GEOGRAPHICAL INFORMATION SYSTEMS
STATE OF THE ART AND FUTURE TRENDS

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Commission VI , Working Group 3

KEY WORDS: Geographical Information Systems

ABSTRACT:

Today, the majority of surveying engineers are concerned with Geographical Information Systems (GIS) in one way or the other. The GIS technology is evolving rapidly and its development is likely to occupy the surveying community for several decades. This article summarises the current status, outlines development trends and perspectives and demonstrates the interaction of different GIS components.

KURZFASSUNG:

Geo-Informationssysteme (GIS) beschäftigen heute die Mehrheit der Vermessungsingenieure. Die GIS-Technologie befindet sich in voller Entwicklung; mit ihrem Fortschritt wird man sich mehrere Jahrzehnte lang weiter beschäftigen. Der Stand der Technik, die Entwicklungsperspektiven und die Wechselwirkung der Komponenten bilden das Thema des vorliegenden Beitrags.

1. INTRODUCTION

Geographical Information Systems (GIS) are becoming increasingly important in our information-based society. In Europe, GIS technology is recognised as a future-oriented business sector which is in a state of rapid development but which is also in need of long-term investment. The establishment of conditions which encourage the creation and exploitation of such systems is acknowledged to be part of the business of government. The European Commission supports efforts aimed at standardisation in the GIS field, in order to avoid the wide variety of requirements resulting in an unlimited number of incompatible solutions. All European countries are currently establishing their own GIS at a variety of levels of generalisation which will then provide the basis for all kinds of specialised developments.

Geographical information management (for which the word "Geomatics" is becoming increasingly accepted in English-speaking countries as well as in its French and German guises of "géomatique", "Geomatik" and "Geoinformatik") has become an independent discipline which represents not only a challenge to all of the geodetic and spatial information sciences but also the true future opportunity for all of the surveying and mapping professions.

2. CONCRETE AND ABSTRACT COMPONENTS OF GIS

Geographical Information Systems consist of technical, procedural and organisational components. The progress of GIStechnology does not depend solely on research in information technology. It is also influenced by the state of the necessary information sources, by innovations in data capture methods in both surveying and cartography, by the needs of users, by the available hardware tools, and by existing legal and organisational structures. An overall view which takes in all of these aspects is necessary in order to understand why some research results do not bear fruit while others rapidly achieve positive results.

The main concrete and abstract components of a GIS are shown in the diagram which follows.

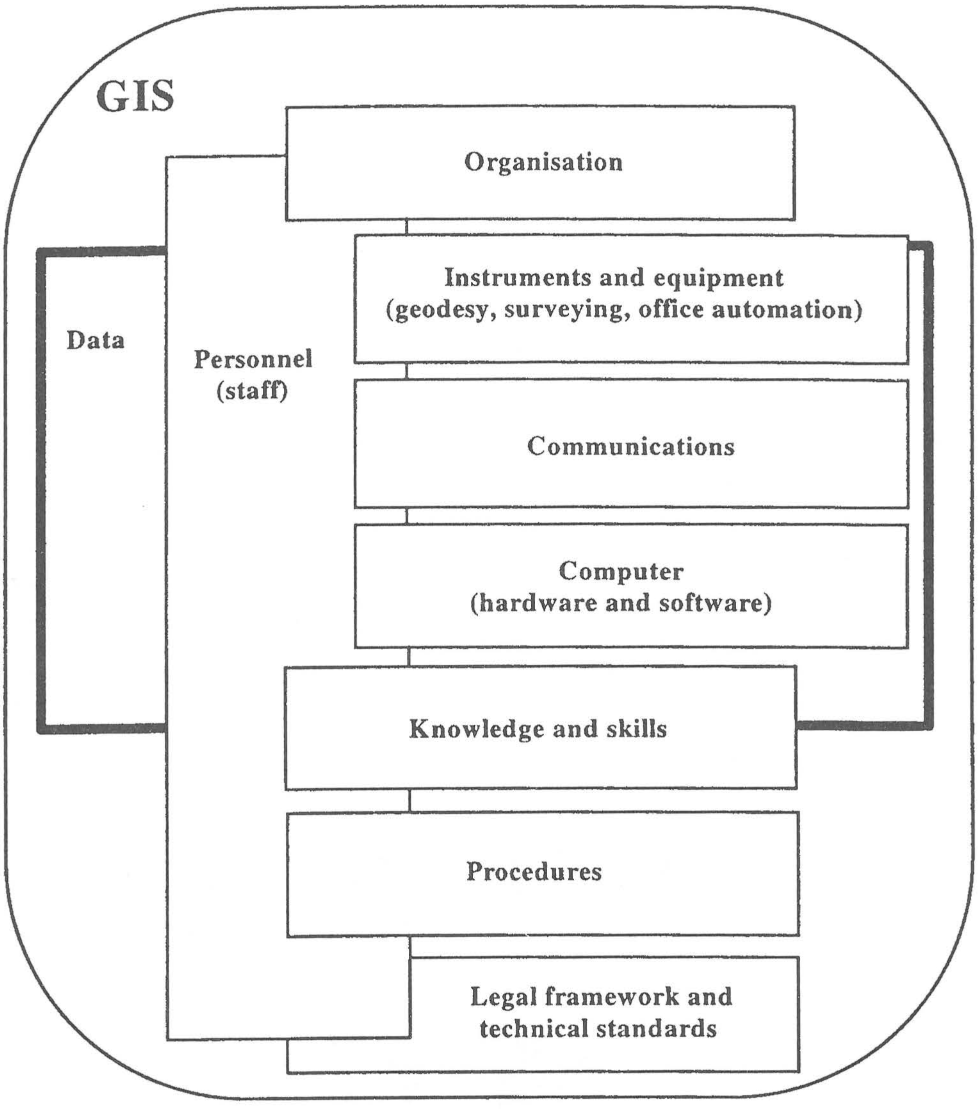

Fig. 1 Concrete and abstract components of a Geographical Information System

The largest part of the investment required for the establishment of a GIS is devoted to the capture and structuring of the spatial and semantic information. Data update subsequently consumes a major portion of the ongoing operating costs. A comprehensive analysis of the problems of acquisition, manipulation and representation of the spatially-referenced data forms the foundation of every GIS project /Bartelme 1995/.

A GIS is a global logical concept in which an organisation involves both its technical and administrative staff, makes use of all of its instrumentation and equipment together with appropriate working methods, knowledge and skills in order to capture, process, manage, analyse and deliver spatial information.

The legal and organisational framework plays as important a role as the skills and qualifications of the staff and he performance of the hardware and software of the GIS.

National GIS such as the Swiss cadastre or the German official topographic and cartographic information system (ATKIS) are often established through networks of independent units which use a variety of different hardware and software systems. In consequence, it is necessary to impose technical standards or legal requirements which directly or indirectly define the minimum information content and standardise the communication protocols.

The procurement of the computer system (both hardware and software) represents only a small part of the establishment of a GIS. However the information technology component exerts a strong influence over technology and methods in the field of GIS.

The following discussion focuses attention on the information technology aspects of GIS. It should be noted that these form only a part of such systems. They should be viewed in relation to all of the other organisational and technical components outlined earlier, including both surveying methods and office automation which do also influence information system structures.

3. COMPUTER ARCHITECTURE OF GIS

Geographical Information Systems have developed in parallel with progress in computer science. They have driven computer science developments and have provided a force for the integration of disparate parts of the information technology field. Developments in databases, computer graphics, ever more powerful processors, the variety of peripheral equipment and the powerful GIS software available today have all fuelled the great growth which we have seen in recent years.

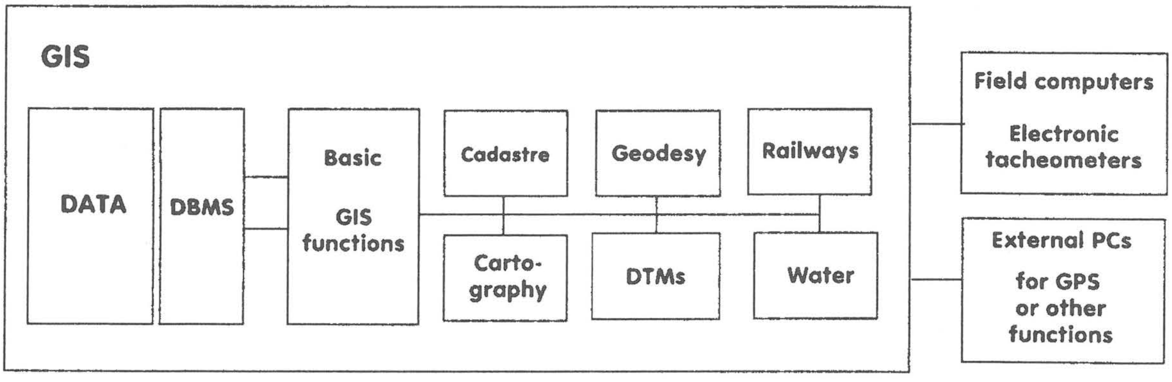

Fig. 2 Hardware and software components of a GIS

4. HARDWARE AND OPERATING SYSTEMS

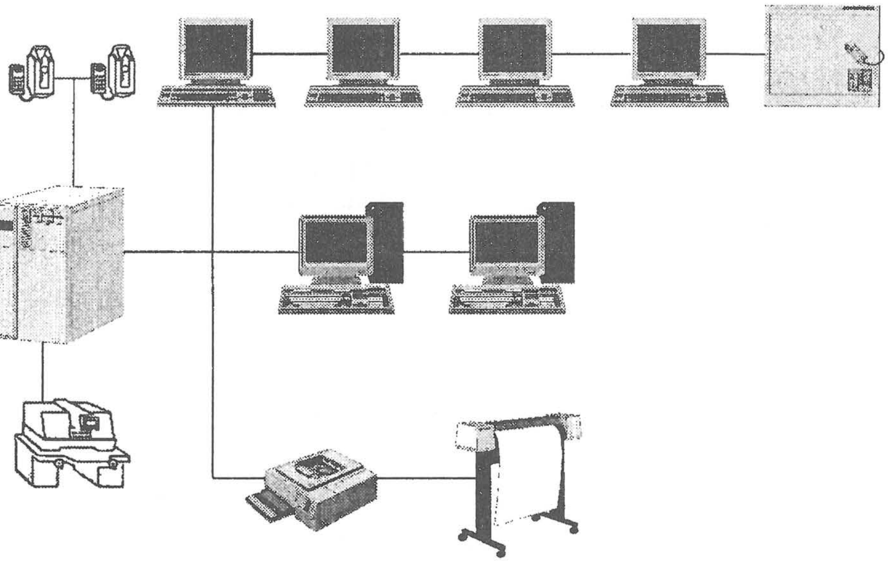

Fig. 3 Hardware of a GIS

4.1 Workstations and processors

A GIS is normally equipped with several workstations at which the operators run the system by carrying out operations and visualising relevant information.

The computing needs are generally satisfied today by powerful networked workstations.The data, common to the whole system, are held on a server with large memory capacity on magnetic discs.

We are now also seeing more and more systems with one or more high performance servers linked to graphics terminals (X-Terminals or PCs with X-Terminal emulation).This modern solution has the advantage of greatly reducing the system administration overheads.

RISC-based processors dominate the market for workstations and servers for GIS. In large systems, several processors may run in parallel.

The power of PCs has also greatly increased in recent times, so there are now increasing numbers of GIS solutions which use PCs rather than workstations; indeed the distinction between PCs and workstations is becoming blurred.

4.2 Operating systems

As most GIS software is implemented on processors with RISC architecture, it follows that UNIX is the usual operating system for GIS at present. However, a proprietary operating system, such as VMS from DEC or BS2000 from Siemens, is of course used where the hardware requires it.

The use of Windows or Windows 95 has not been possible up to now. The increasing performance of PCs, and the spread of Windows NT to other very powerful processors such as DEC's Alpha series or the RS6000 from IBM, show that Windows NT could become the preferred operating system for GIS in the future. Some vendors, including Intergraph, already offer their GIS software on Windows NT platforms.

4.3 Data storage

The manipulation of spatial data demands the long-term storage of large quantities of data as well as rapid access. Magnetic discs are still the most powerful solution for data volumes of the order of 20 to 50 gigabytes (Gb). For the organisation of even larger archives (of the order of terabytes) interchangeable magneto-optical discs may be used. These are slower than magnetic discs, but they can be loaded either manually when required or automatically by means of a jukebox.

For archiving or for security backups, high capacity magnetic tape cassettes (such as Video 8 or digital audio tapes DAT as found in consumer electronics) may be used. These allow the storage of some 2 to 5 Gb per cassette. Larger quantities of data require larger, specialised magnetic tapes with capacities of 20 to 40 Gb.

4.4 Data capture

A great variety of techniques is used in the acquisition of spatial data. Modern geodetic instruments such as GPS receivers and total stations (electronic tacheometers) are periodically downloaded in the office in order to supply the data captured in the field to the GIS.

In photogrammetry today, analytical plotters or fully digital photogrammetric workstations are used and are connected to GIS directly or indirectly.

Digitizing tablets are the classical tools for the conversion of graphics (topographic maps and plans) into digital data. For major digitizing tasks such as whole series of maps, today's preference is for capture by means of a scanner followed by interactive interpretation and coding of the desired detail on the screen. Automated interpretation and analysis of the raster image is also possible to a limited extent and the necessary techniques are being improved. However this is only really suitable for large projects.

4.5 Data output

The graphic output of data remains the most important form of communication between the GIS and the user, even though the demand for digital data for subsequent processing has grown exponentially in recent years.

Interactive work at the graphics screen demands good resolution and rapid computation of cartographic data. Terminals currently in use have changed little over a long period, with colour screens and typical resolutions of 1024 x 1280 pixels. Major modifications are not expected for normal applications in the near future. The price of large screens (20 inch) has fallen, and higher refresh rates provide flicker-free images and hence less tiring viewing.

Output on paper is still required. A choice of colours is indispensable. An important recent development is the ink-jet printer which can now produce large format plans with a good resolution of the order of 400 dpi (16 lines/mm). The most widespread and reasonably priced printers use four basic colours in all reasonable combinations, thereby effectively generating at least eight different colours. Other colours are obtained by a suitable arrangement of the eight colours in a close group of pixels with a significant loss of resolution.

These new techniques have largely replaced pen plotters, electrostatic plotters and thermal transfer plotters, although such equipment continues to satisfy some specific and limited requirements.

Ink jet technology is also used in extremely high quality large format plotters such as those from Iris and Storch. They use an advanced control unit to print the four basic colours with variable intensity (up to 32 levels). This allows a huge variety of colours to be selected. The price of these large format plotters is very high at around $200 000.

Laser printers (black up to A0 and colour up to A3 format only) also offer competitive price and performance.

5. SOFTWARE COMPONENTS OF A GIS

A geographical information system consists of a variety of software modules which provide basic functionality, data management and special functions for particular applications.

5.1 Basic functions

The **user interface** controls communication between the operator and the GIS. In the past, operators used menus on the screen or on a digitising tablet, hardware buttons, or the keyboard. Following today's trends in computing, software is now making use of graphical user interface solutions which are well-known through their wide availability in products such as MS Word, Excel, etc. Thus dialogue boxes allow the selection of principal functions through toolbars and pop-up menus, while buttons and slide switches also allow parameters to be varied. All of this is managed with the help of the mouse or by single keystrokes. This major means of interaction is supplemented by keyboard commands as necessary. The user can also define new functions (known as macros) by means of chains of existing commands, and thus greatly increase the power of the interaction. The efficiency of the work is greatly influenced by the effectiveness of the user interface.

Additions, modifications and **deletions** of geometric and thematic data are the main operations for the update of an information system. These must also include those checks on integrity or consistency which cannot be carried out by the database management system itself. A wide choice of geometric operations is provide to allow the construction and calculation of object geometry.

Queries, analyses and **visualisations** are the basic operations in the use of geographic information. The results of queries are often lists of textual information, such as tabulations of objects with their attributes. This requires tools for the free definition of such tables. However in most cases the result is a combination of geometric and thematic information which is best represented graphically. Thus tools which allow the definition of graphic representations in response to specific needs are also among the basic functions of a GIS. The initial definition of the graphic output should take place in parallel with the introduction of the data structure to the database. Already at this stage several different forms of representation may be called for, depending on the scale and application. But later on also, while using the system, graphic functions are needed to enable the operator to visualise objects and their attributes in a way which suits the required output (whether on screen or in the form of a hard copy on paper or film, for example), as well as the scale and the application. Today, many systems still bind the form of output to the database structure. The modern trend is diametrically opposed to this; the complete separation of data structure and data representation is intended to allow the same data to be used in all manner of different applications.

5.2 Data management systems

The management of data in a GIS, which allows information to be structured in accordance with project needs, follows well known and fundamental database concepts. GIS software has been designed in accordance with the same principles so that it can be used in a variety of application fields. The necessary information is fixed at the planning stage and the corresponding data structure can then be defined in the conceptual model. This is then implemented in the system's logical model. This allows the stored data to be manipulated over a long period, and queried and analysed as required.

Spatial data have certain features which make it difficult to realise in practice the solution outlined above. The following obstacles must be overcome:

- Each query demands a search through a large number of geometric elements
- The search criteria are primarily spatial and may be in two or three dimensions
- The consistency rules are complex

These problems are resolved in most cases by a combination of local memory, managed directly by the GIS software, together with the database itself. The local memory is used mainly to allow storage and access to the geometric data at sufficient speed to allow interactive work on the screen. The database itself serves for the long term management of the information and for thematic queries and analysis, for example of property ownership, pipe diameter, parcel number, land use, etc. Most GIS today are based on this architecture and use a relational database management system.

The individual components of the data management system and the working procedures can vary greatly between different GIS software.

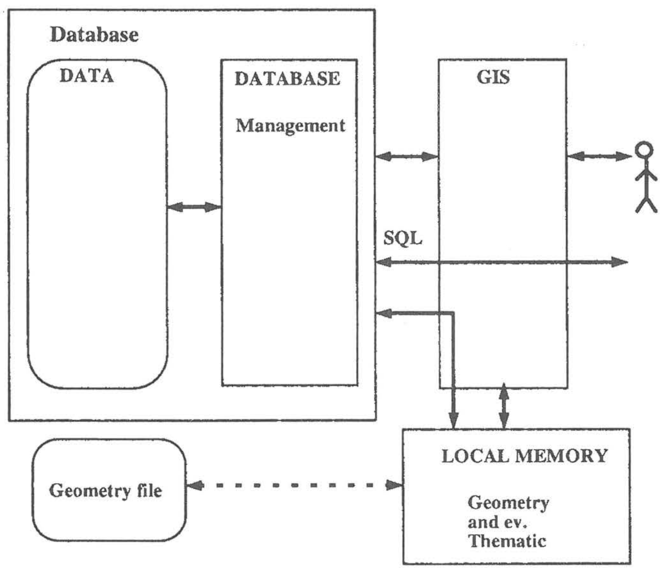

Fig. 4 Software and data management in a GIS

Some systems also use local memory for long term management of geometric data. The data may remain unstructured in a simple file instead of being structured for storage in the relational database. This results in two separate data management processes, for thematic data and for geometric data.

Other systems copy the data for the area of interest into local memory before work begins. This allows very rapid access to the data in the course of the work. At the end of the task, the new state of the information is transferred back into the relational database. The geometric data may be structured and manipulated in discrete objects with attributes inside the database, or it may be stored in the database in blocks without prior structuring.

Very few systems operate directly on the contents of the database itself in the course of the work. For this it is necessary to have a specialised database management system (DBMS) with a modified kernel giving very rapid access to spatial (multidimensional) data.

Current GIS allow the user to define freely the data to be manipulated (objects, attributes and relations), although they do not allow data-specific operations to be defined. Such operations are programmed in the base modules of the GIS software. Thematic or semantic data, which are usually only stored or interrogated, may be structured at the beginning in accordance with the requirement, or if necessary may be finalized later. Geometric data, on the other hand, which require specific operations (for example intersections, constructions, area calculations, etc.) currently have a rigid structure which is fixed by the software producer and cannot be adapted in response to new needs. Only object-oriented DBMS allow the definition of completely new objects with their operations. This solution leads to a heavy extra workload when the data come to be structured. It is thus unlikely that all of the capabilities of object-oriented databases will be exploited in GIS.

Current database research is concentrated on the following problems:

- Management systems with modified kernel
- Models with structured attributes (NF2 models)
- Object oriented databases
- Extensible databases

These new database concepts have so far had only slight influence on practical activities. However they may well contribute to the spatial data management systems of the future.

Relational databases have continued to be developed as universal tools. Their performance has also increased considerably and the range of applicable types of data has expanded, for example to include spatial data. They fulfil the requirements of GIS increasingly well (for example for speed of access), and their combination with a local memory may eventually become unnecessary.

Object-oriented databases abandon the relational model's concept of information primitives, to work with objects at all levels of complexity. Objects are not defined only by their data structure (including their relations), but also by all possible operations upon them, which may be freely programmed. One thus achieves unlimited freedom in the definition of types of geographic data, including their consistency conditions. The great disadvantage of object-oriented models is the work needed to define the objects. Their flexibility is paid for by the costs of project planning and implementation. These costs are both high and difficult to estimate.

A third possibility is offered by **databases with structured attributes** (NF2 models). This form of database uses a relational model in which the attributes are not information primitives but may themselves have unlimited complexity. This allows hierarchies of data to be created which may be interrogated collectively. Two examples are the management of large amounts of raster data or of three-dimensional objects.

The fourth approach to be discussed here uses the **extensible database model** /Schek, Wolf, 1992/. The idea is to extend the functionality of a relational database with operations which may be very complex, by including the necessary interfaces and commands in the database management system while the operations themselves remain as external programs outside the database. Such operations may include compression and decompression of image data, interpolations for surface models, and computations of geometric attributes such as areas or volumes.

New types of database such as the **object-relational model** combine the logical structure of relational models with the flexibility provided by object orientation. These solutions, which offer the possibility of the free definition of new types of abstract data together with their relevant operations, are now being developed within the framework of SQL3 standards /Mitschang, Jaedicke, 1996/.

5.3 Form and structure of data

Thematic information can be easily represented in the form of relational tables which can be viewed as simple thematic objects. Groups of simple objects can define complex objects, which in turn possess attributes and relations with other objects. Depending on the GIS software in question, complex objects may be defined either as networks or hierarchically.

Geometric data, on the other hand, is separated into metric and topological components, which may also be manipulated in the form of relational tables.

Other categories of data are also used increasingly in GIS. These may include:

- Image data in georeferenced raster form (for example orthophotos)
- Cartographic raster data (pixel maps)
- Digital terrain models (DTMs) (with regular grid or otherwise)
- Multimedia information

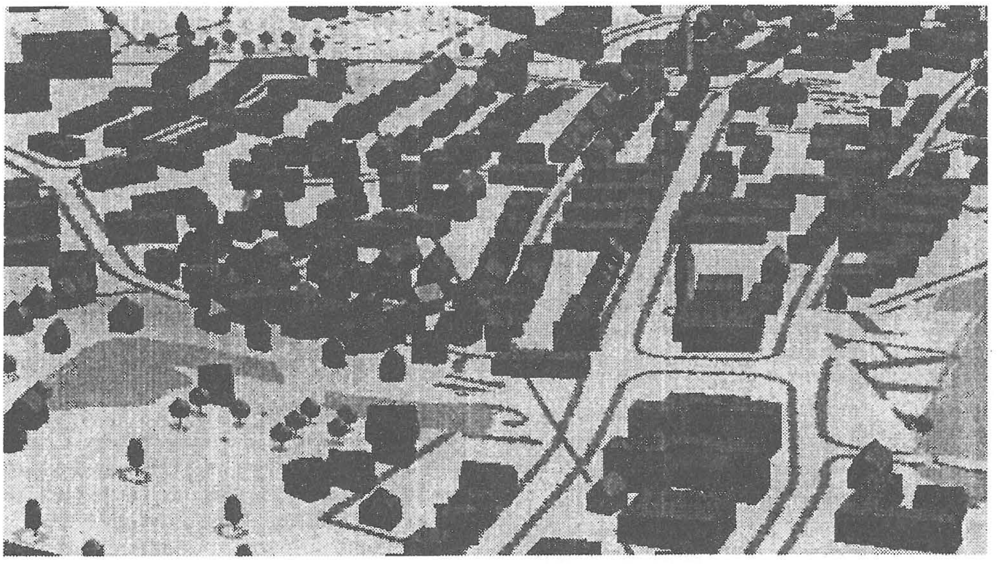

Fig. 5 Combination of planimetry, DTM and three-dimensional objects

At present these non-standard data are managed by specialised programs which store them in ordinary files. Database research is addressing this problem and it will be interesting to see whether improved relational models or other new data management mechanisms are eventually adopted.

The extension of geometric data to the third dimension is increasingly in demand /Carosio, Zanini, 1996/. The current trend uses a combination of different structures:

- current GIS models (with topological and metric elements) for planimetry
- regular or irregular grid DTMs for the altimetric component of the landscape
- either simple 3-D geometric figures (volumes) or CAD models for truly three-dimensional objects such as buildungs, industrial plant and trees /Carosio 1995/

A further development is to be found in the domain of multimedia. Geometric or thematic data may be supplemented by audio (words, music or other sounds) or video sequences, or by photographic or synthetic images, all of which must also be georeferenced. Data structures are based on current standards for these types of data (TIFF, GIF, PostScript, etc.). Animations (which may include changes of geometry or thematic content) and simulations also offer interesting possibilities.

6. COMMUNICATION

Information systems can only serve their purpose if they are easily accessible to a large number of users. Thcommunications are of fundamental importance. At present it is only straightforward to exchange structured and complete data between systems with the same software and data structure. Otherwise the laborious task of writing conversion programs is required. This has also been necessary when a computer system was changed or perhaps even upgraded.

To facilitate **data transfers** one may consider applying technical standards to exchange formats. This is possible, but only if the content of the data to be transferred is known in advance. Such a solution is thus suitable for the activities of highly centralised organisations or very specific applications (for example NATO's DIGEST exchange format).

If the information content itself may vary and if exchange is required between systems with different data structures, **model-based** data transfer is preferable. This type of exchange uses two basic components: a data description language used to describe the structure of the data to be transferred, and a set of rules which allow the exchange format to be derived from the description of the data.

A transfer file contains the data description, followed by the data to be transferred in the format derived from the description.

Following this principle, the European Standards Committee (CEN) is preparing standards for data exchange between GIS. Technical Committee TC287 has selected the EXPRESS data description languag and is now working intensively on the transfer standard.

On the global level, the International Standards Organisation (ISO) is moving in the same direction and has set up TC211 to work on the problem.

For the Swiss Cadastre the INTERLIS data description language was defined several years ago, and the rules for deriving formats were generated by means of a compiler /Gnägi 1995/.

7. QUALITY MANAGEMENT AND QUALITY CRITERIA

The data form the foundation of an information system, and represent a very considerable investment. The quality of the data must satisfy the needs of the applications envisaged, and indeed determines how useful the system will be. To define the concept of quality and to formulate quality requirements for geographic information is difficult because of its complexity /Giordano, Veregin 1994/.

Full solutions for quality management are found in the ISO 9000 series of standards, by which the quality management of production processes, engineering services, etc. can be guaranteed. The methodology used by these standards prescribes checks and documentation of every stage of the process of production or the provision of the service, and independent management responsibility for the monitoring of conformance and assessment of risks. It is the organisation producing the product or providing the service, not the product or service itself, which is assessed and checked by a third party. This form of quality assurance is important in the geographic information field today. In Switzerland several engineering firms active in GIS have already received ISO 9001 certification.

Much more difficult is the formulation of objective criteria by which one can directly describe the quality of data in a GIS. The following are examples of aspects of GIS quality which may be used:

- **Origin of the data**
  Primary and secondary sources
  Data capture processes (methods and instruments used)
  Reliability of capture procedures
  Organisation responsible
- **Data characteristics**
  Description of data characteristics (metadata)
  Description of data structure (entities and attributes)
  Accuracy (checks done, samples taken, precision of metric data)
  Consistency (status and checking methods)
  Content (complete or incomplete)
  Validity (planned, actual, under construction, historic, etc.)
  Generalisation and scale
  Area covered
- **Maintenance of data**
  Currency
  Update procedure
- **Availability of data**
  Methods of access to the information system
  Measures for the protection of the integrity of data
  Copyright regulations, conditions of supply, licensing and pricing

Information about data (metadata) is assuming ever-increasing importance. The description of quality is an important part of this. Successful standardisation in this field is highly desirable.

8. ANALYSIS OF DATA AND APPLICATIONS

The large investments needed to establish geographic information systems can be justified only if the information and services provided meet the needs of customers in the marketplace. However it is difficult to determine systematically all the possible applications or opportunities for analysis using GIS. GIS technology may be applied successfully in extremely diverse fields and disciplines, and each has its own methodologies and requirements. This paper does not attempt to analyse all of these possibilities.

However it is important to recognise that the development of GIS has been based on the needs and problems of users.

9. CONCLUSIONS AND PROSPECTS

Modern information science offers the geographic and geodetic professions the powerful tools which they require in order to meet the spatial information needs of all of society today.

Geographical information systems are much more than a sophisticated computer system. They are a combination of software engineering, database technology, paradigms for user interaction and powerful computer hardware. But they also depend on the price of the components, on the qualifications and skills of the specialists, on the legal framework concerning dissemination and use of the information, on data capture methods and on many other factors.

The success which we are seeking can become reality only if the necessary progress is made in parallel in all of the areas mentioned. If these conditions are satisfied, the challenge of spatially-referenced information systems will become the opportunity of the future, for all of the professions which are jointed together under the new term "Geomatics".

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