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CARTOGRAPHIC GENERALIZATION IN DIGITAL ENVIRONMENT

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Abstract

Throughout the world numerous efforts to automate generalization are in progress. The results are yet to be satisfactory. Ample reasoning can be given to justify the lack of success, the most important being that generalization is an ambiguous process, highly subjective which lacks definitive rules, guidelines or systematization. This paper deals with the problem of generalization of vector data bases through the analysis of recent developments and research in the field. These developments tend to establish a promising framework which, with subsequent refinements and the utilization of state-of-the-art computer technology, may lead to successful results. What is needed is what lacks: Definitive rules in structuring the digital image of the world and development of expert systems which will intelligently manipulate this image.

INTRODUCTION

All charts are reductions of some region of the earth. It would be practically impossible to portray the entire earth at a 1:1 scale. This scale reduction yields a number of undesirable consequences such as:

- decrease in the distances separating features on the map/chart
- loss of visual clarity due to overcrowding
- shift of visual importance from the specific to the general

In order to overcome these consequences, traditional cartographers apply a number of manipulations to the chart data to display and communicate efficiently important information at the reduced chart scale. These manipulations of the chart data are referenced under the collective topic of Cartographic Generalization.

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Generalization is performed for chart display and communication purposes but also for analytical purposes. One of the driving forces behind generalization, is the necessity to understand at which scales or range of scales spatial processes occur (MULLER, 1991).

Attempts have been made recently to automate the procedures of generalization. This development has led to efforts to formalize a process which had remained highly subjective, rather undocumented, interactive, intuitive and holistic in its perception and execution. Computer assisted cartography made cartography faster and more accurate, but computer assisted generalization has lagged far behind. The identification of rules and their implementation into a system which can simulate the work of a traditional cartographer is one of the most difficult challenges current cartographic research faces.

SPATIAL DATABASES

In the last few years a considerable number of cartographic institutions have built databases or otherwise organized the collection of cartographic data they use to produce maps/charts. Such collections are properly called cartographic databases. A cartographic database is a database which contains cartographic data along with the management software necessary for its collection, update and output. It is a database system that contains cartographic data and the procedures to display charts, either on a screen or on paper. In contrast a geographic information system (GIS) is an information system which can respond to a wide array of questions in the form of a chart, a table or a report. The major difference between a cartographic database and a GIS is in what is modelled. A GIS contains "a model of reality" which is limited to some specific tasks and the data needed for them. The cartographic database contains models of maps which in turn are models of reality. It must be admitted that in practice there are no sharp distinctions and many systems which are advertised as GISs are in fact more cartographic databases, and some of the current cartographic databases do allow some extra flexibility in their use (FRANK, 1991).

Successful spatial-database design requires that the database must support a wide variety of products and applications, within the covered geographical area. It has been found that space related applications require a larger set of functions than standard commercial ones. The cost of fulfilling the demands of spatial applications are high in terms of performance, hardware requirements etc. Geometrical, topological and thematic relationships between real world objects are stored or derived computationally. The relational data model has been the most popular one among the commercial systems which store attribute data in relational databases and link them logically to the geometric data. Experience has showed that complex data structures of spatial reality is difficult to fit into the relational model and the relational algebra on which relational databases are founded poses additional difficulties in spatial data processing.

The object-oriented paradigm used in software engineering appears to be applicable to databases and promises a more flexible method for structuring complex spatial data. An object oriented data model should allow methods of constructing complex objects from parts, giving a solution to the relevant generalization problems.

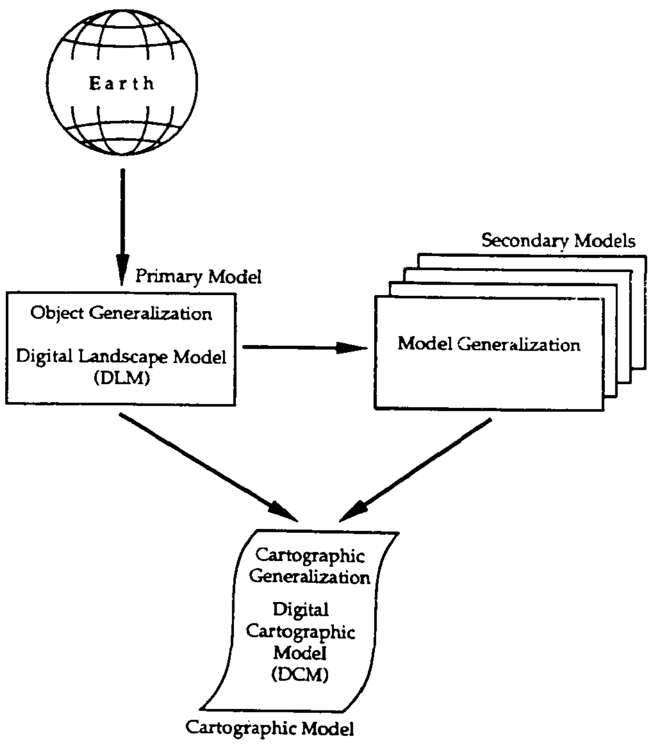

FIG. 1.- The Digital Landscape Model (DLM) and its derivatives (after GRUNREICH 1985).

Spatial data is considered as the most valuable resource, and the more widely is used the better. It is generally acceptable that economical benefits and thus a cost advantage of a database are only attained if multiple applications and users can utilize the data. Generalization is not only motivated by a reduction of scale presentation, something that overemphasizes the display and legibility constraints in map production, but it is prompted by other requirements as well. We have to adhere to the economic principle of singular acquisition and multiple use, a data flow from the original database to a lesser resolution or special purpose database. This can be achieved through "model generalization" (GRUNREICH, 1985). According to GRUNREICH this modelling takes place at two levels (Fig. 1). First modelling occurs during data capture - in digital or analog forms - through sampling procedures.

Data capture involves a primary stage object generalization and results in the primary or Digital Landscape Model (DLM) ie. the geographic database. Thus the original database is considered as the primary or Digital Landscape Model (DLM) which - through generalization - can produce special purpose models (secondary models) which are free of cartographic representational information. Second modelling occurs with digital and symbolic representation of data. Both primary and secondary models can be used to create a cartographic representation of a Digital Cartographic Model (DCM) ie. the cartographic database, through the process of cartographic generalization.

AUTOMATING THE GENERALIZATION PROCESS

Several attempts at automation targeted a particular generalization process (such as simplification of line features) without considering other generalization decisions and the implications that one has to the other. Serial computers logic and conventional programming languages necessitated this "isolated" approach, which is not consistent with the manual generalization approach, wherein generalization decisions are simultaneous and supported by the knowledge of geographical relevance.

Current attempts at automating generalization operations lack the means to incorporate the traditional cartographic intuition - the intellectual basis provided by the cartographer - when confronted with a generalization problem. The ability to exploit existing computing technology to perceive the map as a whole as does the man, does not yet exist. As a result we have not acquired yet the ability to instruct the system to assess the impact of generalization decisions made for one feature upon another feature.

The alternative approach of aiding the cartographer with an interactive digital generalization system in the generalization process, is considered to be a more realistic one and has already given interesting results. Such a system could provide the basis for knowledge acquisition and knowledge refinement. Here we will address both approaches believing that the final goal is the same and experience gained through one of them, will be valuable for the other.

Recent advances in the field of artificial intelligence (AI) offer exciting possibilities to assist in this endeavour. The concept of an artificially intelligent digital generalization system, suggests methodologies which reflect the theoretical aspects of human intelligence and, as such, could closely mimic the human generalization process. A judicious application of the AI concepts and techniques promulgated in the AI field may serve to bring the intuitive basis of generalization to the digital environment (SHEA, 1991).

GENERALIZATION IN A DIGITAL ENVIRONMENT

For the development of an operational automated software for cartographic generalization, three complex problems must be solved:

- A formal, comprehensive conceptual framework for digital generalization must be agreed upon;

- The specific procedures of the process, or generalization operators, must be designed, coded and tested;
- Cartographic knowledge must be culled from expert sources (maps/charts) and individuals and coded into "rules" (MCMASTER, 1991).

Automated generalization models

In order to replace the human generalization process with automated software we have to model this process. Throughout the last twenty years a number of generalization models have been developed. Some of the models have addressed specific components of the generalization process, other have been more comprehensive. The detailed presentation of the various models is beyond the scope of this paper. We will elaborate only on two of them, the BRASSEL and WEIBEL model and the MC MASTER and SHEA model which support each one of the above mentioned approaches.

The BRASSEL and WEIBEL model

This model, best suited for the integration of expert systems for digital generalization, was developed by Swiss cartographers (BRASSEL and WEIBEL, 1988). It is based on the idea that what is needed is "processing based on understanding". To understand generalization means to extract the essential structures of the spatial information available (in the thematic, spatial and temporal domains), to identify the essential procedures for modifying these structures and to formalize these processes of modification adequately as a number of operational steps.

The model identifies five steps: Structure recognition, process recognition, process modelling, process execution and data display (Fig. 2). The original database is first subjected to the process of *structure recognition.* This process is the activity aiming at the identification of cartographic objects or aggregates, as well as the spatial relations and measures of importance. Structure recognition is controlled by the objectives of generalization, the quality of the original database, the target map scale and the communication rules (graphic and perceptual limits). It represents a process of intellectual evaluation which is traditionally performed by visual inspection of a map.

Process recognition identifies the exact generalization operators to be invoked and involves both data modification and parameter selection. Process recognition determines what is to be done with the original database, what types of conflicts have to be identified and resolved, and which types of objects and structures are to be carried in the target database. Once the generalization process has been defined, it is modelled as a sequence of operational steps. This *process modelling* can be considered as a compilation of rules and procedures from a process library and the pre-setting of process parameters that were established in process recognition. The original database and information structures are then subjected to process execution and converted into the target or generalized database.

Process execution consists of a sequence of operational steps as compiled from process functions stored in the *process library.* Examples of generalization processes

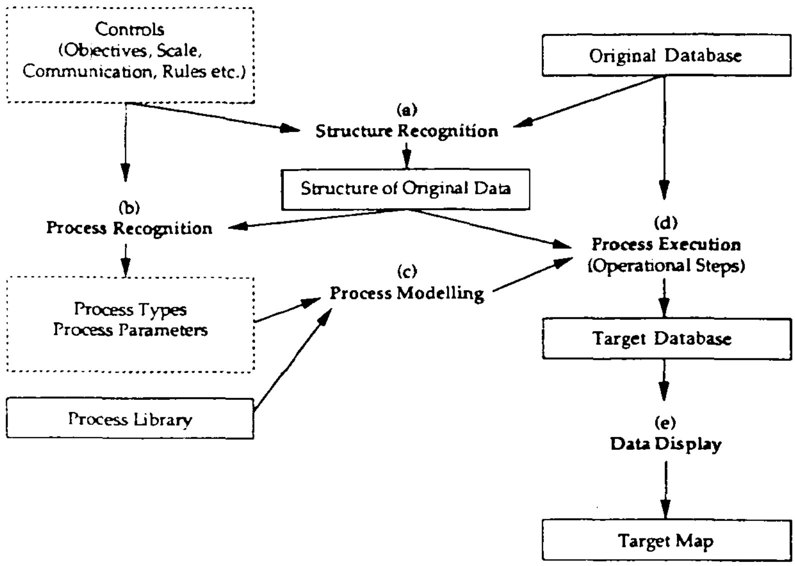

FIG. 2.- BRASSEL and WEIBEL model of generalization (after BRASSEL and WEIBEL 1988).

are selection, simplification, symbolization, feature displacement and feature combination. The last step is *data display* where target data are converted into the target map.

The process library is a critical component of this model and its development for the implementation of an expert system for automated map generalization entails decisions involving the generalization operators and their sequence, the knowledge that must be captured within the system (rules) and what parameters and tolerances are required for the logical implementation of rules and operators.

Knowledge representation

The principal determinant of success in making an expert system to operate, is the sophistication and breadth of the contained knowledge. Before that knowledge can be exploited, it must be formally structured according to the needs of the specific expert system. The selection of formalism for a knowledge representation is a significant distinguishing characteristic when designing an expert system.

ARMSTRONG (1991) identifies three types of cartographic knowledge that must be captured within the system including geometrical knowledge, structural knowledge and procedural knowledge. **Geometrical knowledge** refers to the actual geometry or topology (size, form, distance, connectedness) while **structural knowledge** brings expertise - that ordinarily resides with the cartographer - into the automated generalization process. **Procedural knowledge** guides the selection of appropriate generalization operators for performing generalization tasks. These three kinds of knowledge must be represented in a coherent framework that allows declarative and procedural knowledge to interact as it is evaluated.

Knowledge can be described using object-attribute-value (OAV) triplets, production rules and semantic networks. OAV triplets represent elemental portions of knowledge which can be aggregated into frames, which in turn can be linked into a semantic network. Frames are used here as a tool to illustrate knowledge about cartographic generalization and are useful when both knowledge and data must be represented for an application domain. Each frame has a name and a list of slots or facets. Each facet contains either a value with its associated descriptor, or a procedure that when executed produces a value.

As used here a frame has the following generic structure (DE, 1988):

```
(frame
        (slot ( facet (datum ( label message ....))
                              (datum...)...)
              ( facet...)...)
        (slot...)
...)
```

This frame-based approach to knowledge representation also allows rules to be specified. Rules are encoded using the following generic structural form:

```
Rule example
  (AKO ($Value (Preprocessing_Rule)))
  (Precondition ($Value (<variable value)))
  (Consequent ($Value (Do_something)))
```

The frame has a precondition that consists of an arithmetic operator, a variable and a value of that variable. If this precondition evaluates to true then the consequent (Do_something) occurs. The hierarchical structure of a frame is a rich mechanism for declarative knowledge representation because many spatial relationships fall naturally in this form, and where they do not, the structure can be expanded to represent knowledge by linking additional frames into a network. In this case the structure is given identifying the rule as A Kind Of (AKO) preprocessing rule.

Production rules are very popular systems for knowledge representation. Expert systems that use production rules to represent knowledge are referred to as **rule-based systems**. The use of production rules offers several advantages in knowledge representation (SHEA, 1991):

- Knowledge is extremely readable and easy to understand.
- They behave much like independent pieces of knowledge and, as such, rules in the knowledge base can be added, deleted or modified with little direct effect on other rules.

The rules for selection can be systematized on the basis of user's needs and map functionality. Each single feature in the database can be rated using information requirements identified by user's needs and by examining the relationship of base map elements to thematic features. Necessity factors can be derived for each feature, for each scale and for each theme. rating matrices could be calculated accordingly, and would function as look up tables (MULLER, 1991). A rule based approach represents a quantum step beyond the purely algorithmic treatment, including both the tools and the choice of tools to effect generalization.

Generalization operators

Cartographic generalization researchers have studied several sets of functions or operators to support the generalization process. Common to these generalization operations is the fact that they are categorized as point, line, area and volume feature generalization through a selection process based on geographical and attribute data. Most of the existing generalization software packages have available a number of operators (eliminate, displace, smooth etc.) although which specific operators are provided is specific to user requirements.

MCMASTER and SHEA model

This model identifies three considerations for comprehensive generalization, including:

- Objectives of generalization (Why we generalize)
- Situation for generalization (When we generalize)
- Procedures for generalization (How we generalize)

The **objectives** of generalization can be viewed from three vantage points based upon:

(1) Specific requirements of the product (clarity, scale, map purpose and intended audience).
(2) General cartographic principles or philosophical objectives (reducing complexity, retaining spatial accuracy, retaining statistical accuracy, maintaining aesthetic quality and logical hierarchy, consistency applying generalization rules).
(3) Computational objectives (Cost effectiveness of algorithms, storage/ memory requirements).

The **situation** in which generalization would be required arises due to the success or failure of the chart product to meet the stated goals. The *conditions* under which generalization procedures would be invoked would be based upon the *measures* by which that determination was made and the *decisions* or control of generalization techniques that will be employed to effect the change. The conditions that will occur under scale reduction are congestion, coalescence, conflict, compilation and inconsistency. Conditional measures can be assessed by examining some basic geometric properties of the inter-feature and intra-feature relationships. Some of these assessments are evaluated in singular feature sense, others between two independent features and others are computed in a multi feature sense. These measures are: density, length, sinuosity, shape, distance, gestalt and abstract. Each of the above classes of measures can be determined in a digital environment. In order for the cartographer to obtain unbiased generalization, the following need to be determined: which algorithm to use, the order in which to apply these algorithms and the input parameters to obtain a given result at a given scale. Thus the decision process include procedure control and algorithm selection.

The **procedures** for generalization is the component that actually performs the process of scale reduction. There are five basic categories of procedures to effect the required spatial data changes to support the production requirements. These are line simplification, feature type conversion or refinement, feature displacement, feature smoothing and data compaction. For each of these procedures there is a number of *algorithms* which can be applied. These algorithms are affected by the order of application, frequency of application and the parameters used. There is a wide variety of algorithms available for vector data processing. These are derived from different disciplines and, as such, do not necessarily comply with the specific requirements of spatial data. These algorithms are described and evaluated in NOAA Technical Report (SHEA, 1988) where the above mentioned model is elaborated.

Database dependency on scale

The original database - the one resulted from ground surveys - represents the Digital Landscape Model (DLM). This database is characterized from the accuracy and the level of precision for which the data was captured. In essence data stored in a DLM is scale-independent, since the notion of scale only appears when this data is being transcribed for analytical or representation purposes to a space, which is smaller than the original surveyed space. The ideal would be to move freely from the DLM level of detail to any level appropriate to the scale of display or to the precision of data analysis. This approach can be called scaleless database approach and is considered as the most efficient one for the reasons which will be mentioned later in this paper. In order to support multiple representations (secondary models) from one database, an object-oriented data structure combined with decision rules and generalization operators must be implemented (MULLER, 1991).

The alternative is the multiple purpose, scale specific storage scheme. Different charts produced at different scales are stored independently, yielding scale-dependent databases. Other approaches which are pseudo-versions of scaleless database approach are the use of different scale dependent layers of representation without duplication of data and the allocation of scale dependency values in the database structure.

There are at least three arguments for the development of scaleless databases:

- Storage saving. Spatial features appearing in most presentations (i.e the coastline) will be stored only once.
- Production of flexible scale-dependent outputs. The output can be adjusted to a wide variety of mapping and modelling purposes to satisfy specific user needs and not only to fixed scales.
- Consistency and integrity between the various scale outputs. With scale specific databases, updates must be applied to every version that has been archived. Updating is a time consuming operation and its cost increases with the number of database versions. Of equal importance is the problem

of inconsistencies through errors committed during the propagation of change from one digital representation to the other. Chart specifications require that an object portrayed on a small scale chart must be portrayed on any of the larger scale charts covering the same area.

There are disadvantages to the scaleless approach, the most important being the quantity of data to be accessed every time a smaller scale is required. Moreover solutions to generalization are not fully automated and usually require some further interactive editing before they can be used for output. This editing process must be repeated each time a chart is to be generated from a single database.

Generalization and error

Error and uncertainty have always been an inherent characteristic of cartographic information. It is not surprising that these aspects are also present in digital versions of analogue maps/charts. Neither should it be imagined that any map-related spatial data exist which are error-free. Errors and uncertainty are facts of life in all information systems. Thus any cartographic transformation as chart generalization, constitutes a source of error. Generalization is distinguished to statistical and cartographic. Statistical generalization is a filtering process whose aim is spatial modelling of attribute information attached to locations. Cartographic generalization, the aim of which is display for visualization, can affect locational accuracy to a great extent. Features may be displaced and their original shape may be distorted.

The creation of a database through chart digitization is a source of error due to the fact that the generalization process - acting as a deductive transformation - changes the positions of the various geographic entities. These databases - being a result of cartographic generalization - are not as reliable as those products referred to earlier as Digital Landscape Models (DLMs). When generalization applies to line features, which constitute the dominant cartographic element portrayed on maps/charts, a number of errors arise. An estimation of the consequences of the generalization to derivative measures on charts, leads to the following conclusions (TSOULOS et al. 1994):

- Generalization error on area calculation is proportional to the size of the area in concern. The larger the area the smaller the error. It also depends on the shape of the polygons. Normal shaped polygons give less error in area calculation due to generalization, compared to polygons with complicated shape.
- Generalization error on distance and perimeter calculation is a function of the complexity of the line. The simpler the line the smaller the error due to generalization.
- Topological errors are often one major consequence of generalization.

AN EXAMPLE ON NAUTICAL CHARTS

Generalization of areal features has been one good example of the complexity of the problem in a digital environment. In nautical charts important areal features for the navigator are islands, islets and rocks whose depiction requires special attention and treatment. What is usually sought, is the amalgamation of smaller polygons into larger polygonal units, through a selective elimination of arcs. The operation is based on the statistical generalization of the associated attributes. There are two factors to be considered in areal feature generalization. One is the **area** of the feature in mm^2 at the scale of the chart. Accepted minimum size is 4.0 mm^2. The other is the **significance** of the feature. The significance of a feature is the resultant of factors such as position, isolation, military importance, historical importance etc. If we denote these factors as f1,f2,...fn the significance of the areal feature will be SIG = f1 + f2 + f3 +...+ fn or SIG = w1f1 + w2f2 + w3f3 +...+ wnfn where w1, w2, w3, ..,wn are the corresponding weighting coefficients varying in accordance with the purpose of the chart. The portrayal of areal features does not follow a dichotomic approach. Illustration in Figure 3 shows three zones of significance. **Generalization zone** where the significance is lower than a certain limit and the feature will be eliminated if its area is under the above mentioned size, **dependence zone** where both size and significance must be evaluated and resolved, and **prohibited zone** where the feature at any size will not be generalized (eliminated) due to its significance. It becomes obvious that the successful implementation of this model depends on the structure of the database and the assignment of realistic values to the relevant attributes (factors). The same database contains items where the results of this process (significance value, zone status) are stored.

Next step is the computation of the distances of closely located polygons (each island which will be portrayed with its surroundings) at chart scale. If this distance is greater than the preset graphic limits, then the arcs defining the island are generalized. If this distance is less than the preset limit, then the value of significance is checked. Islands with large SIG values are displaced and those with small SIG values are amalgamated with their neighbours. Generalization and smoothing of arcs is the next step in order to achieve the required aesthetic quality.

This process has been implemented within ARC/INFO environment in the NTUA Cartography Laboratory and has given quite satisfactory results. The reason for choosing a GIS package is the availability of the tools required to implement this process ie. macro language to express the "rule base", functions to amalgamate polygons, tools for creating graphic users interface and finally topologic definition of features. This last characteristic is indispensable in the process in order to secure consistency (ie. to preclude the portrayal of soundings on the amalgamated islands).

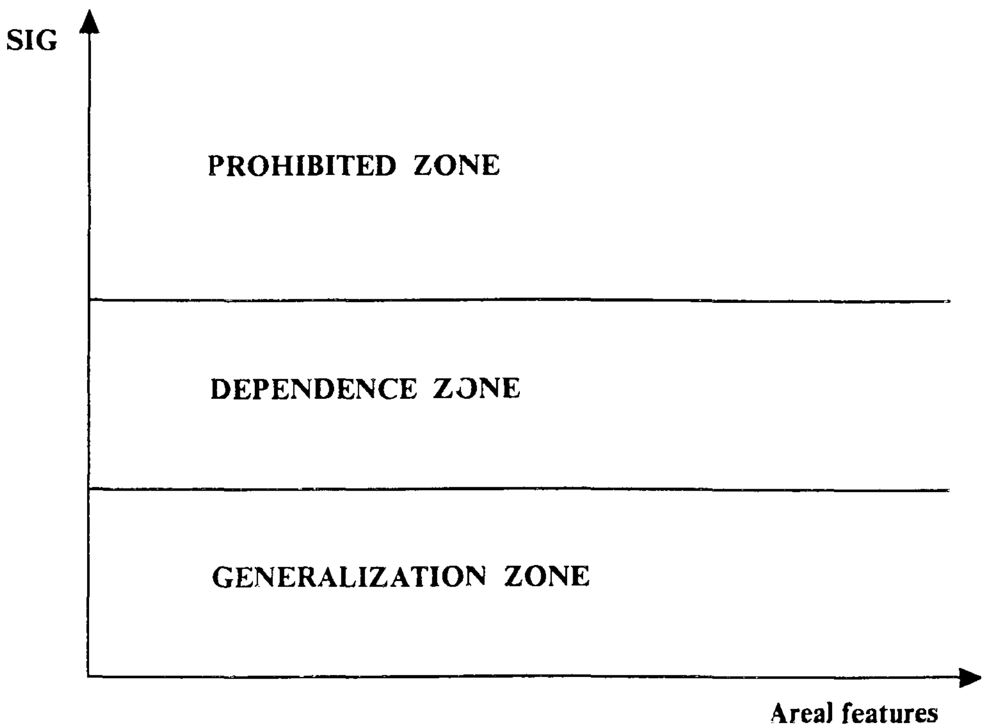

FIG. 3.- Areal features generalization zones according to their significance.

CONCLUSION

Comprehensive understanding of the nature and the mechanism of cartographic generalization supported by explicit documentation, is the foundation for the implementation of a solution of the problem in the digital environment. It requires inter-disciplinary action by cartographers and computer scientists for the formalization of cartographic knowledge, the development of a concise rule base and the optimization of structures and models of the reality. It remains to be seen whether there is a model which relates all features to all factors influencing the process of generalization.

As far as nautical charts are concerned, they represent one of the few cartographic products which are covered by detailed and internationally accepted specifications. This makes the central task of the development of the rule base a more realistic target and brings the solution of the problem for this particular category in the foreseeable future.

References

ARMSTRONG M.P., 1991: Knowledge classification and organization. In B.P. BUTTENFIELD and R.B. MC MASTER (eds) *Map Generalization*. Longman Scientific and Technical.

BRASSEL K.E., WEIBEL R., 1988: A review and conceptual framework of automated map generalization. *International Journal of Geographical Information Systems. Vol 2, No 3.*

DE S., 1988: Knowledge representation in manufacturing systems. In Kusiak A (ed) Expert Systems: Strategies and Solutions in Manufacturing Design and Planning. Michigan Society of Manufacturing Engineers, Dearborn.

GRUNREICH D., 1985: Computer assisted generalization. *Cerco Cartography course*. Frankfurt, Germany.

FRANK A.U., 1991: Design of cartographic databases. In J-C Muller (ed) *Advances in Cartography*. International Cartographic Association. Elsevier Applied Science.

MCMASTER R.B., 1991: Conceptual frameworks for geographical knowledge. In B.P. BUTTENFIELD and R.B. MCMASTER (eds) *Map Generalization*. Longman Scientific and Technical.

MULLER J-C., 1991: Generalization of spatial databases. In D.J. MAGUIRE, M.F. GOODCHILD and D.W RHIND (eds) *Geographical Information Systems*. Longman Scientific and Technical.

SHEA K.S., 1988: Cartographic Generalization. *NOAA Technical Report NOS 127 CGS 12*. U.S. Department of Commerce.

SHEA K.S., 1991: Design considerations for an artificially intelligent system. In B.P. BUTTENFIELD and R.B. MC MASTER (eds) *Map Generalization*. Longman Scientific and Technical.

TSOULOS L., KAVOURAS M., TSAKIRIS G., 1994: Accuracy issues of geographical data and processes for estimating water resources availability. In G. TSAKIRIS and M.A. SANTOS (eds) *Advances in Water Resources and Management*. A.A Balkema.