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From Digital Elevation Model to Topographic Information System

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ABSTRACT

The term "Topographic Information System (TIS)" is defined in the first section as one of three categories of spatial information systems. In the second section, a new solution is outlined for the mathematical surface modelling of a digital elevation model (DEM), as a component of a TIS. In the third section, additional data (digital orthophotos, geo-coded satellite images, scanned topographic maps and three-dimensional vectors with numerous attributes) which serve to create a TIS from a DEM are discussed. Some thoughts on an object-oriented database model for a TIS are introduced in the last section. A "vertical" topology is introduced here, in addition to edge-node topology and surface-topology, and the inheritance of the numerous attributes in a TIS is discussed.

1. TERMINOLOGY

A new scientific discipline always has difficulties in its early stages with its terminology. Historically seen, one should begin here with the English name introduced in the middle 1960s, **Geographic Information System,** a name that was quickly taken over into German as *Geographisches Informationssystem*. In particular, geographers, town and regional planners, public-opinion researchers and others used this name as a comprehensive term covering the extensive field of **spatial information systems**.
A terminology is suggested in this Paper whose roots go back to the time when spatial information systems were still created and used exclusively by analogue techniques. The basic storage medium was then the (analogue) map. Modern spatial information systems, based on electronic data processing, also provide many cartographic products within their broad spectrum of products. The maps - whether produced by analogue or digital means - can be grouped in three categories:

a) **Cadastral maps, city maps and technical plans** (e.g. for public utilities). These maps are produced in scales from 1:500 to 1:5000.
b) **Topographic maps**, showing the ground surface with its features and objects, such as rivers, buildings and roads. Topographic maps have scales between about 1:2500 and 1:100000.
c) **Geographic maps and thematic maps**. The contents of these maps stem from a wide range of sources. Both types normally have scales of 1:100000 and smaller, though some thematic maps do have scales larger than 1:100000.

With this background of three different categories of maps in mind, we can also group modern spatial information systems in three categories:

a) **Land information systems** (LIS), which store the property cadastre digitally. The infrastructure of public utilities is frequently subsumed into an LIS. Land information systems have also been described for some time as **multi-purpose cadastres**.
b) **Topographic information systems** (TIS), which store the natural and artificial landscape in the form of digital models. These are not very closely detailed but, on the other hand, are not significantly generalised. A **digital elevation model** (DEM) is a component of a TIS.
c) **Geographic information systems**, which store the natural and artificial landscape, highly generalised, and also many other thematic contents. If a particular theme is predominant, the information system is often named after the theme, e.g. **Environmental Information System, Hydrographic Information System**, etc.

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A comprehensive name covering the common characteristics - particularly the theoretical basis - of all three categories is desirable. The term **Spatial Information Systems** - already much used - seems ideal for this purpose. In German usage, however, the term ***Geo-Informationssysteme (GISe)*** is favoured. In English, the term **Geographic Information Systems (GIS)** will probably remain as the overall name, although **Geo-Information Systems** is conceivable.

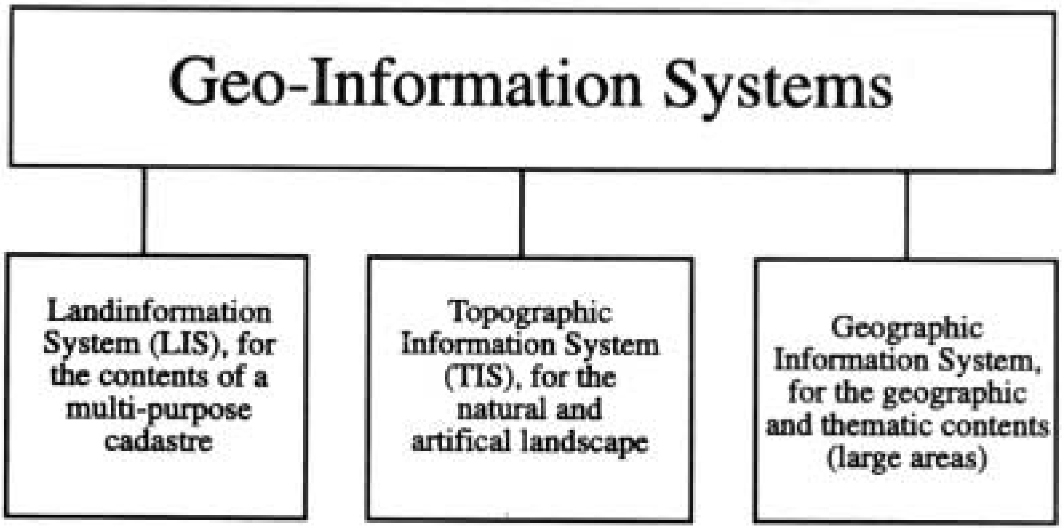

Figure 1: Geo-Information Systems and their three essential categories.

2. QUALITY IMPROVEMENTS IN DIGITAL ELEVATION MODELS (DEM)

In future, a DEM will be a component of a TIS. This new and important role of a DEM poses a challenge to improve the quality of the DEM, improvements that are discussed below.

2.1 Mathematical surface modelling

Three-dimensional digitisation, generally performed by photogrammetry for a TIS, yields individual points plus line data with which the surface is modelled mathematically. Figure 2 shows such a digitisation: it contains an artificial object, a building, while the natural topography is represented only by digitised points along break lines on the surface. From these digitised points and from knowledge of certain geometric properties of the digitised objects, we have to model:

- the artificial object by simple surface elements, planes in the example of Figure 2, and
- the breaklines by networks of lines composed of connected cubic polynomials.

Figure 3 shows the result. The mathematical foundations and the details of formation of the models can be found in the publication (Forkert, Halmer, Kager and Kraus, 1995). Here only the properties of the mathematical modelling are summarised:

- Extensive elimination of the accidental errors.
- Automated localisation and elimination of gross errors in the data.
- Automated reduction of large data sets in regions with very high point density.
- A consistent three-dimensional solution, i.e. the result is independent of the coordinate system.
- Overhangs can occur in the natural topography and the artificial topography can consist of very complex shapes.

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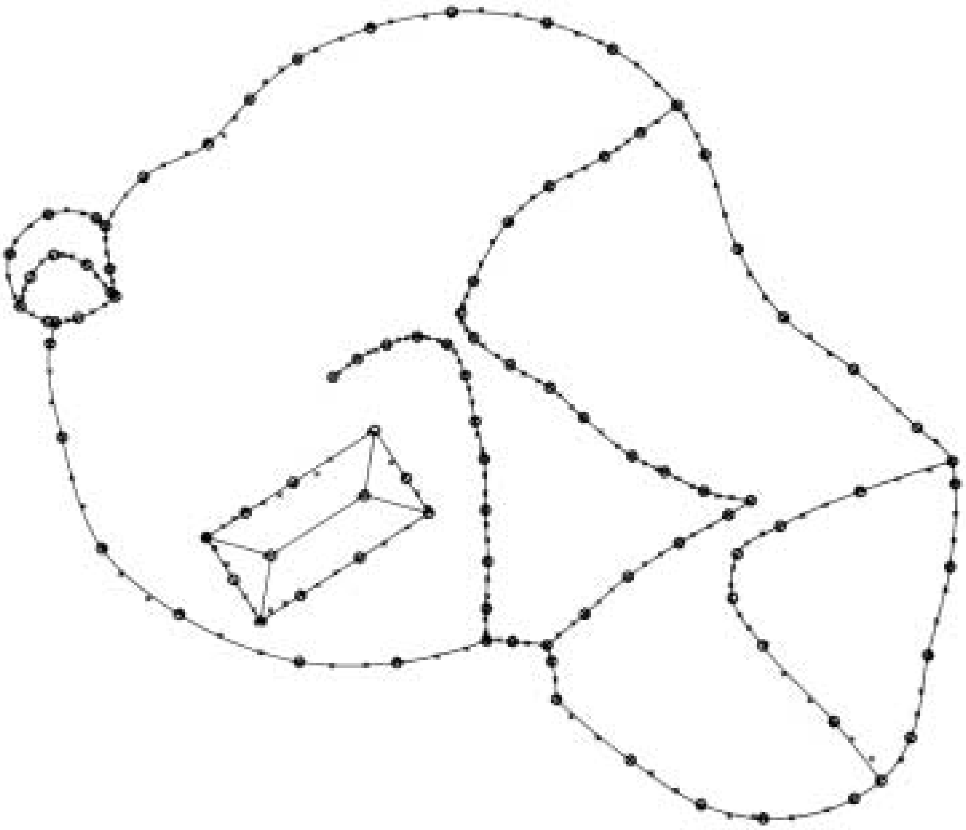

Figure 2: Digitised points (crosses) and adjusted line network (circles: nodes of the network and of the cubic polynomials of which the lines are composed).

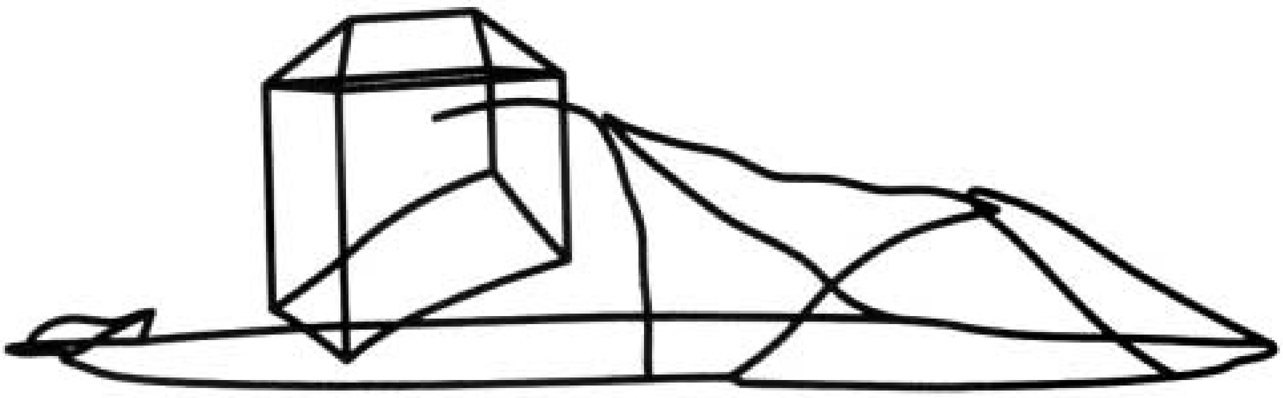

Figure 3: Wire-model of the adjusted line network; viewing angle, 4 gon.

The ground breaklines modelled in this way form an ideal preliminary for a high-quality surface model. The segments of the connected cubic polynomials are suitable as connecting lines for a spatial triangulation, in which the digitised points in smooth regions are incorporated. In a further step, the triangles, mostly bounded by curved lines, are filled by surfaces of higher order.

This method is presently being developed in a project (P09274-TEC) financed by the Austrian Science Foundation. It is a research and development project conducted jointly by staff of the Institute for Photogrammetry and Remote Sensing (I.P.R.S.) of the TU Vienna and Prof. H. Pottmann, Professor of Geometry in the TU Vienna.

The solution being studied will be based on a triangulation in which the relations between neighbouring regions are modelled by the fundamental topological elements: edges, triangles and tetrahedrons. A cubic or quartic Bézier surface is used for each triangle in the triangulation. The new solution, which is based upon the ideas discussed in the publication (Hoschek and Pottmann, 1995), has, inter alia, the following properties and possibilities:

- Unified modelling of the artificial and natural topography.
- Handling of very greatly differing point densities.
- Ability to differentiate between hard and soft breaklines.
- Incorporation of observed angles of slope (for example for hillocks and hollows).
- Use of the information contained in digitised contour lines.
- Efficient data structures for locally effective algorithms, particularly necessary for the maintenance of the data set.

2.2 Modelling the accuracy

A jump in quality of a DEM implies accuracy in addition to the high quality of the model formation. An independent modelling is to be preferred for accuracy. The accuracy begins with the standard deviation of the digitised points that are to be stored in addition to the points in the information system (Hochstöger, 1995), and then defines the accuracy of the results of the DEM according to the laws of error propagation. These results may be contour lines, lines of equal ground slope etc. Examples have already been published (Kraus, 1994). In a further publication (Kraus and Kager, 1994), a procedure is described for the determination of the accuracy of the intersection of DEM results with a polygon network, whose accuracy must also be modelled (Kraus and Haussteiner, 1993).

3. ADDITIONAL TOPOGRAPHIC DATA

A DEM is only one component of a TIS. In most countries, this component was created first, in very varying quality. Great efforts are being expended presently to establish the other components of a TIS as rapidly as possible. Some methods are presented below for the solution of this task of creating a complete TIS.

3.1 Digital orthophotos

The combination of a DEM and a digital orthophoto is already a simple TIS. The advantages of such a TIS (very low cost of production, high accuracy, objectivity etc) and the disadvantages (no interpretation of topographic objects, no differentiation between important and unimportant) are largely known from the comparison between a topographic map and an orthophoto-map.
Despite these known disadvantages, a combination of a DEM with digital orthophotos in a TIS often has much to recommend it. Geo-referenced satellite images, for example, can provide valuable service in the recording of short-period phenomena. Geo-referenced satellite images can also serve as a "tasty morsel" with which to begin the establishment of a country-wide TIS. One has to provide the suppliers of money with quick results in rapid sequence. Satellite images are available today in a wide range of scales, characterised by pixels varying from 2 m (KFA-3000) to 30 m (LANDSAT).
In the large scales, digital orthophotos are produced from aerial photographs, with pixels varying between 25 cm and 2 m. A DEM is needed for this rectification process, one which contains the artificial objects (bridges, buildings etc). Several teams are presently researching and developing solutions for the creation of digital orthophotos incorporating artificial objects. The solution realised by I.P.R.S. is described in the publication (Amhar and Ecker, 1995). The digital surface model - the name given to a DEM extended by artificial objects - for the production of digital orthophotos from aerial photographs need not satisfy the high demands that were formulated in Section 2.1.

3.2 Rasterised topographic maps

Very popular at present is the procedure of scanning the various colour separations of a topographic map (literature for Austria: Strenn and Zill, 1995). Such a TIS is particularly low in cost. One needs a DEM to make spectacular images; this DEM can be produced at very low cost by a raster-to-vector conversion of the scanned contour lines. The quality of this DEM is, however, very modest; it contains no breaklines and is more or less strongly generalised, depending on the map scale. It should be particularly noted that - as for digital orthophotos - the incorporation of descriptive attributes of topographic objects is only possible with great difficulty.

3.3 Two- and three-dimensional vectorisation of the topography

Two-dimensional vectorisation of scanned topographic maps is a relatively well developed, automatic process. It is therefore the cheapest method. Two-dimensional vectorisation can also be performed by means of digital orthophotos. Here, the degree of automation that can be achieved depends on the extent to which lines can be extracted from the digital orthophotos by digital image processing. This process is not yet sufficiently developed for practical use and therefore the vectors are often manually digitised on the monitor screen.
The desirable **three-dimensional vectorisation** lies in the domain of photogrammetry. It is very largely performed manually in analytical or digital stereo-restitution instruments. It is a relatively time-consuming process, but delivers the most valuable data sets.
The two- and three-dimensional vector data can well be expanded into a TIS with many attributes. The structure needed for a comprehensive topographic database is the subject of the following section.

4. TOPOGRAPHIC DATABASE

A widely used technique is layering. Each theme (rivers, roads, breaklines etc) is stored in its own independent layer. The data in a layer will in future be three-dimensional. The introduction of two-dimensional raster data will not be treated here (literature: Molenaar and Fritsch, 1991).
The independence of the layers usually leads to difficulties in overlays, since those points and lines which should be identical vary from layer to layer by the amount of their uncertainty. The individual layers must therefore be built up from a common geometric base. One needs, in addition to an edge-node topology and a surface topology, a **"vertical"** topology.
Such a consistent formation of objects is illustrated below by means of an example, which leans heavily on the publication (Pilouk and Kutouiyi, 1994) which in turn is based upon many publications referred to there.
Figure 4 shows the result of a typical three-dimensional photogrammetric data capture. (A curvilinear representation of the lines, as discussed in Section 2.1, has been dispensed with here.) The photogrammetric data have already been cleaned. (Such a three-dimensional cleaning of data was described by means of an example of the positional relationship between two straight lines in the Photogrammetric Week 1991 (Kraus, 1991).) After such a cleaning of the data, both the geometry of the lines and the assignment of attributes are free from inconsistencies. Thus, for example, traffic routes (Figure 5), rivers (Figure 6) and breaklines (Figure 7) can be extracted. The vertical topology mentioned above can be demonstrated in the line d: this line, with the identifier d, belongs both to the theme "rivers" and to the theme "breaklines".
The results of such object formation are, on the one hand, geometric lines free from inconsistencies, and, on the other hand, the decomposition of individual lines into line-pieces, each with the same attributes.

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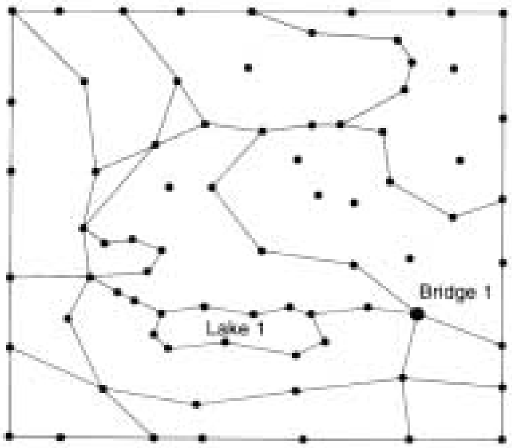

Figure 4: Lines and points captured by photogrammetry.

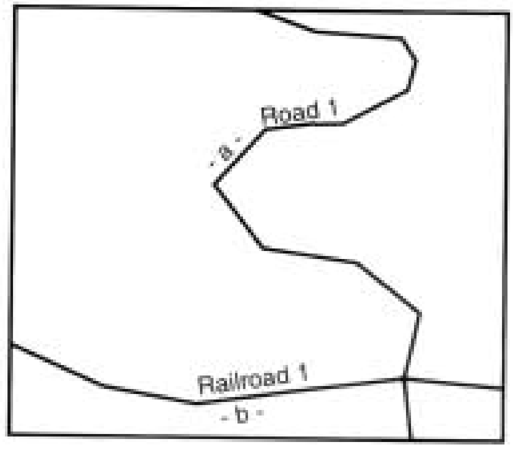

Figure 5: Traffic routes.

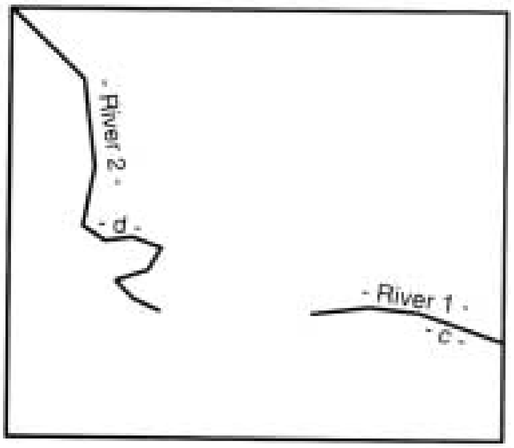

Figure 6: Water lines.

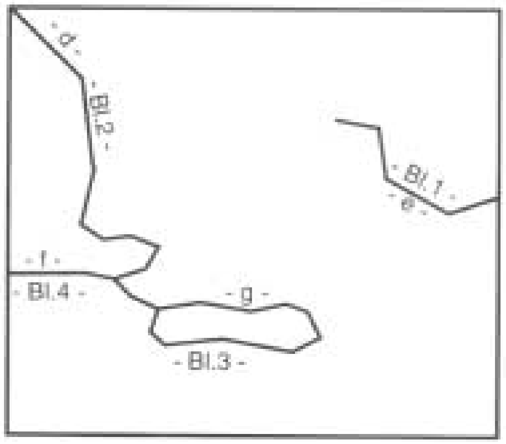

Figure 7: Breaklines.

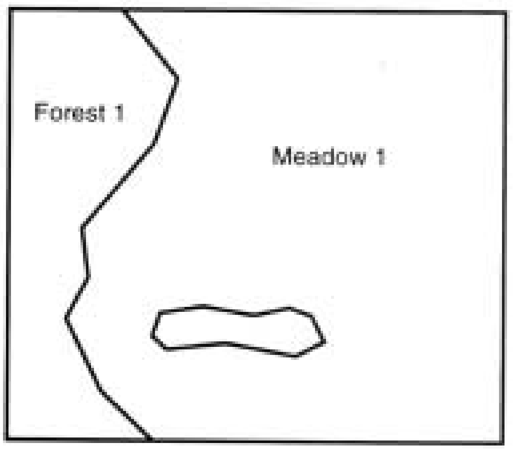

Figure 8: Land use.

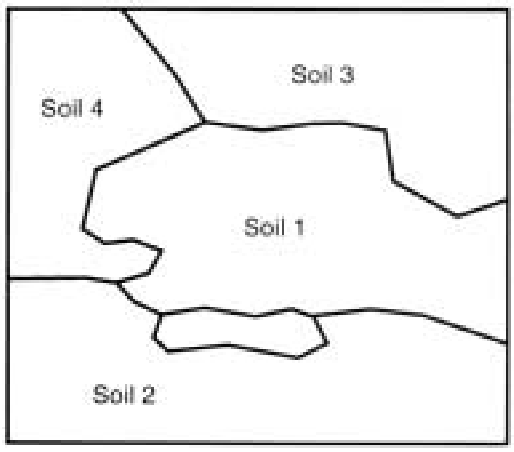

Figure 9: Soil types.

Surfaces are treated in a similar manner by formation of surface-pieces all with the same attributes, a process illustrated in Figures 8 and 9. The land use (Figure 8) is to be extracted from the cleaned photogrammetric data (Figure 4). Another theme, soil type (Figure 9), stems from another source, namely a soil map. An overlay of the land use (Figure 8) with the soil type (Figure 9) will then yield:

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- Firstly, possible geometric inconsistencies along obviously identical lines, inconsistencies which must be removed, preferably by an appropriate specialist.
- Secondly, the smallest areas (identifiers A, B etc in Figure 10) which have the same attributes.

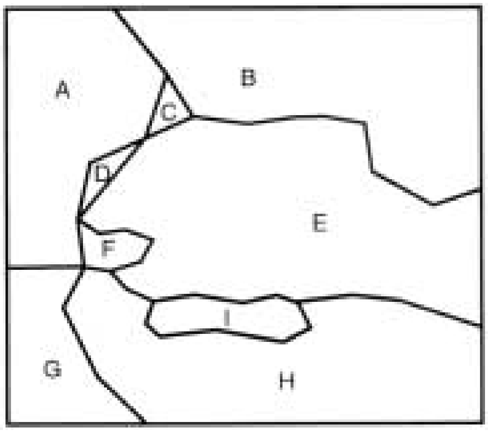

Figure 10: Overlay of land use and soil types.

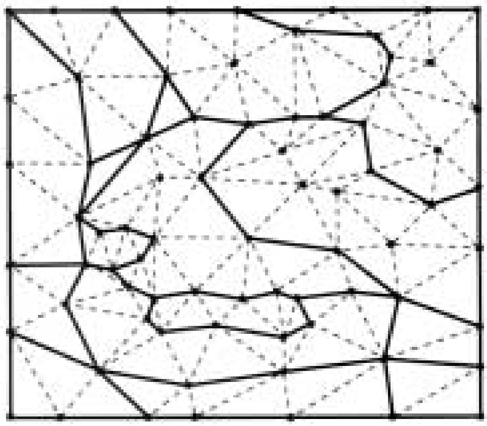

Figure 11: Ground surface.

Whenever a new thematic layer is introduced into the TIS, the procedures described above for the lines and surfaces must be repeated. Only in this way can one obtain data in the database in a state that the user expects when he poses his queries to the TIS.

In the discussion so far, the question of **the introduction of a DEM** into this complex formation of objects has remained open. Earlier, the Author (Kraus, 1991) - together with others - was of the opinion that it was too laborious and too complicated to integrate a DEM into an only one database and that separate databases with appropriate interfaces would be better. The object-oriented concept favoured today forbids the idea of a special treatment of a DEM in its own database, however. A full integration of a DEM in a TIS is hinted at in Figure 11. In the smallest partial surfaces A, B etc of Figure 10, a surface topology of spatial triangles is built up with the help of ground points that define the smooth ground surface (Figure 4). These triangles are not only the elementary units for the smallest areas A, B etc of Figure 10, but also the framework for the mathematical surface modelling referred to in Section 2.1.

The complete **database model** for the modern TIS suggested here is illustrated in Figure 12. The three coordinates X, Y and Z of each point are stored without redundancy in a file. They form the metric framework for the edge-node topology and for the triangle topology. There are no theme-related attributes in this lowest level in Figure 12. Such attributes are only introduced in the level defined by areas (A, B etc), lines (a, b, c, d, etc) and points (Bridge 1). In the object-oriented concept, the possible **inheritance of attributes** is achieved by introducing area classes (forests, meadows, lakes, soil types etc), line classes (roads, railways, rivers, breaklines etc) and point classes (bridges etc), together with super-classes (water, traffic routes etc) (Molenaar, 1993).

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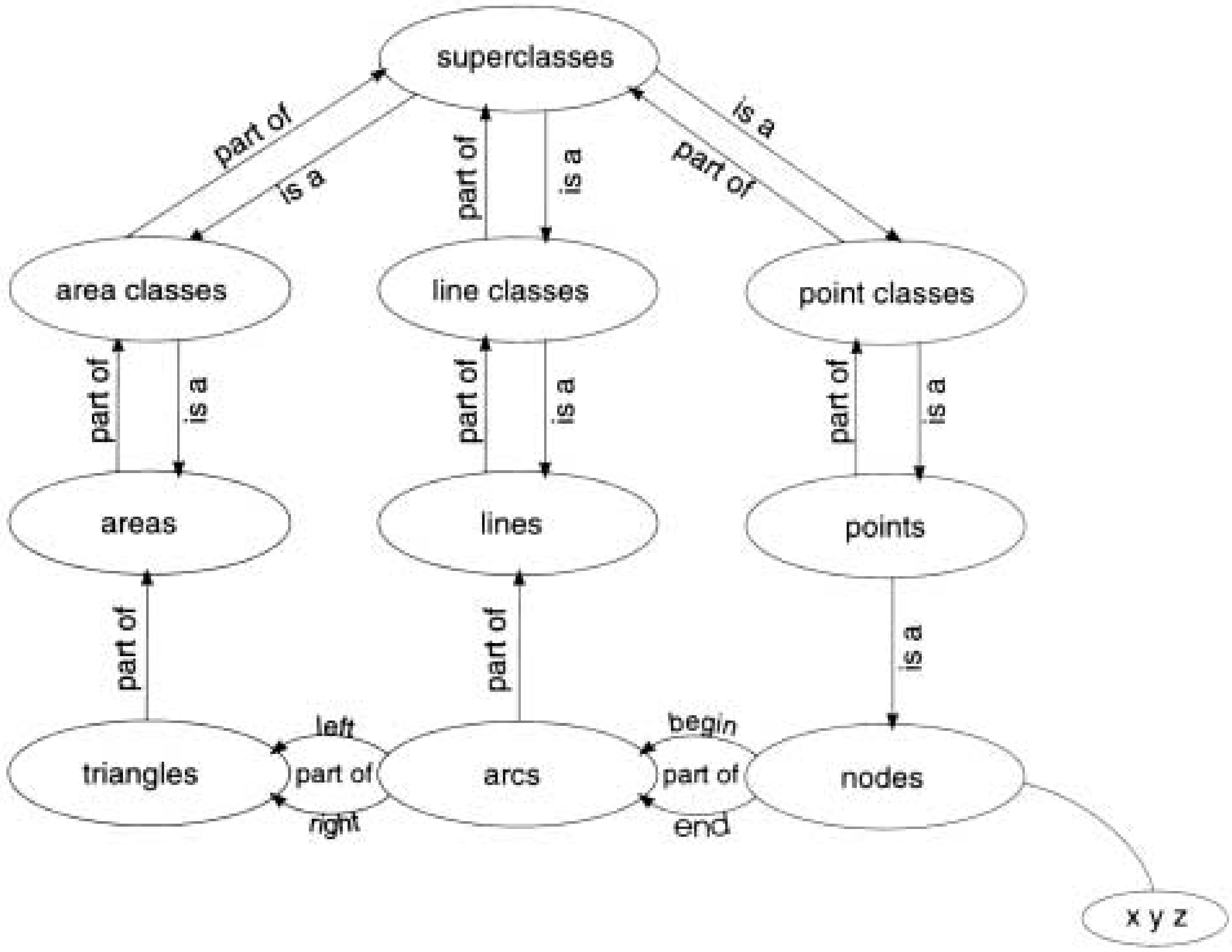

Figure 12: Database model for a complex TIS.

5. CONCLUSIONS

A DEM in a TIS should:

- have a high geometric quality, and
- represent the accuracy permanently.

Data that create a TIS from a DEM can stem from:

- digital orthophotos
- geo-coded satellite images
- scanned topographic maps in various scales
- three-dimensional (photogrammetric) vector data with numerous attributes.

A topographic database should be object-oriented rather than organised on the layer principle (vertical topology, inheritance of attributes).
The great effort required to establish a TIS is only justified if the information it contains can be used for many different purposes.

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