DEVELOPING SPATIAL ANALYSIS FUNCTIONS RELEVANT TO GIS ENVIRONMENTS

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1 Introduction

The GIS revolution that started in many countries in the mid-1980s is creating an immense wealth of spatial information in a large number of different application areas. Sooner or later the analogue map data conversion process will be completed and nearly all the computer databases relevant to many aspects of environment and human society on a global scale will be available with locational referencing attached. Also, quite soon now, the emphasis on GIS database creation and systems building will quite naturally be replaced by a new concern with **analysis**. The massive proliferation of spatial information, a continuing downward trend in hardware costs and the emergence of a new era of computation with computer speeds and memory capacities moving into 'terracomputing' domains will help create an environment where spatial analysis will not merely be of increasing interest and value but in some areas an absolute necessity. More and more users will want to analyse their data with increasing degrees of imperative, for a range of good public, community, commercial and research reasons. An increasing number of these analysis tasks will be real-time (or almost) and the vast majority will probably involve forms of spatial analysis that do not as yet exist except in a most nascent form. The drive behind these future analysis needs is threefold: (1) new requirements to make use of the information resources created by GIS, (2) attempts to gain competitive or other benefits from IT, and (3) hardware improvements that trivialise the computational requirements. Maybe, already, it is a scandal that so many of the key, important, databases are not being properly analysed; for example, morbidity, mortality, cancer data, or crime databases; whilst commercial concerns and government agencies probably waste many millions (if not billions) by poor spatial analysis of needs, inefficient spatial planning of facilities and poor targeting of resources (Openshaw, 1994a). If better, more relevant, spatial analysis tools were available then they would almost certainly be used. Some even claim that their non-availability threatens the viability of GIS itself (Openshaw and Brunsdon, 1991)

The post GIS revolutionary world of the 1990s is quite different from the primeval computing and data environments in which many of the existing spatial analysis and modelling technologies were developed. Are these old technologies still appropriate or is a new period of basic R and D needed to create the spatial analysis tools likely to be required in the late 1990s and beyond?. This paper attempts to address some of these concerns by focusing on the general and generic aspects in an attempt to broadly define the types of new exploratory spatial data analysis that is likely to be most relevant for use within GIS whilst at the same time recognising the usefulness of some of the more traditional spatial analysis tools.

The mid 1990s seems a good time for a far reaching and fundamental re-think on GIS functionality because spatial analysis is entering a new era in the development of quantitative geography and new analysis needs are being created and stimulated as a by-product of GIS. Birkin et al (1996) argues that there are three broad responses to the poor spatial analysis routines currently available in proprietary packages. The first is 'simply' to add more functions as standard menu options. The second recognises that the needs for spatial analysis are increasingly becoming data driven; analysis is to be performed because data exist and a user wants some analysis as an adjunct to other GIS activities. This is quite different from more traditional quantitative geographic concerns performed as acts of scholarship in a research context. The third response is to recognise the usefulness of some existing methodologies and then attempt to couple this sort of analysis into current GIS packages. Birkin et al (1996) describe this approach in some detail using spatial modelling methods. Their basic argument is that we now have a vast experience of applied urban modelling which should not be lost in the new era of data driven spatial analysis but it will be unless the tools become more widely available. Adopting the second and third strategies for GIS futures requires a major change in emphasis and is the subject for the rest of this paper.

This change in emphasis and its implications have not been properly understood. The lack of recognition of these new needs can be seen in the continuing confusion as to what spatial analysis in GIS actually means. Moreover whilst there is a general consensus that spatial analysis functionality is needed in GIS tool-kits, there is no agreement about what kinds of spatial analysis methods are most relevant to GIS and which ones are not. The various Spatial Analysis and GIS initiatives (NCGIA I-14) workshops and conferences and the RRL initiative have not only failed to clarify the situation but have probably, yet unwittingly, contributed to the confusion. It is useful to note at this point that despite considerable publicity for the NCGIA I-14 Spatial Analysis and GIS initiative, it was later admitted to be primarily a public relations exercise. The total resources expended probably amounted to less than £35,000 (Fotheringham and Rogerson, 1993). Maybe the current state of spatial analysis confusion is, therefore, understandable. Despite many promisingly titled books on the subject of Spatial Analysis and GIS (or vice-versa); see for instance Fotheringham and Rogerson

(1994); most of the problems have not been solved although there is now a much improved awareness of some of the issues.

A broader consensus about a set of GIS relevant spatial analysis methods is important for a number of strategic reasons: it defines in an explicit manner the nature of the analysis technology that needs to be provided, it sets a research agenda for developing relevant new methods, and it offers a focus of attention for international attempts to develop spatial analysis tools for GIS via collaborative exercises. The question "What kind of spatial analysis do we want in GIS?" has to be tempered by the feasibility constraint of what kinds of spatial analysis can be implemented in GIS and the sensibility constraint, what kinds of spatial analysis is it sensible to provide for GIS environments? Another set of general design constraints reflect other considerations such as who are the likely users, what is it they want, and what sort of analysis technology can they handle given likely fairly low levels of statistical knowledge and training in the spatial sciences. **Table 1** summarises the principal design questions. It is possible that the answers to these sorts of questions will shape the particular direction future GIS applications will take. It is noted that user ability criteria are very important and the future viability of whatever technologies are proposed will ultimately depend on this extent to which the methods can be safely packaged for use by non-expert users. We often forget that in the future the users are unlikely to be a handful of highly skilled researchers performing basic or pure research but end-users interested in making or supporting decision making that impacts on real people in a broad range of application areas. If the questions (or criteria) in Table 1 are applied to the set of available spatial analysis, spatial statistical, and spatial modelling tools, then it is quite clear many will never fit.

The debate as to whether these methods should be accessed from within or without a GIS package is really quite irrelevant. There is no reason to insist on only one form of integration or interfacing, except the obvious point that to be a GIS tool the spatial analysis operation has to be called from, and end within a GIS environment but in an era of heterogeneous distributed computing there is no longer any need for all the systems to be on the same machine. Equally the extent to which methods are perceived as having to be run within a GIS environment is often overplayed. What does GIS have to offer spatial analysis that is unique? In practice, it often amounts to little more than spatial data and consistently defined contiguity lists; in which case much system complexity can be avoided by the simple expedient of separating out the different components needed by the analysis process and developing a high level system to call a GIS here, a model or analysis tool there, and a map drawer if one is needed. It is no longer the case that only those methods which can be physically put

Table 1 **Basic design questions**

What kinds of spatial analysis are:
relevant to GIS data environments
sensible given the nature of GIS data
reflect likely end user needs
compatible with the GIS style
capable of being used by end users
add value to GIS investment
can be an integral part of GIS
offer tangible and significant benefits

into a single GIS, or which have access to fully functional spatial data bases at a low level can perform any kind of spatial analysis.

2 Statistical geographic hangovers

It is useful to start by trying to put many existing traditional spatial analysis methods in a proper historical context. Quite simply, many do not belong to the GIS era. Similar 'unkind' thoughts can also be applied to many largely aspatial statistical methods originally designed for use in survey sampling contexts with data collected by simple random sampling. These are seldom spatial analysis relevant methods because they treat spatial information as if it were equivalent to sampled survey data, and generally fail to handle many of the key features that make spatial data special (i.e. spatial dependency, non-sample nature, modifiable areal unit effects, noise and multivariate complexity) The vast literature of historical statistical geographical books should, in general, be seen for what they really are; introductions to statistical methods that are of geographic interest mainly because they have been written for a geographical audience. The application of aspatial statistical methods in GIS might appear sensible but it has to be recognised that the technology may often be inherently unsuitable and, whilst most methods may be harmless, they are not all safe. An example of the latter might be ranking zones by a Z-score, a widely used procedure in targeting areas for resource allocation. This seemingly simple and safe procedure has a number of fundamental problems. These include: spatial autocorrelation which might inflate Z-score values, the zones being ranked are not comparable entities, the data are not measured with the same degree of precision (more extreme results are more easily obtained in small zones rather than big ones), and the results depend on the scale of the areal units used.

Many of these problems associated with the analysis of spatial data are not new and their existence have been known about for at least 25 years. As a result, most of the statistical geographical literature is simply not relevant to GIS. We believe that key texts such as Ebdon (1977) Gregory (1963), Taylor (1977) Haining (1992), Griffith and Amrhein (1991) and many others of a similar nature contain little or nothing relevant to GIS. They are simply not appropriate as a source of GISable spatial analysis tools even if they are all excellent texts describing the use of statistical methods to spatial data. Anselin (1989) clearly recognises some of the statistical problems exists when he argues:

"With the vast power of a user-friendly GIS increasingly in the hands of the non-specialist, the danger that the wrong kind of spatial statistics will become the accepted practice is great. Since the 'easy' problems have more or less been solved, a formidable challenge lies ahead." (p14-15).

Indeed developing new and more relevant purely statistical methods suitable for use with spatial data looks like being too difficult for current technology particularly when it has to be performed in a rigorous fashion within a classical statistical framework. But is this really what GIS needs? Might it not be easier to contemplate more data map descriptive and less statistical theory dependent technologies? Maybe the statistical problems are just too hard to be resolved at present, so why not change the nature of the problem to make it easier to handle? It should be possible to do this because purely spatial statistical analysis is probably not what most GIS end-users want or need. Futhermore geographers have in the traditional concept of the map probably the best visualisation tool ever invented. Why not use it rather than feel embarrassed about it, as it seems many human geographers now tend to do? New map based spatial analysis technologies are probably what is needed most.

The problem with much traditional statistical analysis in geography dates back to Cliff and Ord (1973). The assumption (based on the 1950s spatial statisticians) is that it makes sense to summarise whole map patterns by a single numerical index or test whole map statistics for departures from randomness. The classic Irish County (N = 27 observations) data was too small for the dependency of the results on a particular set of areal units (at the time no other set was probably available) and the fundamental limitations of interpreting whole map statistics to be evident. Scale the methods up by applying them to much larger sets of zones and all manner of geographical problems appear The need now is to disaggregate the whole map statistics and to develop effective means of identifying localised spatial heterogeneities and localised patterning within rather than over maps.

The real challenge that GIS presents is to re-think what GIS relevant spatial analysis is now needed, free from a bias that insists on this or that pet method always being applied. It is becoming important to dump much of the obsolete baggage of the statistical geography past and try to develop some new spatial analysis tools that are simultaneously: GISable, relevant to the needs of GIS based users, and appropriate for spatial data. In so doing it is particularly important to be aware of the misinformed and of the very considerable sensitivities that exist in some areas about the quality of the spatial statistical analyses performed by geographers. Martin (1990) expresses this as follows:

> "It seems unfortunate to me that non-statisticians who publish statistics, however flawed, are held in high esteem in their professions, whilst statisticians who publish statistics, however good, are seen as doing no more than trade." (p. 117).

The answer in many cases can be simply to replace the term statistical analysis by geographical analysis but this really misses the point because geographical analysis involving numbers is, by definition, statistical analysis. The problem of geographical common sense also needs to be addressed. Far too many statisticians seem to hold (or have once held) the naive view that the role of the geographer is to define the problem, pass them some data, and wait for the definitive statistically approved results to appear. However, it is not satisfactory to separate spatial analysis functions from an understanding of the geography of the problem. Neither statistical nor geographical knowledge are by themselves sufficient; both are necessary, and it is important that both sets of skills are brought together. This is particularly so because there is a growing recognition that there is no easy, theoretical solution to many of the problems of statistical spatial analysis. There are a number of areas of difficulty: many hard to solve statistical problems: no clear statement of needs: probably no sound theory based multivariate spatial statistical methods available in the short term: and at least some users who have unrealistic expectations.

3 Spatial Modelling Hangovers?

So far we have been particularly critical of statistical methods in GIS as we believe that adding a new regression or spatial autocorrelation procedure to this or that GIS is not the answer for many 'real-world' GIS users. In some respects, the same arguments might apply to a number of mathematically-based modelling procedures. We note with some concern the current trend for each GIS to offer some kind of, usually pre 1970s, spatial interaction modelling capability. Whilst we are convinced that many such methods will remain applicable to GIS environments of the future the whole question of how to access good mathematical models of spatial systems still needs to be resolved in a satisfactory fashion. Maybe, here is a classic example, of a technology that does not need to be imprisoned within the straight jacket of a proprietary GIS where it may only utilise 1% of the available GIS functionality.. The major advantage of models lies in their ability not only to address what-is? questions, but also the crucial what-if? questions that many organisations desperately require for future planning. Spatial modelling procedures based on spatial interaction or location optimisation etc are generally very good at addressing these sorts of questions. However, those now appearing in proprietary GIS are both inadequate and often presented as black-box solutions ignoring 25 years of work on the problems of model specification, parameter estimation, and model evaluation. Benoit and Clarke (1995) provide an evaluation of the appropriateness and ease of use of spatial interaction models for retail analysis in proprietary GIS packages. Thus, whilst it is likely that spatial modelling procedures will continue to be coupled to GIS software, most of the specialist modelling will take place outside, but loosely linked to, the main package environment. The skills required to handle the complexities of applied spatial modelling makes 'generic' solutions difficult but it is important to stress that not all progress should be technology-led. If applications demand what-if? planning then geographers have a role to provide these solutions. These arguments are taken further in Birkin et al (1996).

4 Ten basic rules for identifying future GISable spatial analysis technology

It is useful to try and be quite clear as to what is needed without being to concerned initially with how to achieve it. The aim here is to create a list of criteria able to discriminate between GISable and GIS-irrelevant technology; see also Openshaw (1994b) and Openshaw and Fischer (1996).

4.1 A GISable spatial analysis method should be able to handle large and very large N values

In the GIS era data sets typically have large N values. It is interesting that the N values in many databases will soon reach their theoretical maximum values. For example, in the UK there are about 150,000 census enumeration districts, 1.6 million postcodes, and an ultimate limit of about 55 million persons whose homes will soon have a sub 1m grid-reference. This may seem a lot but computer hardware can now handle these dimensions with ease. Hardly any GIS users will be interested in 20 or 50 zones; if they are, then they should realise that data of two or three order of magnitude greater resolution exist and might be preferable even for local and sub regional scale studies. Accordingly any statistical method that involves the use and manipulation of several N by N matrices is probably not sensible to include in a GIS. Of course it is possible to perform matrix operations on quite large N values but perhaps not within a regular GIS environment. As computer power increases then the problem of matrix size in mathematical modelling (such as spatial interaction models) also diminishes but it is likely to remain problematical for a long time yet.

4.2 Useful GISable analysis and modelling tools are study region independent

Spatial pattern analysis results that depend on, or are determined by, the arbitrary definition of a study region are not useful. This observation is a simple extension of the modifiable areal unit problem. It is also geographical common sense. At one level it is a trivial and obvious problem. If you study data just for Scotland and then repeat the analysis for England and Scotland, or just Leeds, then the conclusions obtained from the results will probably differ. The differences reflect variation in the phenomenon under study, the choice of study region, and interactions between the two. However, the effects of this are so obvious that it is often completely ignored. For example, if you wish to summarise the distribution of pubs in Leeds by a nearest neighbour statistic then the results depend on the definition of Leeds and on the patterning of pubs within Leeds. In the north, it might be systematically and spatially even, in the south it might be random, and in the city centre clustered. The result for the whole of Leeds averages out all these differences and will almost certainly be a meaningless outcome unless the spatial pattern of pubs is more or less the same everywhere.

Another example might help clarify this further. Imagine a cancer data set with one very strong cluster. If a small study region is selected that includes the cluster (probably by chance) then virtually any spatial pattern statistic will detect its existence. If this is done deliberately then it is a form of gerrymandering the results by boundary tightening. If the study region is then increased in size by expanding its geographic extent and adding randomly located cancer cases there comes a point when the cluster is lost in a sea of randomness. As the study region decisions may be arbitrary and are seldom part of the analysis process, so it follows that *whole* map statistics should not be used. They are not as helpful in GIS except where the whole map region is characterised by only one distinctive type of spatial pattern. The concern now is therefore to define and measure localised patterns rather than global ones. This distinction is of fundamental importance.

Scale effects provide an additional level of complexity. For example, if the answer to the question 'does a disease cluster at the District scale?' is no, this does not mean that some Districts will not have localised clustering within them nor that at a small area level there might be considerable clustering. What it does indicate is that when viewed at an aggregate District scale, clustering is not a characteristic phenomenon of the disease under study. This may be a useful but limited result with a great potential to mislead. From a geographical point of view it is the localised clustering of small scales that are of greatest interest. Indeed, it is hard to imagine why District level clustering (given the heterogeneous nature of Districts) should be of any great interest to anyone. The disease processes simply do not operate at that scale unless they are somehow related to causative agents that are specific to Districts!

It is argued, therefore, that in most analysis applications spatial pattern detectors are needed which can look within the map to find patterns and relationships that are geographically localised in extent and not global. This is important to avoid the modifiable study region effect and because geographic space is not characterised by uniform densities of anything. In a spatial context techniques that can detect or model only global patterns or relationships need to be used with great circumspection and, ideally, not at all.

4.3 GIS relevant methods need to be sensitive to the special nature of spatial information

To be relevant to GIS the spatial analysis tools should be able to handle spatial information in a reasonable manner, taking into account rather than ignoring any special features that matter. The corollary of this statement is that if an analysis tool has been developed for use with aspatial data then it will probably be inappropriate for use with spatial data without major modification.

Table 2 lists some of the features that characterise spatial data. Of particular importance is the spatially structured nature of data precision and errors. They are not spatially random. Database anomalies might be detected as patterns but could just as easily be data error and reflect other data inconsistencies. Also, the data to be analysed are often known to be wrong but still have to be used. An example is the analysis of cancer data consisting of incidents for 1969-84 using denominator for either 1971 or 1981. The temporal resolution of the different components of the data differ. The data riches of the GIS world is often achieved at the expense of accuracy and the spatial analyst faces the prospect of what might be termed 'poor data analysis', and of having to analyse data containing a mixture of different levels of error and uncertainty about which nothing can be done. Similarly, in relation to spatial data, more extreme results are often found in areas with the smallest denominators. Such areas tend to be geographically structured; e.g. rural rather than urban. Likewise the internal heterogeneity of all zoning systems varies and this must influence the results. If the data are converted into continuous form, as surfaces, then the problems do not disappear. They are simply hidden and appear in a different way.

Openshaw (1989) argues that a key principal in spatial analysis in GIS is to handle rather than ignore the problems. It is simply unacceptable to assume that the modifiable areal unit problem does not exist. In many instances, a handle on the problems can be obtained via Monte Carlo simulation, by sensitively analysis, by boot-strapping, or seeking out high leverage data values. Some of the extra CPU power that is now available should be used to make the spatial analysis tools less 'naive' and more robust in the face of the known characteristics of spatial information.

Table 2 **Features that characterise spatial data in the GIS era**

many cases/objects/points
many variables
large data volumes
spatial autocorrelated values
spatial data error of various types
non conformity with standard statistical distribution
data precision can be spatially structured
errors need not be random
not samples in usual sense
surrogate variables abound
nonlinearity is the norm
a high degree of complexity
modifiable areal unit, scale and aggregation effects
mixtures of scale and data resolution
mixtures of measurement
small number problems can be important

4.4 The results should be mappable

GIS is a highly visual and graphics orientated technology. The results of GIS spatial analysis operations should also be available in a graphic and mappable form. This is very important and in some ways represents a major design constraint on the forms of spatial analysis that might be considered as GIS relevant. The output cannot just be a set of statistics or model parameter values embedded in a text report. The outputs also have to be visual and mappable. This provides for a different spatial analysis paradigm in which the emphasis is firmly on visibility and visualisation (see also Batty 1993). Figure 1 summarises what is intended and how the three basic components (human knowledge and intuition, analysis tool, and GIS) interlink.

The role of spatial analysis is essentially that of a filter designed to remove the rough from the smooth or to highlight areas of 'unusualness'. Far too many geographers seek complex statistical solutions to problems that are best visualised, at least initially, so that when the time comes to apply more sophisticated methods there is at least some idea as to what to look for. The spatial analysis paradigm in Figure 1 ideally should be applied iteratively; each iteration has an input of human intuition and knowledge and with each successive iteration more insight is gained.

4.5 GISable spatial analysis is generic

The GIS tool kit consists of a set of generic, application independent tools for data capture, storage, manipulation, mapping and analysis. Very little, if anything, is application specific. The tools are generic. It follows that spatial analysis methods with the greatest claim for inclusion in proprietary GIS should be similarly application independent. It is claimed here the generic, general purpose, data invariant spatial analysis methods can in fact be defined. For example, methods that examine point data for clustering can be applied to disease data, crime data, earthquake, lightening, gas or water bursts, telephone faults, traffic accidents, etc. The function is application in dependent. It was with concept in mind that Openshaw (1991) listed a set of general spatial analysis procedures; these are reproduced in Table 3. At the present point in time it is probably more useful to agree on broad areas of analysis functionality than it is detailed how to achieve it.

4.6 GISable spatial analysis methods should be useful and valuable

If users are to be lured into using spatial analysis then there has to be a good and compelling reason. The GIS relevant tools will not merely have to meet academic research needs but should have something tangible and valuable to offer genuine end users in applied contexts. The benefits have to outweigh the end users' perceptions of the 'costs' of applying spatial analysis; an area where

Figure 1: Exploratory spatial analysis paradigm

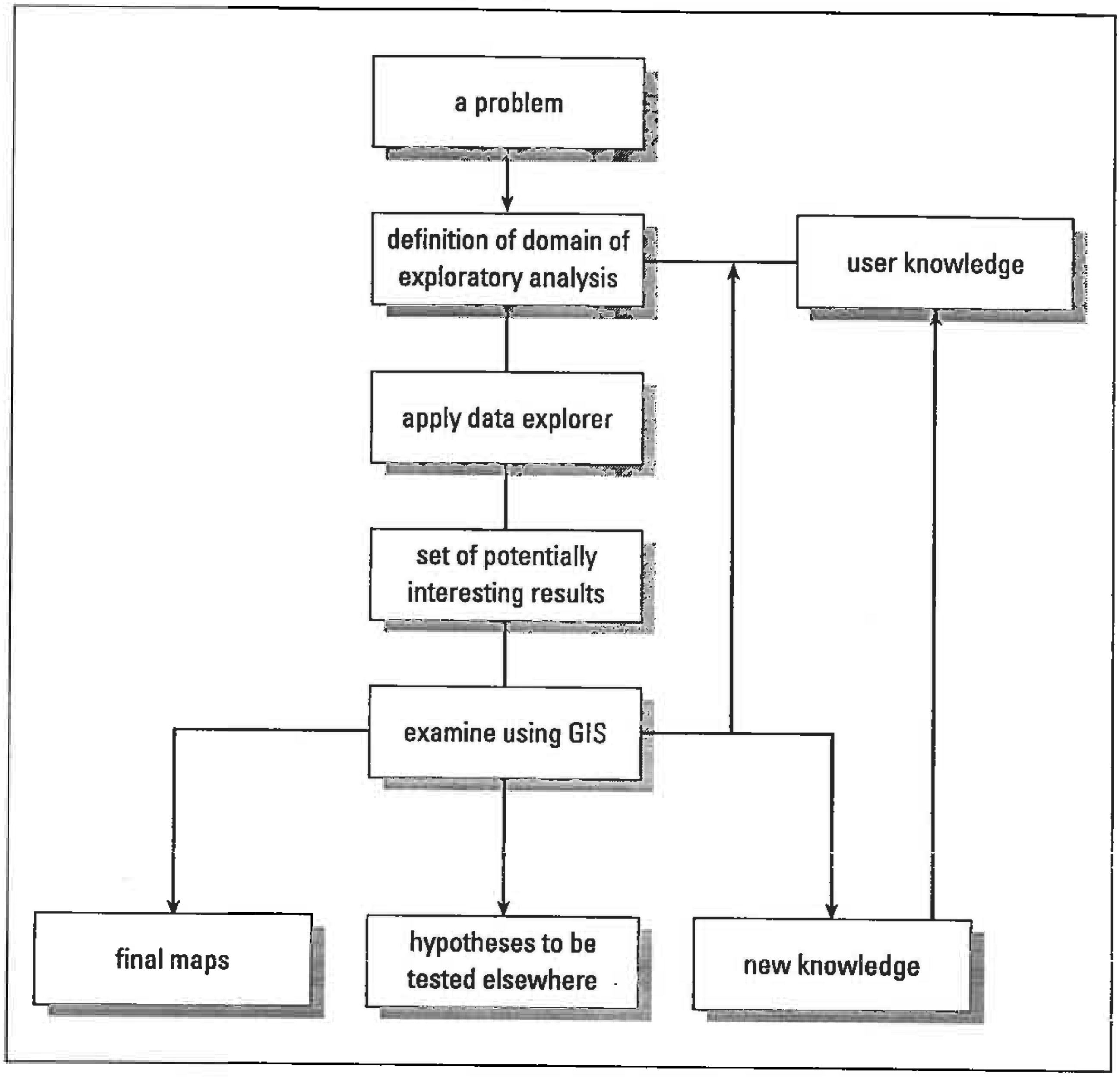

Table 3 **Basic generic spatial analysis procedures relevant to GIS**

pattern spotters and testers
relationship seekers and provers
data simplifiers
edge detectors
automatic spatial response modellers
fuzzy pattern analysis
visualisation enhancers
spatial video analysis

Source: Openshaw (1991)

perceptions of statistical and mathematical complexity might give the impression of outstanding difficulty (for more discussion see Clarke and Clarke 1995). This unfavourable impression is not helped by the usually complex and very technical nature of spatial analysis conferences and workshops.

It also follows that if GISable spatial analysis methods can be defined, then they should not be free. In the GIS world where all aspects of everything are owned, copyrighted, licensed, and commercial, it is a mistake for vendors and system developers to assume that spatial analysis tools will simply appear and be 'free'. It cannot be left to the research sector to develop, because what they will concentrate on is the research-interesting methods that are probably least likely to be of general interest or meet end usability criteria. What is needed is a new generation of explicitly user friendly spatial analysis tools that are designed from first principles centred around the needs of users. In short they have to be user-centred and this is an attribute that is hard to add to methods designed without it! Not only must users find spatial analysis methods to be easy to use but they should also want to use them and then be able to communicate the results to others in a language relevant to decision makers and action (Openshaw and Perrée, 1996).

4.7 Interfacing issues are initially irrelevant and subsequently a problem for others to solve

In seeking to develop spatial analysis methods for GIS, the nature of the linkage should be irrelevant. At the present moment in time, it is far more important to demonstrate the utility of GISable and GIS relevant spatial analysis tools. The philosophical rights and wrongs of programming in this or that trendy language or system, of embedding or not embedding, of tight or loose coupling, of integrated or stand alone, is largely if not completely an irrelevant distraction. The computing world is moving towards open, distributed, heterogeneous systems with multiple special or single function hardware being invisibly interlinked. This is not the spatial analyst's prime concern. Their task is to create the most useful and relevant technologies for analysis. Likewise, compute intensiveness is no longer a critical issue. If it can be done at all at present and there is a good case for doing it, then it will one day become common practice on affordable hardware located somewhere on a global network. If the concern for interfacing reflects the need for access to low-level GIS databases, then that too is probably misplaced. Whatever is there that matters can be exported. The great benefit of GIS is that it provides useful data such as contiguity information for cleaned up and topological correct digital map databases. Once this exists, the GIS has done its work, now lets use whatever system is most relevant. So may researchers seem to overlook the fact that whilst the availability of generic spatial functions in a GIS, such as find the k nearest neighbour of a point, is useful; it typically runs three or more orders of magnitude slower than could be programmed in standalone software.

4.8 **Ease of use and understand ability are very important**

GIS ability is not just about relevance to GIS environments and relevance to the needs of GIS users, it is also about the ability of the typical end users to use it. For this reason highly statistical technology and raw statistical methods will not usually be appropriate. They fail on ease of use and usability grounds. The statistical packages demonstrated long ago how even the most mathematically and complicated of methods can be presented in a fairly easy to use form. There are dangers in hiding complexity and allowing the statistically ignorant and unskilled to use highly advanced methods; but no more so here than in the other areas of GIS. The converse is also unproven. There is no guarantee that statistical experts will only perform sensible analysis with GIS data. GIS is based on the proposition that the complexity is hidden; for example how many users understand the computational geometry that lies behind many of the methods in their GIS packages? There is no good reason why the complexity of any relevant spatial analysis technology cannot also be hidden behind suitable user interfaces but the real question is how to aid or foster a meaningfully deep understanding of what the results mean. This understandability criteria is not a problem with many GISs because most basic GIS operations are almost instantly understandable independent of the technology used to perform them. The need now is for a similar type of almost instantly obviously and understandable spatial analysis tool-kit.

It should be noted that there is no reason to assume that GISable spatial analysis tools must only involve statistically and mathematically complex methods. It is possible that the most relevant spatial analysis need not use any advanced forms of conventional statistical technology. It is also not clear that any conventional statistical analysis skills are really needed. Maybe the GIS vendors lack of interest in spatial analysis reflects a mistaken assumption, that advanced statistical skills are a prerequisite before even the simplest method can be used. Indeed, it might be observed that quite often there is an inverse relationship between the degree of mathematical complexity present in a spatial analysis method and the associated level of applied geographical usefulness. On the other hand the statement may be misleading because maybe those researchers who are most likely to indulge in statistical spatial analysis may not see themselves as doing anything particularly applied.

4.9 GISable analysis should be safe technology

The applied nature of GIS makes it important that naive methods (or those methods with a high innate propensity to generate spurious results) should be avoided. Spatial analysis results should be reliable, robust, resilient, error and noise resistant, non-parametric, and not based in any important way on standard inference. Monte Carlo significance tests, boot strapping, jack knifing and other computational statistics tools should be used wherever important analysis is being performed. GIS databases contain errors and uncertainties of various kinds and it is important that they do not mislead the innocent. The basic null hypothesis in GIS is not of randomness but of database error! Only if this can be rejected is it worth applying anything sophisticated. The main problem with the analysis of GIS data is not that the data contain error and uncertainty or is wrong in various ways, it is that the analysis technology does not know or expect or understand such problems. The errors and uncertainties inherent in spatial databases can be handled only if allowance is made for them (Openshaw, 1989). Methods should be developed to be self-checking numerically and the basic rule of the user having to validate any really interesting results via independent data needs to become an established practise. Conventional significance testing is a very minimalistic barrier to cross and this important message needs to be universally understood.

4.10 GISable methods should be useful in an applied sense

It has to be faced that GIS is primarily and predominantly an applied technology. Those spatial analysis methods most relevant to it will be applied and seek to meet generic, important (in the sense of being useful) and valuable goals. They should also focus on spatial analysis tasks that are relevant to GIS environments. Academic research needs fall into a different category. It has to be recognised and accepted that there are many wholly GIS inappropriate methods lying around that may well need to be discarded or never introduced into GIS tool kits. Indeed, there would appear to be many more designated unsuitable for GIS use methods than those that are! However, we should not throw away the baby with the bath water - there must be room for both new generic spatial analysis routines which solve applied problems as well as conventional spatial analysis (i.e. spatial modelling) which has a proven track record of applied problem solving (Birkin et al 1996). The problem is that of emphasis and balance.

5 Developing a spatial analysis paradigm that is appropriate for GIS

5.1 A basic typology

It would seem to follow from the previous discussion that future GISable spatial analysis methods will be:

(i) essentially descriptive;

(ii) essentially exploratory;

(iii) probably not inferential in a traditional spatial hypothesis testing sense; and

(iv) they may have to be invented from scratch although often the basic techniques already exist and merely need to be integrated

On the other hand, it is apparent that some suitable methods already do exist and that these can be readily ported into GIS environments without too much difficulty (we argue that at present these are most likely to be spatial modelling techniques with a small number of recent spatial analysis tools invented since the mid 1980s). The principal problem is that of discriminating between those that are useful, those that might usefully be reconditioned or refurbished for spatial data applications and those that are not.

5.2 Learning to live with exploratory spatial data analysis and spatial modelling

One major awareness problem concerns the perhaps surprising lack of appreciation of the GIS world's needs for spatial analysis technology. They are not necessarily the same as found in other areas, where quantitative methods have traditionally been applied. The needs and views of GIS can be different, and the data are different.

Table 4 outlines some of the basic design principles that have been deemed important (Openshaw 1995). Clearly not all GIS users will agree with them and probably even fewer statisticians, but they do at least draw attention to the need to think about the underlying design aspects; in particular who the end users are, their levels of skills and what they see GIS as providing them with. The typical GIS end user should not be assumed to be an academic mainly interested in high level research activities that need extensive research training and high skill levels. Equally, designers of GIS relevant spatial analysis technology should not be mesmerised by a search for a 'holy grail' of soundly based statistically theory rich methods: such things in general do not yet exist for use with

Table 4 **Technical specification**

high degree of automation
self-checking
constantly seeking to improve performance
capable of real-time operation
can be presented as a black-box but is understandable
contains mechanisms for user interaction and incorporating human knowledge
can handle localised spatial heterogeneities
not hindered by lack of knowledge of what, where, or when to look for
handles rather than ignores spatial data characteristics
can respond to the unexpected in intelligent ways
can generate new hypotheses as an output from the analysis process

spatial data generated by GIS. The real problem is that users do not know what patterns or relationships exist in the data. They do not know where to look, when to look or even what to look for. GIS databases are multivariate data rich. There are lots of them and it is likely that whatever prior knowledge the user has will either be wrong (maybe only partially) or inappropriate (due to the unexpected presence of much more distinctive but initially unknown orderliness).

The goal is easily stated: a search for spatial orderliness and regularities that are either recurrent elsewhere, or are of purely local importance. The problem is, as Openshaw (1994, 1994c, 1995) explains, we are blind to the spatial patterns and processes that exist in the 'geocyberspaces' generated by GIS technologies. We have probably only ever found a minuscule fraction of the regularities that exist and worse still what we have found so far might well be artefacts created by the arbitrary selections and restrictions imposed on the data just so that it can be analysed. There is a desperate need for new smart spatial data explorers and modellers that can function without being told, in advance, what to look for. AI technology holds some promise and there are a number of potentially interesting ways forward based on neurocomputing and artificial life, as well as other forms of machine learning (Openshaw, 1992). However, in many ways these methods still need to be developed. Here it is more appropriate to develop a more general specification of the sort of GIS relevant technology that meet the design criteria that have been discussed.

5.3 **Handling the human knowledge interface**

A key need is the ability to create a means of incorporating human knowledge, human skills, and human intuition into the spatial analysis process. No automated spatial analysis technology will develop far by itself, but equally it does not make much sense to cripple the new methods by expecting all the critical and hard decisions to be made by humans. As we have suggested earlier, model specification or a priori hypothesis are not easy in a GIS context. There is need for a conceptual view of exploratory analysis and modelling in GIS that can combine the strengths of both the human being and the power of AI based machine learning technology, whilst simultaneously attempting to avoid their weaknesses. Figure 1 outlined in a general schematic fashion how this might be operated. It is independent of the exploratory analysis and modelling technology being used; precisely what is 'plugged' into the "Spatial Analysis" or "Exploratory Analysis and modelling box" is irrelevant. Far more important is the notion of trying to create a spatial analysis tool or model builder that combines both human and machine abilities in a symbiotic manner or partnership, with inbuilt feedback and learning mechanisms which in time can be formalised and incorporated into intelligent software systems; but that is still 5-20 years away (at least).

Implicit in Figure 1 is the assumption that the initial human being inputs should be broad-brush rather than specific; they should reflect general goals rather than precise specification; and that rather than start by defining the variables to be used, the universe of potentially relevant variables should be tested. It is also important to provide a means whereby the end user can visualise what is going on. Animation of the spatial analysis process is one possibility here. Openshaw and Perrée (1996) offer a highly visual approach to spatial analysis that is designed to be almost instantly understandable by offering the user four different views in the form of MPEG computer movies of an intelligent exploratory spatial analysis procedure operating on data.

5.4 The SAT/1 proposal

It is in this context also that the recent Spatial Analysis Tool kit (SAT) for GIS proposal (SAT/1) should be placed. The idea here is to develop a set of GIS independent and generic or application independent spatial analysis tools that in general conform to the principles outlined in section 2 and which would initially be interfaced to Arc/Info (although the interface design is the only non-portable part). Table 5 lists the initial procedures that have been suggested as potentially suitable: others could be added.

SAT/1 is designed to be 'loosely coupled' for the following reasons:

(i) ease of creation
(ii) independence of any particular GIS
(iii) separation of vendor software from SAT/1 consortium code
(iv) none of the methods need a high degree of geographical interaction
(v) it is always possible to convert loosely couple into closely coupled integration if needed, later.

Each SAT/1 procedure will have its own AML, but it could also be a standalone system in its own right. By these means the investment of time and effort in creating the tool kit is preserved and considerable system specific programming avoided. Clearly the SAT/1 approach could be extended beyond the initial consortium of Lancaster, Leeds and Newcastle Universities into an international project. Anyone interested?

Table 5 **Suggested SAT/1 tools**

Diggles point density method
a simple GAM
Besag-Newell method
cartogians
Kernel estimated surfaces
Stones method
Getis-Ord g statistics
zone design methods
regionalisation and classification
zone ranking
spatial regression modelling

5.5 **Database pattern hunting creatures**

The ultimate machine oriented implementations of Figure 1 is to develop smart pattern and relationship seeking tools to handle the analysis and modelling aspects. Openshaw (1994c, 1995) outlines one way of achieving this goal using ideas borrowed from Artificial Life (ALife); also see Langton (1989) and Langton et al (1992). The basic idea is very simple and involves converting the spatial analysis and modelling tasks into a search problem; i.e. where is the pattern or what form of equation fits best? Genetic algorithms and genetic programming techniques can then be used to explore the full complexity of the GIS database in a bottom-up manner. The ALife forms of Openshaw (1994c) and Openshaw and Perrée (1996) consist of the hyperspheres that move around the data trying to engulf unusual concentrations of points, under their own control. The degree of 'unusualness' is measured via a Monte Carlo significance test. These hypersphere creatures can be left permanently roaming in a never ending search for pattern. The genetic algorithm will allow them to adapt to whatever local environments they discover in the database. There are, of course, other mechanisms for driving the search process and neural nets might equally be extremely effective in bottom-up pattern recognition. These ideas still need to be fully developed and are still sufficiently 'blue skies' research that they might form yet another area for international collaboration.

6 **Where to now?**

There are at least three ways forward. The first is to develop special single purpose generic tools and this has been the main route considered here. These may or may not be embedded in a particular GIS or its map interface; or the GIS may be embedded within the method. One example was the Openshaw et al (1987) Geographical Analysis Machine. Developments in heterogeneous distributed computing suggest that networking specialist spatial analysis and modelling tools on a national, European and international scale is in fact a viable proposition. It would not matter at all what the hardware was or where it was located on which a particular highly specialised task was being run. This strategy could be particularly useful for highly complex analysis tasks. However, as hardware speeds improve during the 1990s, it will downsize onto personal workstations. A second strategy is to develop more generally useful GIS independent generic spatial analysis tools that are subsequently interfaced to a particular GIS. For example, the NAG subroutine library is one instance of this approach, albeit in a different context. This might also be appropriate for spatial models in general at some future date. GIS vendors or developers could gain access to the basic technologies and design whatever interfaces they considered necessary in whatever way was deemed appropriate. A third strategy is to import traditional methods into GIS, or vice versa, and disregard the wider objectives that are of such importance. This will happen and is already happening and whilst academically attractive and better than nothing, it is clearly not at all satisfactory when viewed from a GIS end user's viewpoint.

From a GIS DATA perspective, it is collaborative aspects that matter most. This book is testimony to the international collaboration now underway on improving the levels of spatial analysis within GIS. We hope we have offered some ideas on one possible research strategy for the future.

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