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Geographic Information Systems and Spatial Modelling

Potentials and Bottlenecks

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1. Introduction

Cost-efficient and accessible information systems are vital to economic performance and effective decision-making. Therefore it is no surprise that the information intensity of many activities in a modern society is rapidly increasing. It is increasingly recognized that NIT (New Information Technology in a broad sense) will be as important in the last decade of the 20th century as canal, rail and road transport infrastructures were in the last century (cf. Nijkamp 1990).

Especially the rapid development of digital and electronic technologies opens a new potential for sophisticated voice, data and image transmission, such as digital recording and transmission of sound and pictures, optical fibres for very fast transmission of information, super-fast computers and satellite broadcasting and video transmission.

From a geographical viewpoint the trend towards advanced information systems has led to the design and use of GIS. GIS serve to offer a coherent representation of a set of geographical units or objects which, besides their locational position, can be characterized by one or more attributes (feature, label or thematic component). Such information requires a consistent treatment of basic data, via the stages of collection and storage to manipulation and visualisation. In recent years, GIS have increasingly been linked to computer supported visualisation techniques such as CAD/CAM systems, as well as to remote sensing and tele-detection.

All such information systems may be highly important for planning of our scarce space, not only at a global scale (e.g. monitoring of rain forest development), but also at a local scale (e.g. physical planning). In this framework, spatial information systems are increasingly combined with pattern recognition, systems theory, topology, statistics, finite element analysis and computer-aided mapping (cf. Dueker 1987). Such techniques are not only relevant for scientific research, but may also act as information bases for physical planning.

The GIS technology has become an important part of NIT, both in terms of hardware and software. This new computer power has been able to create not only sophisticated data base management systems and high resolution graphics and maps, but is increasingly also used as an important vehicle for local/regional decision-making (e.g., infrastructure planning, health care, environmental management). A new challenge is now the integration of the GIS technology with spatial models as descriptive, explanatory, planning or predictive tools. Especially the multi-media features of GIS-related model frameworks may enrich the potential of both GIS and spatial models (see e.g. Clarke 1990; Despotakis et al. 1992).

2. GIS and Spatial Analysis

Spatial analysis - which in its widest sense can be considered as analysing spatial and non-spatial information of phenomena in spatial or space-time systems as a tool for their description, explanation and prediction - offers a wide range of methodologies and procedures relevant to GIS research. Spatial analysis is more general than statistical analysis of non-spatial information because it requires access not only to attributes (non-spatial information), but also to locational (and topological) information. The poor analytical and modelling capabilities of current GIS, however, are paralleled by a similar lack of special statistical software packages for spatial data.

There is an enormous range of basic spatial analysis procedures and techniques available which might be used to increase the analytical and modelling functionality of geographic information systems. Based on Goodchild's (1987) view seven fundamental and generic types of spatial analysis operations may be distinguished from a GIS-oriented perspective:

- operations which require access only to attributes of one class of objects (for example, classification procedures for an object class of areas; such operations do not belong to spatial procedures in a strict sense, but are important in spatial analysis too),

- operations which require access only to locational information of one class of objects (for example, point pattern analysis),

- operations which require access to both attributes and locational information of one class of objects (for example, homogeneous rgionalisation procedures for an object class of areas),

- operations which create object-pairs from one or more classes of objects (for example, pairing of points to generate a line object class),

- operations which analyse attributes of object-pairs (for example, spatial autocorrelation indices, nearest neighbour analysis),

- operations which require access to attributes and locational information for more than one class of objects or object-pairs (for example, spatial interaction models, shortest path procedures, optimum tour routing),

- operations which create a new class from one or more existing classes of objects (for example, Thiessen polygons from point objects, polygon overlay).

No current commercial GIS product is able to fulfil these tasks. Evidently, both GIS and spatial analysis can benefit from more integration. The potential value of GIS lies in their ability to analyse spatial data using procedures of spatial analysis, but in practice GIS technology is often used for little more than mapping and answering simple spatial queries. Spatial analysis might take advantage of the extremely rich amount of spatial data from new data sources available in GIS. But there is no easy bridge which can be established between GIS and spatial analysis technology. From a technical point of view four ways to link GIS and spatial analysis may be distinguished (see Openshaw 1990; Goodchild 1987, 1991):

- *First*, the strategy to develop generic spatial analysis function tools to be integrated into proprietorial GIS as standard GIS operators (full integration of spatial analysis tools into GIS technology).

- *Second*, the strategy to write user-friendly interfaces to special statistical software packages for spatial data (loose coupling of GIS and spatial analysis due to the lack of GIS-oriented spatial analysis technology in statistical software packages).

- *Third*, the strategy to develop a basic spatial tool box for inclusion in standard statistical packages (SPSS-X, SAS, GLIM, GAUSS or RATS) to provide a set of independent portable spatial analysis macros which can co-exist with a targeted GIS (close coupling of GIS and spatial analysis).

- *Fourth*, the strategy to embed GIS procedures (a strategy inverse to the first one) within spatial analysis or modelling frameworks which attempt to exploit the unique capabilities of GIS technology to devise new and more relevant analytical procedures (full integration of GIS procedures into spatial analysis and modelling frameworks).

Irrespective of the specific approach adopted in practice, there is a wide agreement in both the GIS and the modelling community that the future success of GIS technology will depend to a large extent on incorporating more powerful analytical and modelling capabilities (see Fischer and Nijkamp 1992a).

3. GIS and Spatial Modelling

In the context of an interplay between GIS and spatial modelling, Birkin et al. (1987) speak of a necessary marriage between these two research tools in order to provide adequate decision support to policy-makers. They distinguish techniques for: transformation of data, synthesis and integration of data, updating information, forecasting, impact analysis, and optimisation. They conclude that the two approaches have barely come together because of different historic traditions and research foci.

The following procedures may be considered as a non-exhaustive set of examples of GIS-relevant spatial analytic procedures and techniques (see also Openshaw 1990):

- exploratory point pattern and area data analysis procedures for identifying spatial patterns and relationships,
- regionalisation (i.e. classification with contiguity constraint) to deal with the zone design and spatial representation issues, and aggregation procedures suitable for use with large spatial data sets,
- spatial response models of various kinds including regression procedures coupled with the Moran coefficient function and its standard error to test for spatial autocorrelation in residuals,
- space-time statistical models for acquisition, storage, analysis and forecasting,
- tools for handling origin-destination relationships in spatial and space-time systems,

- location-allocation models,
- optimum route procedures,
- spatial search procedures,
- spatial data interpolation procedures (co-kriging interpolation),
- Thiessen models in which point information is modeled into a series of polygon definitions, using nearest neighbour concepts,
- Gaussian diffusion models for a single point and for multiple points,
- techniques for monitoring the propagation of errors (Monte Carlo Simulation),
- fuzzy set based analytic procedures to deal with imprecision in measurements, inconsistency of data and imprecision in concept,
- artificial based spatial analysis models.

No current commercial geographic information system comes close to provide these spatial procedures. Advanced spatial analysis modules may be considered to be critical elements for the next generation of more intelligent geographic information systems based on principles of artificial intelligence.

How the question of an integration between GIS methods and spatial models and techniques depends on the existence of a compatible intermediary (following Hempel's 'bridge principle' of a one-to-one mapping). It is noteworthy that in the area of spatial modelling there is a wide variety of such models, ranging from input-output models to multiregional multi-objective models or urban land use models. On the other hand, in the GIS tradition the spatial component is explicitly present in overlay tools of analysis (cf. Bailey 1988). Now the main question is whether it is possible to ensure a one-to-one mapping between GIS overlay information and model input or output (cf. Lewis 1977). This would require editing, updating, performing algebraic operations, using statistical methods, performing simultaneous queries and geographically displaying of all layer information. In this context, a relational data base system is a necessity. For instance, the well-known SPANS, in which the user can enter geographic data from digitizers, manually or by transforming existing types of data, allows to transform various layers of information from point, line or areal data in vector or raster form, or in a quadtree. The spatial resolution of the data depends then on the a priori established scale of the area and the data precision. Digital data sources such as digital elevation data, digital base maps and remote sensing data are necessary for a proper treatment of data input and output functions (by using e.g. scanning and manual digitizing), while both vector and raster technologies can be used for GIS colour monitor displays. Further details on these issues can be found in Fischer and Nijkamp (1992b).

In principle, GIS and spatial modelling can be complementary approaches in two respects:

- in the area of spatial pattern and flow recognition, where spatial differences - in multiple dimensions - can be shown either by statistical representation or by GIS computer graphics and maps; the choice for one of the two representations depends on the complexity of the pattern to be represented (in various cases colour maps give a more direct visual image of main features of a data set);

- in the area of explanatory and predictive analysis, spatial models are usually more powerful than GIS in carrying out precisely numerical experiments (unless geographic information is very precisely digitized), but the final results can again be used by a GIS as an input for a user-friendly computer presentation.

The main problem is that current GIS are less suitable for explanatory or predictive modelling compared to conventional spatial analysis. Nevertheless, it is noteworthy that some progress has recently been made, e.g., in the field of spatial location-allocation modelling, where traditional spatial interaction tools have been linked to a GIS representation of the resulting patterns and flows. To some extent one may claim that GIS seems to be a more proper tool for perception/visualisation methods for impact analysis rather than a direct impact tool in itself.

Also in dynamic modelling the same remarks hold essentially. GIS is so able to produce dynamic maps in connection with the result of a dynamic descriptive explanatory or predictive dynamic model. In this context GIS is a meaningful vehicle for dynamic scenario analysis. A good example can be found in Despotakis et al. (1991), who used a dynamic system model in a GIS environment in order to identify and evaluate various strategic development scenarios for a sustainable evolution of the Greek Sporades islands.

In recent years, much attention has been given to the coherent and joint use of GIS and spatial models in spatial analysis and planning. An integration of both modes seems for the time being a too ambitious task. However, there is a field where GIS and spatial modelling may provide immediately and consistently analytical support, viz. in the area of policy analysis (evaluation and planning).

4. GIS and Decision Support

Decision support and expert systems may be viewed as systems which achieve expert-level performance, utilising artificial intelligence (AI) concepts and programming techniques such as connectionist models (for example, the concept of neural networks), symbolic representation, inference and heuristic search. A fully fledged decision support and expert system may be considered to have four essential components (see Benfer et al. 1991, Forsyth 1989b, Fischer and Nijkamp 1991c) (see Fig.1):

- a knowledge base consisting of spatial and non-spatial knowledge about some substantive domain,

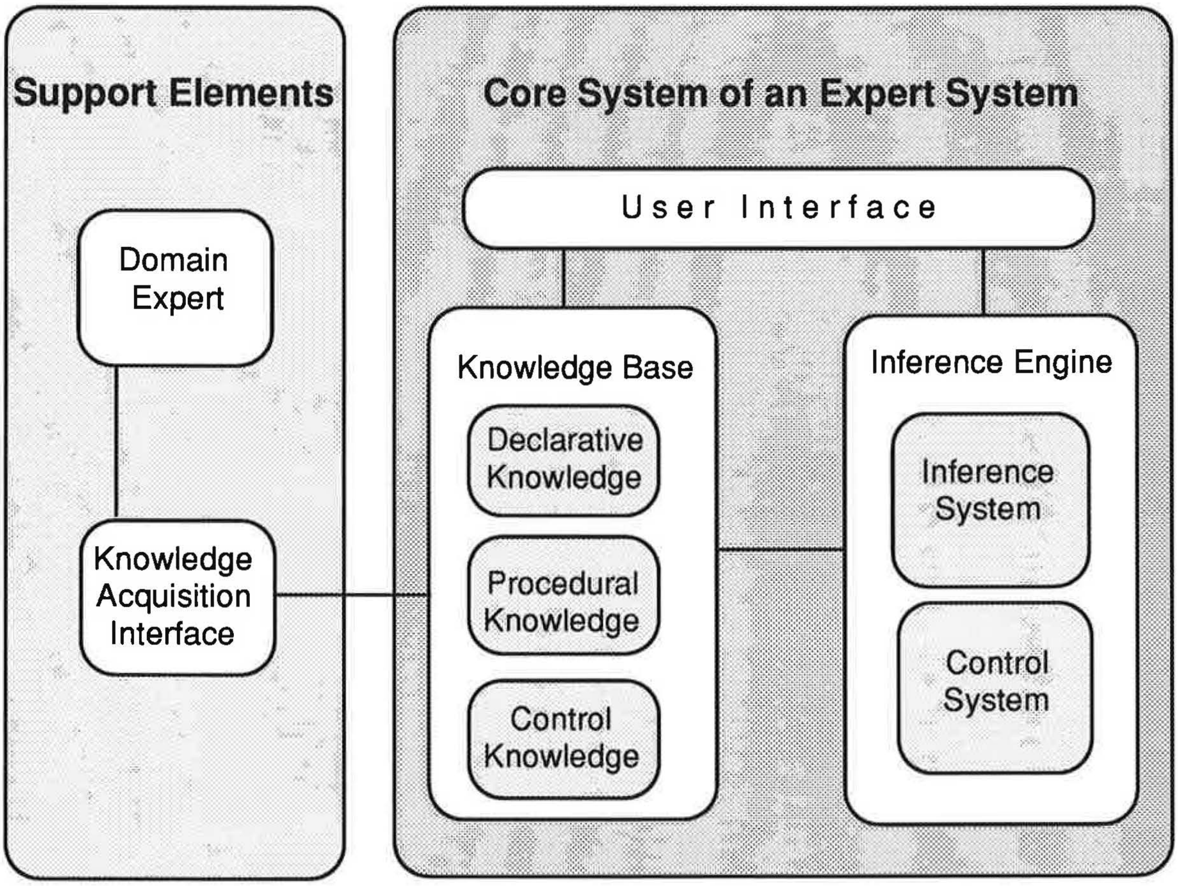
- an inference engine consisting of a set of general (search and) inference procedures to reason from knowledge in the knowledge base and to infer additional conclusion,

- a knowledge-acquisition module to assist in expressing knowledge in a form suitable for inclusion in the knowledge base,

- an user interface which assists the user to consult the spatial expert system.

The knowledge base is elicitated from a domain expert and reformulated as a collection of rules, a network of facts or a frame-based structure. The relative maturity of decision support and expert systems is reflected in the variety of alternative, and sometimes complementary knowledge representation techniques. The mainstream approach to knowledge representation has been inspired by the insights of mathematical logic and is symbolic in nature. The production rules format, simple condition-conclusion or condition-action statements (IF condition THEN action, or IF condition THEN action 1 ELSE action 2), is the most widely used way of symbolic encoding of knowledge. More complex representations are mostly frame or object-oriented systems. In contrast to a symbolic representation of knowledge the connectionist architectures, strongly inspired by the concept of neural networks, are more committed to the principle of inter-connectivity (Shadbolt 1989). One major difference between symbolic and connectionist types of knowledge refers to whether knowledge has to be explicitly or implicitly represented (see Forsyth 1989c).

Fig. 1: System Architecture of a Knowledge-Based GIS



In general, the knowledge in a knowledge base may consist of three types:

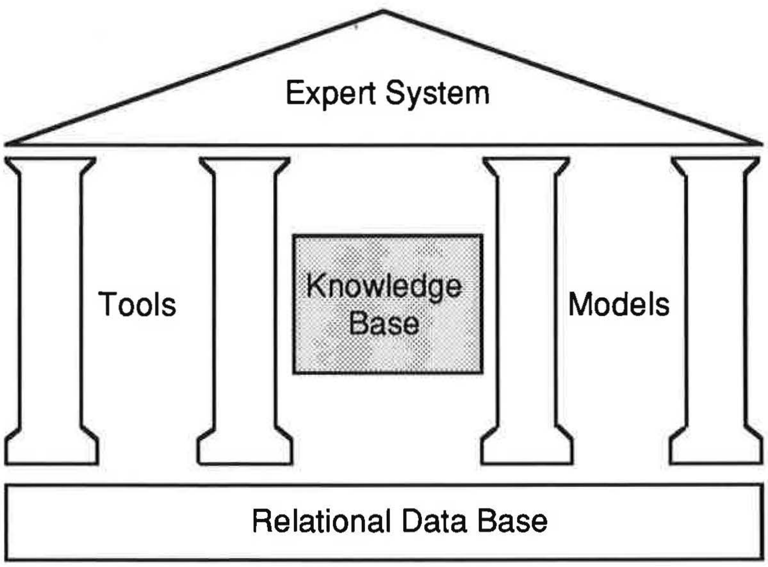
- Declarative or factual knowledge (spatial object knowledge and useful spatial and non-spatial feature information about the objects),
- Procedural or strategic knowledge (the core of a knowledge base) including concepts and various relationships (definitional, taxonomic, associational and empirical relationships) among them,

- Control knowledge (usually based on rules of thumb) for a variety of control strategies which allow to rule out obviously wrong solutions and to focus on the mere promising ones.

Such knowledge-based systems are particularly useful in case of 'qualitative reasoning', one of the scientific fields that forms the basis for artificial intelligence (see Weld and De Kleer, 1990). Qualitative reasoning aims to make good quantifications of continuous properties of the world in the absence of a set of fully descriptive equations (see Forbus 1988). Applications may relate to quality of life analysis in urban areas, neighbourhood quality analysis, search analysis on the housing market, marketing etc. All such issues are multidimensional in nature and a spatial mapping of such items via GIS based systems offers a great potential for a comprehensive and solid analysis.

The previous observations can also be summarized in the so-called information system temple sketched in Figure 2, where a relational data base is regarded as the foundation of a knowledge base, which - in conjunction with mathematical, statistical and software tools - form the ingredients for an expert system. It is evident, however, that so far the operationalisation of such analytical approaches is very rare, and therefore there is a need for a further investigation of experiences in this field.

Fig. 2: The Information Systems Temple



After this overview of recent developments at the interface of GIS, spatial modelling and decision support methods, we will in the next section discuss in a concise manner some illustrations of interesting applications, followed by a sketch of open research questions.

5. Applicability of GIS-Based Models: Some Illustrations

The GIS revolution is apparently causing a major shift in the use of mathematical models and spatial analysis techniques, ranging from hybrid GIS-DSS (Decision Support Systems) Models and Intelligent Knowledge Based Systems (IKBS) to Artificial Intelligence (AI) methods and neurocomputing. From this broad spectrum of interesting and promising approaches we have selected here a few operational contributions which by far do not claim to be representative nor exhaustive.

A GIS-linked decision support system for urban policy evaluations and resource management

In a recent paper (Hirschfield et al., 1992) the authors describe some key features of an information system designed by URPERRL (Liverpool) for monitoring urban needs and targeting resources in a large metropolitan local authority (St. Helens Borough Council) in North West England. Particular attention is paid to the identification, assembly and integration of the various data sets required for monitoring purposes, and how these are used in a GIS-linked decision support system to provide intelligence and guidance on questions of resource allocation and in planning for the future. The system created for St. Helens incorporates a wide range of spatially-referenced data sets covering demography, social conditions and basic infrastructure, handled within an Arc/Info-based GIS framework. The database has been used to address a number of policy-relevant questions concerning the operation of the Urban Programme in St. Helens. These include:

- reviewing the existing definition of priority areas;
- targeting projects to specific areas and beneficiary groups; and
- assessing the impact of projects against objectives and output measures.

The authors describe the steps required to achieve all of this (such as, for example, searching for data, capturing data, designing the information system) and describe the ways in which GIS features have proved useful in the production of outputs from the process (such as, for example, in priority profiling). The authors indicate also how the system might serve as a model to support strategic planning in other local authorities.

Residential quality assessment by means of GIS

Another recent GIS contribution offered by Can (1992) focuses on the construction of operational measures of residential quality based on socioeconomic indicators to identify homogeneous areas which will assist in the delineation of neighborhood boundaries in urban areas. Specifically the effect of spatial scale and the method used in the measurement of quality scores is addressed. With respect to the former, two major socioeconomic reporting zones of the US Census Bureau, namely tract and block group, are employed. With respect to the latter, factor analysis and generalized concordance analysis are selected as representative methods from multivariate statistics and the multicriteria evaluation framework, respectively. The spatial distribution of quality scores based on different scales and methods are examined using spatial autocorrelation statistics in order to discriminate between tract and block group as the spatial unit that should be used in the formation of neighborhoods. To illustrate these concepts the City of Syracuse in New York state has been selected as the study area. The spatial analysis undertaken in this project is integrated into a vector-based GIS environment via ARC/INFO. This facilitates both the integration of attribute information with locational information and the generation of intermediate information needed in the construction and evaluation of quality indices. US Census Bureau's TIGER files are used to create geographic base maps, whereas the Census of Population and Housing is used in the generation of the attribute data base. Algorithms developed in the C programming language for the generalized concordance analysis and spatial autocorrelation statistics are integrated into ARC/INFO using macros. This not only adds to spatial analytical capabilities of a vector-based GIS but also illustrates the benefits obtained in the application of GIS to decision making in urban applications. The spatial query and analytical capabilities of a GIS definitely facilitates the incorporation of criteria based on topological characteristics in addition to enhancing simple visual examination.

The scope of GIS-based models is clearly reflected in a recent study by Despotakis (1991). In his large-scale regional development study he focused attention on principles and actual policies for co-evolutionary planning and development of the Greek Sporades islands. A Geographical Information System (GIS) which may assist Sustainable Development (SD) for an area was developed in this study. This GIS-SD system was linked to a Decision Support System (DSS) for an evaluation of its spatio-temporal results in the context of selected SD criteria. The whole system was then applied to the test area of the Greek Sporades islands in the Aegean sea, for which relevant data at various spatial levels and with different degrees of reliability were selected. The results showed that GIS may be successfully employed to assist, monitor and control ecologically sustainable economic development for a region. This is achieved by applying certain strategic policies which are based on optimum - from the sustainability point of view - development scenarios generated by our system. The underlying model system was based on a combination of meso-economic models for the area and micro land use developments (including the marine environment). GIS appeared to be able to create the intermediate link between these layers of the model system, while the results - originating from scenario and simulation experiments - can be visualized in an attractive computer graphic way. Alternative development alternatives for the islands group could next be evaluated by means of multi-criteria analysis.

The previous illustrative descriptions point out one important message: GIS-based modelling is at a rising edge, but has certainly not yet reached its maturity.

6. Future Developments

GIS-based modelling has a rich potential which should be focused in any case on the following promising research areas:

- *Improved Models*

  Spatial and non-spatial models should in terms of design, specification and underlying database be made much more compatible seeking for an integration of GIS approaches and conventional mathematical models.

- *Integration with Remote Sensing*
  The potential of the remote sensing satellite data lies in their capability of providing researchers with (1) multispectral and (2) multitemporal raster data. These data may serve as additional data layers for the region under investigation.

- *Improved error analysis*
  An improved error analysis module which may operate in parallel with the whole GIS-based model system is necessary. Such a module would provide detailed information on the expected quality of the data and the model results. If we would like to increase the output quality, we would have to collect more data or improve the models; in case the predicted quality was sufficient, we would proceed with the model simulation runs.

- *Intelligent Spatial Decision Support Systems*
  The use of fuzzy logic (e.g., fuzzy sets in database design, or representation of fuzzy spatial concepts), expert system technologies and GIS is a likely fruitful new research direction. In this context, Leung (1992) has recently developed a interesting system architecture comprising a fuzzy-logic-based expert system shell (with a maps display module), a fuzzy information retrieval module and a database management system.

- *Link with AI Techniques*
  The recent advances in the field of AI technology offer a new potential to be explored by GIS. Especially in the field of spatial analysis, the new AI tools offer many possibilities to be utilized. These include amongst others the application of neural networks, pattern recognition methods, group method data handling methods and genetic algorithms for analyzing 'soft' (input or output) information.

References

Bailey, R.G. (1988): Problems with Using Overlay Mapping for Planning and Their Implications of Geographic Information Systems, **Environmental Management**, vol. 12, no. 1, pp. 11-17.

Benfer, R.A., Brent, E.E. Jr. and Furbee, L. (1991): **Expert Systems**. Sage University Paper 77, Beverley Hills.

Birkin, M., Clarke, G.P., Clarke, M. and Wilson, A.G. (1987): Geographical Information Systems and Model-based Locational Analysis; Ships in the Night of the Beginnings of a Relationship?, WP-498, School of Geography, University of Leeds, Leeds.

Can, A. (1992): Residential Quality Assessment: Alternative Approaches Using GIS, in Fischer, M. M and Nijkamp, P. (eds.): **Geographical Information Systems, Spatial Modelling and Policy Evaluation**. Berlin: Springer Verlag (forthcoming).

Clarke, M. (1990): Geographical Information Systems and Model Based Analysis, in Scholten, H.J. and Stillwell, J.C.M. (eds.): **Geographical Information Systems in Urban and Regional Planning**. Dordrecht: Kluwer. pp. 143-161.

Despotakis, V. (1991): **Geographic Information Systems for Sustainable Development Planning**, Ph.D. Dissertation, Dept. of Economics, Free University, Amsterdam.

Despotakis, V., M. Giaoutzi and P. Nijkamp, (1992): Spatial Depiction of Local Sustainable Development, in Breheny, M. (ed.): **Sustainable Development Planning**. London: Pion (forthcoming).

Dueker, K. (1987): Geographic Information Systems and Computer-Aided Mapping, **Journal of the American Planning Association**, vol. 53, no. 3, pp. 383-390.

Fischer, M., and Nijkamp, P. (1992a): GIS and Spatial Analysis, **Annals of Regional Science** (forthcoming).

Fischer, M., and Nijkamp, P. (1992b) (eds.): **Geographic Information Systems, Spatial Modelling and Policy Evaluation**. Berlin: Springer Verlag.

Fischer, M., and Nijkamp, P. (1992c): Design and Use of Geographic Information Systems, Spatial Models, in Fischer, M.M. and Nijkamp, P. (eds.): **Geographic Information Systems, Spatial Modelling and Policy Evaluation**. Berlin: Springer Verlag (forthcoming)

Forbus, K. (1988): Qualitative Physics: Past, Present and Future, in Shrobe, H. and American Association for Artificial Intelligence (eds.): **Exploring Artificial Intelligence**. Palo Alto (Cal.): M. Kaufmann. pp. 239-296.

Forsyth, R. (ed.) (1989): **Expert Systems, Principles and Case Studies**. London et al.: Capman and Hall.

Goodchild, M. (1987): A Spatial Analytical Perspective on Geographical Information Systems. **International Journal of Geographical Information Systems 1**, pp.327-334.

Goodchild, M.F. (1991): Progress on the GIS Research Agenda, in Harts, J., Ottens, H.F.L. and Scholten, M.J. (eds.): **EGIS '91. Proceedings, Second European Conference on Geographical Information Systems**, Volume 1, pp. 342-350. Utrecht: EGIS Foundation.

Hirschfield, A., P.J.B. Brown and J. Marsden (1992): Matching Resources to Urban Needs, in Fischer, M.M. and Nijkamp, P. (eds.): **Geographical Information Systems, Spatial Modelling and Policy Evaluation**. Berlin: Springer Verlag (forthcoming).

Leung, Y. (1992): Towards the Development of an Intelligent Spatial Decision Support System, in Fischer, M.M. and Nijkamp, P. (eds.): **Geographical Information Systems, Spatial Modelling and Policy Evaluation**. Berlin: Springer Verlag (forthcoming).

Nijkamp, P. (1990): Geographical Information Systems in Perspectives, in Scholten, H.J. and Stillwell, J.C.H. (eds.): **Geographical Information Systems for Urban and Regional Planning**. Dordrecht: Kluwer. pp. 241-252.

Openshaw, S. (1990): Spatial Analysis and Geographical Information Systems: A Review of Progress and Possibilities, in: Scholten, H.J. and Stillwell, J.C.M. (eds.): **Geographical Information Systems for Urban and Regional Planning**. Dordrecht: Kluwer. pp. 153-163.

Shadbolt, N. (1989): Knowledge Representation in Man and Machine, in Forsyth, R. (ed.): **Expert Systems. Principles and Case Studies**, pp. 142-170. London et al.: Chapman and Hall.

Weld, D. and De Kleer, J. (eds.): (1990) **Qualitative Reasoning about Physical Systems**. Palo Alto (Cal.): M. Kaufmann.