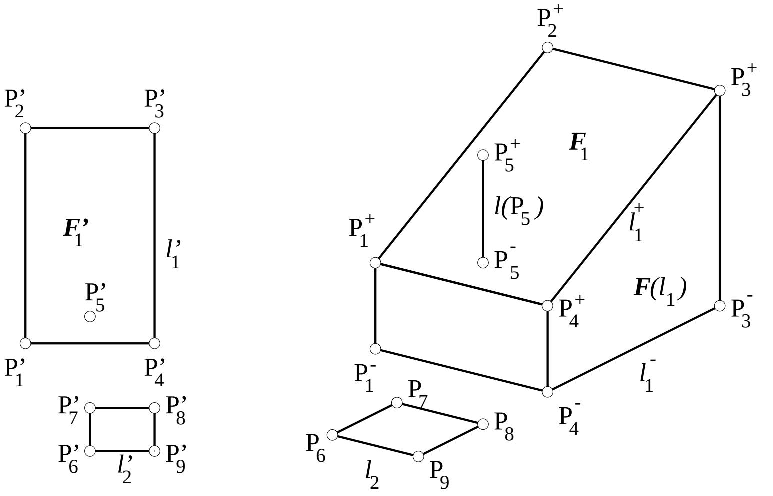

Fig. 3 shows an example for the representation of buildings with vertical walls.
Point P_5' is of type v, thus represents the triple $(P_5^-, l(P_5), P_5^+)$.
Line l_1', also being of type v analogously represents the triple $(l_1^-, F(l_1), l_1^+)$.

As a consequence we have the following positive properties:

- All basic elements can be addressed explicitly. They are typed according to their dimension.
- Any type of information can be linked to the basic elements. Thus also reflectance properties of the faces can be adjoined to general and to vertical faces.
- The topology of the representation is clear.
- The topology of a 2D-representation can be used.
- As the surface has no holes there is a topological mapping from the surface to a planar graph in $\mathbb{R}^2$ allowing to use all types of topological reasoning.

The following problems need to be investigated further and are part of our current research:

- Which type of real world objects can be represented? This needs to be stated explicitely in order to have guidelines for data acquisition. Moreover, it needs to be estimated which percentage of buildings actually can be represented in this form.
- How is the relation between the new representation and a classical map? Especially, under which conditions can a 2D-map be uniquely interpreted and translated into the new representation?
- How is the relation between topological reasoning in 2D and in the new representation?

5 Conclusions

The paper wanted to demonstrate the urgent need to develop tools for managing 3D-data in GISs. Both, acquisition and analysis techniques will increase their performance in the near future making the use of 3D-data more appealing. However, many applications will be manageable with 2D-GISs. Developing a smooth transition between 2D- and 3D-applications not only is an interesting research topic but seems to be necessary, in order to increase the acceptance acquiring and using the information about the third dimension of our data.

References

[Breunig *et al.* 1994] Breunig, Martin; Bode, Thomas; Cremers, A. B. (1994): Implementation of Elementary Geometric Database Operations for a 3D-GIS. In: *Proc. of the 6th International Symposium on Spatial Data Handling*, pages 604–617, 1994.

[Egenhofer *et al.* 1989] Egenhofer, Max J.; Frank, Andrew U.; Jackson, Jeffrey P. (1989): A Topological Data Model for Spatial Databases. In: Buchmann, A.; Günther, O.; Smith, T. R.; Wang, Y.-F. (Eds.), *Proc. of First Symposium SSD '89* Design and Implementation of Large Spatial Databases, pages 271–286. Springer LNCS 409, 1989.

[Egenhofer *et al.* 1994] Egenhofer, Max J.; Clementini, Eliseo; di Felice, Paolino (1994): Topological relations between regions with holes. *International Journal of Geographical Information Systems*, 8(2):129–142, 1994.

[Fritz 1995] Fritz, L. W. (1995): Recent Developments for Orbital Earth Observation in the United States. In: Fritsch, D. abd Hobbie, D. (Ed.), *Photogrammetric Week '95*, pages 75–83. Wichmann Verlag, Karlsruhe, 1995.

[Gruber *et al.* 1995] Gruber, M.; Pasko, M.; Leberl, F. (1995): Geometric Versus Texture Detail in 3D Models of Real World Buildings. In: A., Grün; O., Kübler; P., Agouris (Eds.), *Automatic Extraction of Man-Made Objects from Aerial and Space Images*, pages 189–198. Birkhäuser, 1995.

[Krzystek 1991] Krzystek, Peter (1991): Fully Automatic Measurement of Digital Elevation Models. In: *Proceedings of the 43rd Photogrammetric Week, Stuttgart*, pages 203–214, 1991.

[Lang and Schickler 1993] Lang, Felicitas; Schickler, Wolfgang (1993): Semiautomatische 3D-Gebäudeeerfassung aus digitalen Bildern. *ZPF*, 61(5):193–200, 1993.

[Lindenberger 1993] Lindenberger, J. (1993): *Laser-Profilmessungen zur topographischen Geländeaufnahme*, Band 400 der Reihe C. Deutsche Geodätische Kommission, München, 1993.

[Molenaar 1989] Molenaar, M. (jan 1989): Single Valued Vector Maps - A Concept in Geographic Information Systems. *GIS*, 1:18–26, jan 1989.

[Pilouk *et al.* 1994] Pilouk, Morakot; Tempfli, Klaus; Molenaar, Martien (1994): A Tetrahedron-based 3D Vector Data Model for Geoinformation. In: Molenaar, Martien; de Hoop, Sylvia (Eds.), *Advanced Geographic Data Modelling*, pages 129–140, Delft, 1994. Netherlands Geodetic Commission.

[Weidner and Förstner 1995] Weidner, Uwe; Förstner, Wolfgang (1995): Towards automatic building extraction from high-resolution digital elevation models. *ISPRS Journal of Photogrammetry and Remote Sensing*, 50(4):38–49, 1995.