GEO-INFORMATION THEORY: WHY AND WHAT

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Commission number III Working Group I

ABSTRACT

Decision-makers depending on geo-information are often confronted with too many data. The problem is then how to extract relevant information on how to eliminate the relevant data. The problem is then how to extract relevant information and how to eliminate irrelevant data. Selection, generalisation and aggregation of data in a given context (decision framework) are the tools that need to be understood by the user in order to have faith in the resulting decisions. The paper argues that this is not possible without a consistent theory on geo-information. This theory describes the structural and semantic aspects of geo-information including aspects of uncertainty. The theory gives a framework for the development of methods and techniques for data modelling, for data processing and for dealing with uncertainty of geo-data.

KEY WORDS: Geo-information theory, Information technology strategy, data modelling.

INTRODUCTION

After the Kyoto Congress of ISPRS in 1988 the President of Commission III decided to establish a working group on geo-information theory.
This decision was based on resolution No III-1, of this congress stating in its recommendation that:

1. Studies be directed towards the theoretical aspects of GIS, including data structure, knowledge representation and mathematical modelling.
2. The spread of knowledge of this field is stimulated by organizing courses and the production of lecturing materials and tutorial papers in cooperation with Commission VI.

The technical development of GIS happened in its first stages without a clear theoretical frame work, and even to date we observe that the existence of such a theory is hardly a pre-requisite for a further technological progress. On the other hand organisations dealing with geo-information seem to have tremendous problems when they try to make efficient use of the opportunities offered by this new technology. The introduction of modern GIS tools in these organisations seem to be not only a technical problem, it often effects the whole organisation in different ways. The management will have to make important policy decisions. A geo-information theory will be useful to obtain a deeper understanding of GIS technology and its possibilities. But such a theory will not only be of importance for the management. On an operational level it will be useful for experts as a framework for the formulation geo-data models and processing models. The following sections of this paper will elaborate on these

MANAGEMENT PERSPECTIVE

There is growing and compelling evidence that implementing information technology (IT) of which geo-information technology is a subset, without making deliberate organisational innovations often results in systems that fail to live up to expectations. In establishing these expectations we tend to focus on the technical output of the systems. It is clear that this is only part of the picture. To be more precise it only is one third of it. The expectations should be reflected in a well articulated vision of the organisation which spells out what the organisation wants to be. To work towards its achievement three major strategies are needed which to be successful must be aligned and in balance. These are: a business strategy, a technology and an organisations strategy (Walton, 1989). This can be shown in Walton's Strategic Triangle (fig.1).

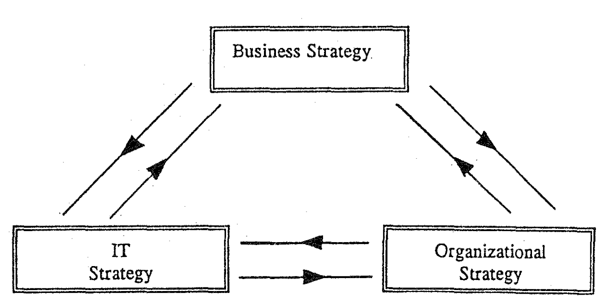

Fig. 1 Walton's Strategic Trianle (Source: Walton 1989)
Simple representation

If for example the business strategy is to continue with the production of standard topographic mapseries in established production lines and not to benefit from the opportunities for customisation and decentralisation offered by the new technology, then the technology strategy will likely be to make these production lines more efficient, exercise process and costcontrol and pacing of work with technology. To expect that it would then be possible to have a successful organisation strategy that emphasises unleashing the creative potential of the staff, empowerment and direct contact with clients would be completely unrealistic.

Yet many organisations in N-America and Japan aim to have such organisations which are variously called continuously learning or empowered organisations. The paradox of IT is that it can be applied to enslave or to liberate us. Walton calls this the dual organisational potential of IT as shown in Table 1.

Dual Organizational Potentialities

Compliance Effects	Commitment Effects
Monitor and control	Disperse power and information and promote self-supervision
Routinize and pace	Provide discretion and promote innovation
Depersonalize	Enrich human communication
Dispossess individuals of their knowledge	Raise skill requirements and promote learning
Decrease dependence on individual	Increase importance of individual skill and internal motivation

Table 1 [Source: Walton 1989]

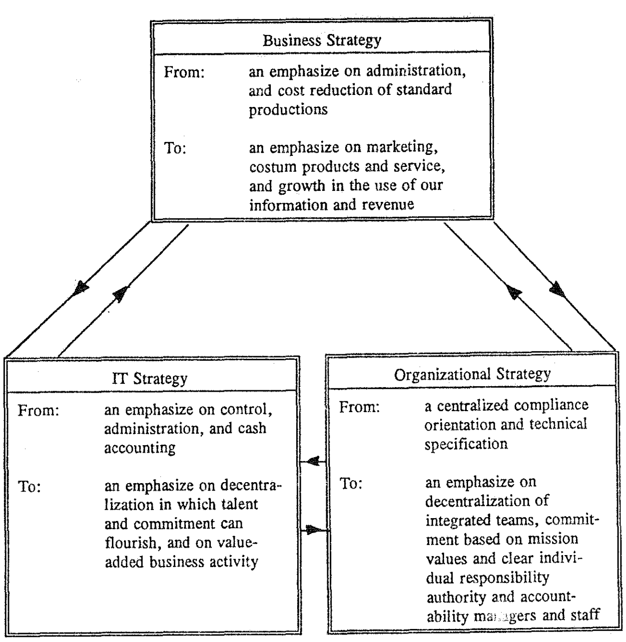

Fig. 2 Walton's Strategic Triangle

Even if we work with an organisation that has a well aligned and balanced set of strategies such as for example in Fig.2 in which Walton's Strategic Triangle has been filled in for a hypothetical organisation, what assurance do we have that the product diversity, direct client contact with production staff and decision making at the lowest possible levels can be successfully achieved? No doubt it would enhance motivation of staff, improve morale and responsiveness to clients if that could be done.

Let us assume for the moment that we work in an organisation with well constructed strategies as in Fig.2. To realise these strategies we want to take advantage of the customising and the decentralising opportunities offered by the technology (Groot 1991). On the side of the customising aspect it is assumed that it will be a low cost effort to derive geo information products from a digital geo information database. On the side of decentralisation we should expect that the staff will have the capacity to work with systems technically and in an integrated way to satisfy customer need. Essentially there are no technical barriers today that would stand in the way of such an operation. There are however a number of pressing questions that need to be addressed before one could responsibly and therefore meaningfully achieve such a form of organisation.

(i) What are the limits of application of a database in contexts that are different that the one for which it was created? Who makes such judgements and based on what parameters and criteria?

(ii) If we empower our staff at the closest possible contact level with the clients to find solutions to information product requirements what do they need to know to responsibly carry out this task?

(iii) On what basis and using what language do producers and users of information products communicate on issues of quality and reliability?

The tendency has been to focus on technical capabilities and less on meaning. As long as our staff knows how to deal with the transformation technologies to make a product from a database we felt that our aims were being achieved. But gradually there is more and more recognition that there are compelling economic, legal and organisational reasons to have access to models that express the context and time dependency of information classification, as well as methodologies to systematically express matter of quality and reliability.

Without such models or a consistent theory on these matters the technology and the organisation strategies expressed in Fig.2 may not succeed fully and that in turn would put the business strategy at risk.

There is no doubt that staff of mapping agencies and other geo information producing organisations will require capabilities that are different from the traditional interpretation and eye-hand coordination skills. If we want to put people central at achieving a more diversified client driven production environment we must provide them not just with the technical but also with the intellectual tools to do that successfully.

The point is that consistent theories need to be developed that describe the structure and character of geo information. That can deliver models for its classification, qualification, time-dependency, generalisation and selection aggregation etc.

Without this it will be difficult to proceed responsibility in achieving the three strategies proposed in Fig.2 which are today espoused by many organisations.

SOME STRUCTURAL AND SEMANTIC ASPECTS OF GEO-INFORMATION.

The previous discussion explained why from a management perspective a geo-information theory is needed. If we interprete the requirements that have been formulated this theory should deal a.o. with the structural (syntactic) and semantic aspects of geo-information, with the implementation in the logical datamodels developed in computer-science and the theory should deal with the uncertainty aspects of geo-information, see [Molenaar 1991a]. The further discussions in this paper will emphasise the syntactic aspects and their relationship to semantic modelling in GIS. That will help us to understand why data definition should always be embedded in a particular users context. In many cases it will be difficult to transfer data from one context to another without data transformations, which will then be called context transformations [Molenaar 1991a and 1991b]. The topics of logical data modelling and uncertainty will be referred to only shortly.

In GIS there are two important methods for terrain description. The first method is to link values of some thematic attribute to positions. E.g. terrain heights are given either in randomly distributed points or in a regular grid. Other examples are the observations of ground water depth or soil characteristics etc.

The other method is to identify terrain objects which have thematic and geometric characteristics. A representation in an information system will consist of an object identifier (e.g. a name, or a number) which is linked to a set of thematic data and to a set of geometric data as in fig. 3.

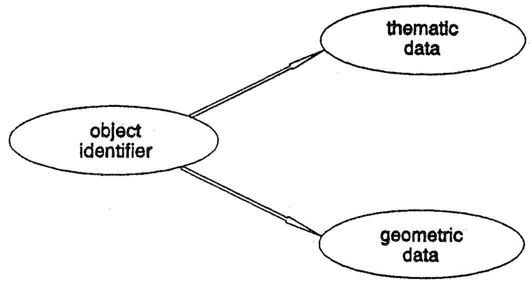

Fig. 3. Information structure for representation of terrain objects.

This basic structure has been applied in many information systems for cadastre, urban management, utilities and many other applications.In most cases the thematic aspects play a dominant role in the object definitions.

That is why a geo-information theory should emphasise the thematic context of the object definitions and provide a structural framework for dealing with these thematic aspects. In this respect there is not much difference with information models for administrative databases. An important specific aspect of geo-information theory is the link between the thematic and the geometric object descriptions. A more detailed description of object hierarchies will be helpful to understand the problems met in spatial data modelling, the concepts presented here have been discussed in more detail in [Molenaar 1991b].

TERRAIN OBJECT CLASSES

In most applications the terrain objects will be grouped in several distinct classes, according to their thematic aspects, a list of attributes is connected to each class. Terrain objects belonging to one class inherit the attribute structure from the class. This means that each object of the class has a list containing a value for each attribute of the class attribute list

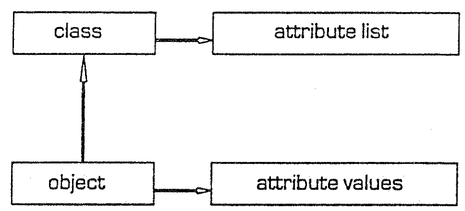

Fig. 4 Class structure of objects

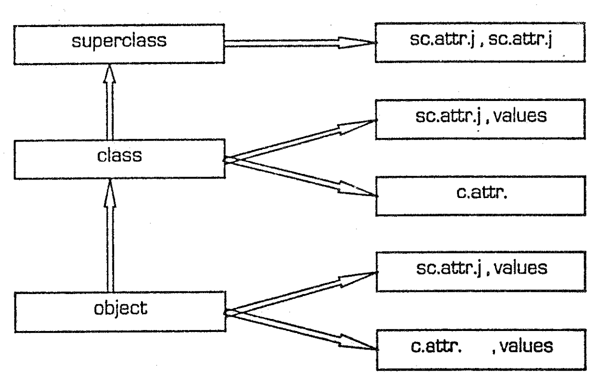

Fig. 5 Class and superclass structure of objects.

When two or more classes do have common attributes, then a superclass can be defined with a list containing these common attributes, these will then be called super class attributes. The classes at the next lower level will be subordinated to these superclasses. To each class a list of class attributes will be linked, in general these lists will be different for different classes. The terrain objects are then subordinated to these classes. With these observations we find the class hierarchical structure of fig. 5.

It is possible to add more hierarchical levels to the structure of fig. 5. Each level inherits the attribute structures of the next higher level and propagates it possibly with an extension to the next lower level. At the lowest level in the hierarchy are the terrain objects, at this level the attribute structure is not extended anymore, here the inherited attributes are evaluated.

If the classes are disjoint then the terrain objects will get their attribute structure only through one inheritance line in the hierarchy, i.e. they have a unique thematic description.

The terrain objects occur at the lowest level of the classification hierarchy. They can be seen as the elementary objects within the thematic field represented by the classification system. This implies that the decision, whether certain terrain objects should be considered as elementary or not, should always be made within the frame work of a thematic field. Objects that are considered as elementary in one thematic field should not necessarily be considered as elementary in another thematic field.

AGGREGATION HIERARCHIES

The introduction of "elementary" objects implies the existence of composite objects. They can be defined through aggregation hierarchies which are quite distinct from classification hierarchies.

An aggregation hierarchy shows how composite objects can be built from elementary objects and how these composite objects can be put together to build more complex objects and so on. Suppose that we have houses, roads, parks, factories, office buildings and shops as elementary objects. From these several composite objects can be build as in fig. 6:

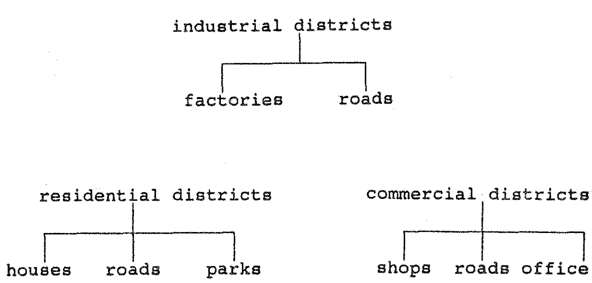

Fig. 6 Hierarchical relationships among elementary and composite objects.

The composite objects of fig. 6 can be combined to build towns or cities as in fig. 7, and these can be put together to build urban areas.

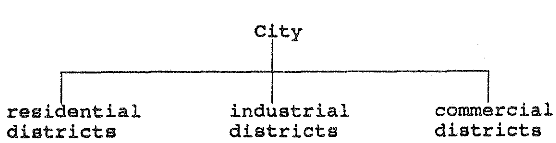

Fig. 7 Hierarchical relationship between different aggregation levels.

The aggregation hierarchy has a bottom up character in the sense that starting from the elementary objects composites objects of increasing complexity are constructed in an upward direction. The composite objects inherit the attribute values from their constituents parts.

The fact that elementary objects can be aggregated into composite objects implies that also their attribute values may be aggregated. If one of the attributes of houses is the number of people living there, then it is easy to calculate the total number of inhabitants of a residential district.

In literature on semantic modelling [Algic 1989] [Brodie 1984] [Brodie e.a.1984] [Egenhofer e.a.1989] [Oxborrow e.a.1989] the upward links of the classification hierarchy are labelled respectively as "ISA" links and those of the aggregation hierarchy as "PARTOF" links. ISA links relate particular objects to a class and to superclasses, where the class and superclass will be defined by their general characteristics i.e. attribute structures. The PARTOF links relate a particular set of objects to a specific composite object and on to a specific more complex object and so on.

Another distinction between the two hierarchies is that elementary objects belong to exactly one class, whereas they may belong to several composite objects. That means that composite object types are not necessarily disjoint. A river can be part of a hydrological system, which is a composite of rivers, lakes and streams. That river can also be part of a water traffic system consisting of rivers, lakes and channels. But that river will be part of only one hydrological system, i.e. an elementary object only belongs to one particular composite object of one type.

OBJECT ASSOCIATIONS

Both hierarchies of the previous sections where clearly defined. A classification hierarchy represents a stepwise introduction of the attribute structure of terrain objects. An aggregation hierarchy is defined by the generic models describing how composite objects at one level are constructed from the objects of the next lower level. The levels in the hierarchy represent objects of an increasing complexity. Object association form a third type of object sets, these are defined less sharply, they build no hierarchies. They are just sets of objects which do have something in common. This means that associations of one type are not necessarily mutually exclusive. Their nature can best be explained by some examples.

In a road network (which might be considered as an aggregation), the route from town A to town B forms an association. The route will consist of several roads, or segments of roads. In its construction this association shows similarities with aggregations. The difference is that members of the route from A to B might also belong to other routes. Hence these routes are not mutually exclusive.

Other examples are the set of all companies which do have an office in Amsterdam and all cities in which a particular company has an office. These two are typical examples of associations based on m:n relationships.

DATA MODELLING

The previous discussion suggested that (elementary) terrain objects should always be defined in the framework of a classification system. Such a system will be defined within a users context, which will have several aspects. The first aspect is the discipline or disciplines of the users, i.e. are we working in a cadastral environment, or soil mapping, or demography etc. Each discipline will have its own definition of terrain objects, classes and attributes. These definitions depend also on the scale level or other aggregation level of the mapping, i.e. a local level, a regional level, a national level or even a continental level. At each level different sets of elementary objects will be relevant. These different levels may be linked by the fact that the elementary objects at one level can sometimes be considered as aggregates of elementary objects at a lower level; e.g. at a municipality level a GIS may contain houses, streets and parks, while at a national level a GIS may contain towns and urban areas.

Another aspect is how the data will be used: is it for monitoring the terrain situation, or is it for the analysis of the situation, or will the data be used for planning purposes etc. Each field of activities puts its own requirements the type of terrain description, although there are often overlaps between these requirements. A fourth important aspect that in many disciplines the relevance of data changes with time. In agriculture for example, the requirement for soil information has changed during the last decades. Originally the main interest was to analyze the suitability of soils for sustaining different crops. At present the interest changes to e.g. the capacity of the soil to store chemical elements which could do harm to the environment.

These observations show that the decision of what data are relevant is always context dependent, i.e. the elementary objects with their classes at the different hierarchical levels and linked to these classes the attributes with their value domains. For these elementary objects it should be decided also to which geometric type they belong. This will depend on the geometric role they play in the terrain description, this role should not be confused with the appearance of these objects in reality. It may be that a river is treated as a line object in a data base for hydrological purposes, whereas the same river is treated as an area object in the data base of the authority responsible for its maintenance. Similarly a town may appear as an area object in a data base for demographic purposes, whereas the same town appears as a point object in a data bases containing air traffic routes. The decision which geometric aspects of an object are important is always made in a particular context and that implies the decision whether it should be treated as a point-, line- or area object. Within such a context one should also decide what are the relevant object aggregates and associations that should be constructed from the elementary objects.

Data modelling should be done with care, the discussion of the structural and semantic aspects and the context dependency of the data explains why. Therefore tools should be developed to assist us in the process of spatial data modelling, to find out what can be modelled and what not. The Modul-R Formalism of [Bedard e.a. 1992] is one example of such tools.

In the explanation of some of the concepts that play a role in a geo-information theory reference was made to elementary and aggregated terrain objects. These are high-level concepts, very close to the conceptual level a GIS user would like to think at. Operational GISystems and DBMSystems require that these high-level objects are broken down into low-level data types that match the logical data structures of these systems. The data management in these systems has in most cases been organised so that the user is forced to think and operate at this low level. This often frustrates the use of these systems, because the user may have great problems analyzing his complex high-level problems when he forced to work at such a low level. Data management tools should be developed that bridge the cap between these two levels, [Lee e.a. 1992] discus this problem and propose a solution.

UNCERTAINTY

Data models are prescriptions how objects should be represented in an information system. Once these models have been defined we are faced with the problem of data acquisition to fill the database. This means that terrain objects should be identified, they should be classified and their geometry should be measured and their attributes evaluated. This should be done by measuring operations and it is through these operations that uncertainties of different types are introduced in the data. Three major types of uncertainty will be described shortly here (see for a general treatise [Klir e.a. 1989].

The criteria for assigning terrain objects to a certain class might be fuzzy: e.g. the definition of nature districts is not always clear. Does it mean that people do not interfere with the development of flora and fauna? If it means that there is only a limited interference of people, then how little should that be. No sharp criteria can be formulated.

The geometry and the attributes of the terrain objects should be evaluated through measuring procedures or through the processing of measuring data. Measuring operations introduce in general stochastic components in the observed data. These stochastic components propagate through the processing steps applied to these data. This type of uncertainty is generally expressed in accuracy models in terms of variances and probabilities.

The third type of uncertainty is related to evidence theory. It may be that the object classes are clearly defined and the object data are accurate, but still the data do not contain sufficient information to decide whether a particular object belongs to a certain class or not. This case is well known in remote sensing image classification. If a classification is made to determine the landcover of an area, then the landcover classes might be well defined. Still the spectral information in the image might not give sufficient evidence to assign the parcels with certainty to those classes.

In [Brimicombe 1992] the problem of uncertainty in GIS is treated and proposals are formulated how to deal with it.

CONCLUSION

The introduction of information technology does not only confront organisations with technical problems, but it does have a significant organisational impact. Consequently it requires a redefinition of the organisational structure and of staff expertise and responsibilities. More direct is the effect on the information flow through the organisation. This concerns the technical and structural aspects of the information flow, but also (and not the least) the definition of the data and data processing models.

Tools should be made available to experts involved in this task. For organisations dealing with Geo-Information these tools should be embedded within the framework of a theory dealing with the structure or syntaxis and semantics of GEO-information and the structure of its processing models. Several structural and sematic aspects of data modelling have been explained in the previous sections. [Bedard e.a. 1992] [Lee e.a. 1992] and [Brimicombe 1992] explain how tools for some of these modelling tasks can be developed.

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