NATIONAL CENTER FOR GEOGRAPHIC INFORMATION
AND ANALYSIS

Research Initiative 6:
Spatial Decision Support Systems

Closing Report

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ABSTRACT

NCGIA's Research Initiative 6 is concerned with the integration of geographic information systems and geographic information analysis to support problem-solving and decision-making; the Initiative was active from March, 1990, until April, 1993. This report describes the Center's research activities on the four major themes identified at the Initiative's Specialist Meeting and on related activities. Since the closing of the Initiative's active phase, research has continued on several projects while other areas of research have been adopted by Initiatives 14 (GIS and Spatial Analysis) and 17 (Collaborative Spatial Decision-Making). This report concludes with an assessment of the Initiative against five criteria.

OVERVIEW

Initiative 6 concerns the integration of geographic information systems (GIS) and geographic information analysis (GIA) to support decision-making. The Initiative is led by Paul Densham (NCGIA Buffalo) and Michael Goodchild (NCGIA Santa Barbara). The specialist meeting was held in Santa Barbara during March 1990 and brought together over 30 participants, primarily academics but with strong representation from the private sector. A preliminary research agenda for the initiative was discussed in a presentation at GIS/LIS '89 and appears in the proceedings (Densham and Goodchild, 1989). This agenda was refined substantially over the three working days of the specialist meeting. Besides design issues, the meeting was particularly concerned about the extent to which work on spatial decision support systems (SDSS) could shed light on the decision-making process, or provide an experimental environment in which to study it.

The possible scope of the initiative was narrowed in two directions. First, the definition of decision support systems (DSS) proposed by Geoffrion and others was adopted: although a DSS is by definition oriented to the solution of ill- or poorly-structured problems, it nevertheless contains a number of well-structured models. This is in contrast to arguments that GIS and SDSS are, in effect, synonymous. Second, because it would be impossible to consider all possible applications of SDSS, the focus was narrowed to the general area of marketing, retailing, location theory and socioeconomic modeling. This narrowing of focus was not intended to suggest that these are the only areas of application of SDSS; rather, this allowed the research agenda to cover a broad range of possible applications, returning to a narrower focus as appropriate.

The results of the Specialist Meeting have appeared as a Center Report (Densham and Goodchild, 1990) and have been reported on elsewhere (Fotheringham, 1990). The Initiative's Research Agenda focuses on four major themes: decision-making processes, modeling and data, technology and implementation, and user requirements and organizational issues. Presentations on the research agenda have been made by Densham and/or Goodchild at commercial organizations, government agencies, academic symposia and professional meetings (see below). A working bibliography, distributed at the specialist meeting, has been supplemented and published as a Center Report (Gould and Densham, 1991). To promote interaction between participants in the specialist meeting and other interested parties, an initiative newsletter, edited by Bruce Ralston (University of Tennessee), was established.

Initiative 6's active phase was three years in length, rather longer than the two years of most other Initiatives. In part, this time-scale reflects the considerable overhead involved in designing and implementing prototype systems that link GIS and GIA. Indeed, many of the projects falling under the aegis of Initiative 6 are still in progress. Although some of these projects are in the areas of marketing, retailing, location theory and socioeconomic modeling, several more concern environmental modeling. This general broadening of application areas is consistent with the pressing needs of environmental scientists and society in general to apply new technology to fundamental problems.

PROGRESS ON THE RESEARCH AGENDA

The Research Agenda

The research agenda developed at the Initiative Specialist Meeting consists of four major research areas:

1) Decision-making processes with SDSS:

- What system architectures can best support a SDSS that acquires knowledge from a decision-maker?

- How should transformations occur among the decision space, model space and objective space?

- What exploratory strategies are most appropriate for ill-structured problems?

2) Modeling and data in SDSS:

- Develop a taxonomy of spatial models which are relevant for SDSS.

- Develop a taxonomy of the atomic elements that are common to these SDSS-relevant spatial models.

- Develop a knowledge base on the sensitivity of spatial models to parameter changes, data quality, calibration procedures, data aggregation, parameter stability over time and space, and data availability.

3) Technology and implementation of SDSS:

- What is the scope for object-oriented programming techniques in SDSS? Does object-orientation provide a conceptual framework for implementation?

- How does the system adapt during decision-making, both to elicit a user's evaluation and to respond to changes in their preferences?

- What kinds of multiple representations are necessary to support spatial decision-making?

- What forms of visualization must be supported in a SDSS?

- How do we elicit, identify, represent, and use knowledge in a SDSS?

- How can we provide "adequate" system responsiveness?

4) User requirements and organizational issues for SDSS:

- Develop a body of case studies of the use of SDSS.

- Undertake a literature search to identify the factors present in semi-structured spatial

problems and the tools required to resolve them.

- Evaluate the significance of these factors and determine whether tools are available to solve the most significant.

The set of research projects related to Initiative 6 are diverse and provide only partial coverage of the items in this agenda. The next section describes those projects undertaken with NCGIA funding and other, related projects that were affiliated with the Initiative.

Initiative 6 Research Projects

Equitable Vehicle Routing Models for SDSS

Traditional models for routing vehicles optimize some performance criterion - the cost of a tour, its total distance, or some other, composite measure. Such models are used by a variety of organizations to assist in the collection and/or distribution of goods and services. In some cases, garbage collection routes for example, routes often are invariant through time because all clients/consumers must be serviced at regular intervals. In contrast, other routing problems change daily because both the number and the geographic distribution of clients vary. Overnight couriers typically face routing problems which fall between these two extremes - they service both regular and irregular clients. Retaining regular clients, in a competitive environment, is a problem for these companies. Traditional routing models do not take into account issues of client equity. A regular client who is always at or near the end of a delivery tour, receiving their overnight packets just before the promised deadline, may perceive that they are not being served as well as another customer who normally is at or near the start of a tour.

Rajan Batta (NCGIA Buffalo) received funding from Federal Express ($16,500) to investigate equity in routing models. Their approach was to treat the problem as a multi-day routing problem in which the objectives are to minimize transportation costs whilst also treating equally valued customers in a similar manner. The model of this problem is formulated as a modification to the well-known travelling salesman problem; specifically, multiple tours are generated using a range of time windows to ensure that valued clients receive their overnight packets at varying times. Both optimal and heuristic solution procedures have been developed which have been tested on real data provided by Federal Express: a day's service of 1,448 deliveries in Palo Alto. The principal finding of the research is that by judiciously selecting routes, one can incorporate equity at little additional cost.

The results of this research have application in a variety of routing applications where the issue of equity can be raised. Police patrol vehicles, for example, are expected to provide equitable coverage of their patrol area and serve as a deterrent (Gopalan, Batta, and Karwan,

1990). Similarly, the movement of hazardous materials by road and rail involves assessing risks to the surrounding population and other users of the transportation system (Gopalan *et al.*, 1990; Dutton, Batta, and Karwan, 1991; Sivakumar, Batta, and Karwan, 1992, 1993).

A Modelbase Management System for a Locational Analysis SDSS

A modelbase management system (MBMS) is analogous in purpose and design to a database management system (DBMS). A DBMS provides mechanisms for storing, managing, manipulating and retrieving data. This is achieved by decomposing data into individual components which can be stored without redundancy by representing and exploiting relationships among them. The concept behind a MBMS is to do the same for the components, or atomic elements, of analytical models. Many algorithms within a modeling domain contain similar steps or operations. By decomposing models into their atomic elements, they can be stored in the model base without redundancy. The MBMS can support different algorithms by combining atoms in the appropriate sequences.

As a first step in the development of a MBMS for locational analysis, Paul Densham (NCGIA Buffalo) and Gerard Rushton (The University of Iowa) developed a set of implementation strategies for the vertex substitution location-allocation algorithm and its derivatives. These strategies are built around a data structure called the "allocation table". This data structure permits the exploitation of the spatial structure of location-allocation models to minimize the number of calculations carried out; the volume of data to be processed; and access times to that data (Densham and Rushton, 1992a, 1992b). A microcomputer-based location-allocation package - the Locational Analysis Decision Support System (LADSS) - has been implemented using these strategies (Densham, 1992). The package's modular design reflects the decomposition of the vertex substitution algorithm into its atomic elements and their representation as operations on the allocation table and its supporting data structures. The atoms in the model base support both the vertex substitution algorithm and one of its variants. When compared with other software, this package solves larger problems and dramatically reduces solution times (Densham and Rushton, 1992a). Moreover, the operations on the allocation table supported by the MBMS enable the user to combine both "goal-seeking" (algorithm-based) and "what-if" (direct manipulation) approaches to problem-solving.

The second phase in this project was to use the allocation table and the implementation strategies to develop a new heuristic location-allocation algorithm (Densham and Rushton, 1992b). This algorithm reduces solution times further while retaining all the qualities of solutions generated by the vertex substitution heuristic. Because many of the atomic elements used in the vertex substitution algorithm are common to this new algorithm, its implementation in the microcomputer package was relatively easy. A third phase of this project has been to use the core data structures and operations in the MBMS to implement location-allocation algorithms in

ARC/INFO's NETWORK module (see below). The final, and continuing, phase of this project is to evaluate other heuristic location-allocation algorithms for inclusion in the MBMS. The development of a MBMS for locational analysis, using the allocation table and its associated atoms, provides an environment in which to evaluate the use of object-oriented programming techniques in SDSS. A first step in this direction has been made by Armstrong, Densham, and Bennett (1989).

Visualization of Results from Location-Allocation Models

Jim McKinney (NCGIA Buffalo) carried out research into the design and evaluation of cartographic displays for his M.A. Project. Supervised by Barbara Buttenfield and Paul Densham, this project cuts across Initiatives 3 and 6. McKinney investigated the use of color and geometrical complexity in the depiction of solutions to location-allocation models. Typically, results of location-allocation models have been displayed as spider maps: a series of vectors linking demand locations to their allocated service location. McKinney's displays investigated the utility of depicting the routes linking demand and supply locations and, using hue to represent magnitude, the volume of demand traversing links in the transportation network.

To evaluate the utility of the displays, a survey was conducted using experts and neophytes in locational modeling. Respondents were shown six displays, obtained by sampling a three by three factorial design. In each group of displays, the underlying network was rotated to prevent respondents from learning the spatial structure and no legend or explanation of the thematic content was provided. Each respondent was asked to complete a questionnaire for each of the six displays they viewed. Preliminary findings suggest that the expert group recognized the displays as depicting solutions to locational models and were able to deduce the information contained in the map elements. The neophyte group were unable to do so, however, and did not understand the maps until they were explained after all testing was completed. These results suggest that specialized displays of the solutions to models will be of different utility to disparate groups of SDSS users. Thus, SDSS must assist users in interpreting specialized forms of displays.

Cartographic Displays to Support Locational Decision-Making

The purpose of this project was twofold: first, to develop a functional taxonomy of cartographic displays for use in locational problem-solving and decision-making; and, second, to improve our understanding of the types of displays that can be used to visualize different components of models and their results. In the first phase of the project (Armstrong *et al.*, 1991), three classes of displays were identified: chorognostic, monoplan and delta displays. Chorognostic displays are used to show general information about an area, including the locations of places, to provide a

context or point of reference for a study. A series of maps fall into this class: demand displays show the distribution and magnitude of demand in the problem being examined; supply displays depict the distribution and magnitude of services consumed by this demand; annular displays present situation information - distance from facility locations, for example. Monoplan displays are used to convey information to decision-makers about single solutions: they depict the locations of service centers and the allocations of demand to them. Thus, where demand is represented by areas, center-border displays show the locations of facilities and the boundaries of their service areas while center-region displays use chorochromatic shading to depict associated service regions. When demand is represented by point locations, nodalchromatic maps use color to associate demand with facility locations while spider maps use vectors or paths through a transportation network to achieve the same end. Finally, delta displays enable decision-makers to assess differences among alternatives. Two types of display are used for this purpose: center-delta displays depict differences between sets of facility locations; and allocation-delta displays show differences in the attributes of demand associated with facilities, travel times, for example.

In the second phase of the project, this classification of displays was used to design a prototype user interface (Armstrong *et al.*, 1991) that supports visual interactive modeling (Densham, 1994). In a visual interactive modeling environment, linkages between the objective space of mathematical models and the graphical space of cartographic displays enable decision-makers to select appropriate analytical models and to intervene and change their decision criteria. The model user interface adapts to the display requirements of the user at distinct stages in the decision-making process.

Visualization of Urban Spatial Structure Using Integrated Land-Use Transportation Models

The purpose of this project, involving Michael Batty and Yichuan Xie (NCGIA Buffalo), is threefold. First, it involves the design and implementation of a visual environment based on state-of-the-art computer graphics which enable the inputs, outputs and mechanisms of land use transportation models to be visualized (this project has links to Initiative 7 and makes extensive use of the workstations and software donated to the Buffalo site by Sun Microsystems and Environmental Systems Research Institute). It is hoped that new insights might be generated with respect to the spatial patterns in data, the quality of associated models and the relevance of model predictions. Second, the project is designed to develop new varieties of urban model which incorporate some of the theoretical developments in this field produced over the last ten years. The third purpose is to develop an operational model of urban spatial structure in the Buffalo region, to link this to a GIS (ARC/INFO), and to provide a basis for studying some of the key problems of the region such as cross-border trade and retailing patterns.

This project has resulted in a prototype which demonstrates the capabilities of the graphical interface (Batty, 1992). Similarly, a pilot model of residential location has been built. This integrated prototype can be used to compare data sets using spatial analyses, to calibrate

the residential location model, and to predict future urban structures. Currently, the integration of the prototype with GIS functions is under investigation. The construction of a database to support analysis of cross-border retailing patterns in the Buffalo area is also taking place.

A Spatial Analysis Module for ARC/INFO

This module provides a mechanism for integrating spatial analysis with commercial GIS. Developed by Yuemin Ding (NCGIA Buffalo) to work with ARC/INFO, the module was written using a mixture of ARC Macro Language and C; it runs entirely within the ARC/INFO environment and has a menu-based interface. The module currently calculates statistics of spatial autocorrelation and spatial association. Results from analyses, with topological and attribute data stored in an ARC/INFO coverage, can be displayed graphically. A description of the module has been published as a Center report (Ding and Fotheringham, 1991) and, renamed SAM, has been released through the NCGIA Software Series (S-92-4). Ding won an award for this work in the student paper competition at the 1991 ESRI Users' Conference. This project also has links with Initiatives 1 and 14 and made extensive use of the workstations and software donated to NCGIA Buffalo by Sun Microsystems and Environmental Systems Research Institute.

Linking Locational Models with ARC/INFO

This project involved Rajan Batta, Alok Baveja and Yuemin Ding (NCGIA Buffalo) who linked three types of locational model to ARC/INFO (Ding, Baveja, and Batta, 1994). The first model uses a planar or continuous representation and a Manhattan district metric to locate p facilities to serve a geographically dispersed population. These p locations are selected to minimize total travel when barriers (rivers) and forbidden regions (lakes, cemeteries and parks) are present on the plane. The second model also locates p facilities to minimize total travel but uses a mixed planar and network representation. Finally, a hypercube queueing model was linked to enable the solution of police districting problems. Linking these models to ARC/INFO provides the user with meaningful graphical displays of model solutions. Furthermore, ARC/INFO's database management capabilities can be exploited to support the data requirements of both the models and the graphical display of model solutions. This project made extensive use of the workstations and software donated to NCGIA Buffalo by Sun Microsystems and Environmental Systems Research Institute.

Embedding Location-Allocation Models in ARC/INFO's NETWORK Module

This project concerns the development of location-allocation algorithms for use in ARC/INFO's NETWORK module. Paul Densham (NCGIA Buffalo) has received funding from Environmental Systems Research Institute ($ 5,650, plus $ 43,400 in software licenses) for this project. In

October of 1991, Densham visited Environmental Systems Research Institute, Redlands, CA., and worked with Dale Honeycutt to develop a conceptual design for future versions of ARC/INFO's NETWORK module. The next phase of this project, with David Wong and Mark MacLennan (NCGIA Buffalo), was the conversion of Densham's (1992) microcomputer-based location-allocation software to run on a Sun SPARCStation. This software was linked to NETWORK by Kristi Lombard at ESRI to yield a prototype system. In September of 1992, Densham again visited ESRI to work with Dale Honeycutt and Jay Sandhu on embedding the location-allocation modeling capabilities into NETWORK. This implementation, part of ARC/INFO Release 7.0, makes use full use of the other capabilities of ARC/INFO and employs some of the cartographic displays for locational models described by Armstrong *et al.* (1991, 1992). This project made extensive use of the workstations and software donated to NCGIA Buffalo by Sun Microsystems and Environmental Systems Research Institute.

A Prototype SDSS for Locational Analysis

This ongoing project has developed a prototype SDSS for location selection problems. This project has received funding from several sources at various stages in its development, including Manufacturers and Traders Trust Company, an Industrial Affiliate of NCGIA Buffalo, Caliper Corporation, and the National Science Foundation. The system integrates a commercial GIS (TransCAD, Caliper Corporation) with location-allocation software (Densham and Rushton, 1992a, 1992b; Densham, 1992).

An early version of the system was used to investigate locational strategies for bank retail networks. In this version, TransCAD was used as a database management and graphical display engine. Its database management system stored locational, topological and attribute data to support spatial query, cartographic display and location-allocation modeling. Data were selected and exported from the database using TransCAD's SQL module. The procedure interface was used to automate the linkage with the location-allocation software. A menu-item in the analysis software invoked TransCAD, which imported information about the solution generated by the model. This information was stored in the database and mapped for the user. David Willer wrote his Master's Project on the implementation of this version and its application to banking problems (Willer, 1991) - his project has been published as an NCGIA Technical Report.

A later version of the system replaced the locational analysis module of the system with the LADSS package (Densham, 1992). This revision necessitated changes in the linkages between TransCAD and the analytical module. Instead of embedding the analysis system's menus in TransCAD's menu structure, TransCAD was embedded in the LADSS interface. This switch places the emphasis on the analytical capabilities of the system, and provides the user with an interactive flowchart from which to invoke the SDSS's capabilities. Densham has continued to enhance the system, replacing some of the LADSS programs with parallel

processing versions (Densham, 1993).

A Prototype SDSS for Retail Location: MARKET1

MARKET1, developed by Hsueh-Cheng Chou and Stewart Fotheringham (NCGIA Buffalo), is a microcomputer-based system consisting of two elements: an analytical module written in FORTRAN and a visualization module written in C. In concert, these modules enable the decision-maker to observe the characteristics of a retail system within which a new store may be built. Consequently, the system enables the decision-maker to target particular socioeconomic areas while simultaneously trying to maximize the market share of their outlets.

The system uses census data at the tract level, including variables on age, home-ownership, economic standing and race. The analytical component of the system allows the user to enumerate the effects of either adding or subtracting a store from the system. The display component enables the user to visualize these effects. A range of thematic displays can be produced which depict the changes in the trade captured by each store and the socioeconomic characteristics of their respective trade areas. These outputs inform the user about the socioeconomic demand potential of the retail system. The benefits of such a system to store developers are twofold. First, the system enables users to carry out `what-if' analyses, evaluating locations selected exogenously. Second the system helps the retailer to determine appropriate store inventory strategies, matching product lines to the clientele. Thus, the system can be used to help retailers maximize their own market share by poaching demand from competitors.

A SDSS for Corridor Location Problems

Richard Church, Kristi Lombard and Scott Loban (NCGIA Santa Barbara) have devised methods for generating and displaying spatial alternatives in planning problems (Church, Loban, and Lombard, 1992). Many models used in planning and analysis are devised to identify either the optimum or a set of Pareto-optimal solutions. Some researchers suggest that all solutions that are near optimal or all solutions that are better than most should be considered. Church has been involved with the development of approaches that can be used in the exploration of good but spatially different alternatives in several selected planning problems. One component of this problem is to produce a spatial decision support interface that can support the search and exploration of alternatives. One prototype designed to analyze corridor alignment alternatives has been completed. It is based on an object oriented design and is flexible for potential expansion. The user interface involves the presentation of graphical displays for decision space and objective space as well as the presentation of tabular information. Solutions and performance can be viewed in terms of all three problem representations. Tools are provided so the user can explore a wide number of possible alternatives. Similar techniques for a multifacility location

problem are under development.

Timber Harvest Decision Support System for the US Forest Service

The U.S. Forest Service manages 191 million acres of forest and grassland. Operational plans for each National Forest have been based on the use of a large-scale Linear Programming model called FORPLAN. Results of FORPLAN are often spatially infeasible and therefore difficult to implement. Richard Church and David Lanter (NCGIA Santa Barbara) have received two grants from the US Forest Service to develop a SDSS to assist in this management/planning dilemma. This SDSS called Visualization of the Implementation Process (VIP) has been developed to help validate FORPLAN results and search for acceptable solutions. VIP is currently being used in fourteen national forest districts in California and the Pacific Northwest.

VIP integrates a map-based display, database, model set, and a user interface that allows the user to change model parameters and query the database. The system is designed to help analyze different harvest and management strategies over a number of spatial units. Management models based on linear programming can be set up using the map-based interface. Decision variables can be fixed, targets can be varied, and constraints can be added or deleted within the interface. Results from the models are presented in map form with color codes representing constraint flexibility or objective realization. The user interface is designed to be intuitive, easy to understand, and uses a mouse and menu as a primary form of data entry and option selection. Refinements to the system are currently being developed to support further model manipulation as well as to support the Forest Service hierarchical decision-making process called the Spatial Disaggregation Process (SDP). SDP involves the analysis of land use decisions at three levels: 1) forest wide, 2) sub-watershed units, and 3) individual stand level units.

Aggregation Errors in Linked Spatial Models in SDSS

The propagation of error through linked spatial models has received scant attention in the literature. Because SDSS will provide users with the capability to link models sequentially, an understanding of how errors are generated and propagate through models is crucial in evaluating solutions. This project - involving Paul Densham, Stewart Fotheringham, and two students, David Wong and Andrew Curtis (NCGIA Buffalo) - seeks to quantify the effects of using aggregated data on linked demographic and locational models. Specifically, it examines the effects of using data aggregated in different ways on the stability of model outputs - termed the modifiable areal unit problem (MAUP) by Openshaw.

The base data set consists of the 871 block groups of the Buffalo metropolitan area from the 1981 census, with associated socioeconomic data. These block groups were aggregated to six different levels - 800, 400, 200, 100, 50 and 25 zones - using a double random procedure. At

each aggregation level, 20 different zonal patterns were generated, yielding 120 data sets. The populations in the 871 block groups were projected by a cohort component model over four ten-year periods. Taking the fourth projection period provides a second group of 120 data sets. All 240 data sets were stored in ARC/INFO. The second model is a location-allocation model. The demand data for the model are the over-65 cohort, represented by the centroid of each aggregated zone. The model is used to locate ten day-care facilities for this elderly population, using all of the demand nodes (centroids) as candidate locations. Models are solved for both the p-median and the maximal covering objective functions using Densham's LADSS software (Densham, 1992). Solutions to the models were stored in ARC/INFO and used to generate maps of the solutions. Preliminary results show that geometric arrangements of facility locations vary widely and that, as expected, the values of objective functions decrease systematically with increasing levels of aggregation (Fotheringham, Densham, and Curtis, forthcoming). Current work involves comparing the aggregated results with those for the 871 block groups to enumerate the distortions in the solutions and to determine their source. This project has made extensive use of workstations and software donated by Sun Microsystems and Environmental Systems Research Institute and has been adopted as one of the major themes of Initiative 14: GIS and Spatial Analysis.

Research and Funding Proposals Related to Initiative 6

Improving Human-Computer Interaction in SDSS

Initiative 6 has spawned an offshoot Research Investigation, led by Paul Densham (NCGIA Buffalo) entitled Parallel Computation and GIS. The broad goal of this research is to improve upon the processes of supporting interactive locational decision-making. Paul Densham (NCGIA Buffalo) and Marc Armstrong (University of Iowa) are funded for this project by three programs in NSF (the Geography and Regional Science Program, $39,810; the Information Technologies and Organizations Program in the Directorate for Computer Science and Engineering, $25,000; and the Computation and Life Sciences Initiative in the Division of Instrumentation and Resources, $35,000). Yuemin Ding (NCGIA Buffalo) and Panos Lolonis and Demetrius Rokos (University of Iowa) worked on the project as research assistants.

A crucial step in designing and implementing parallel software is to decompose the problem and its solution algorithm into parallel processes. One research thread of the Investigation has been to examine approaches to decomposition that exploit the peculiar structure of spatial problems (Armstrong and Densham, 1992; Ding, 1993). These approaches have been used to decompose several spatial algorithms and to implement them on a Transputer array: shortest path algorithms (Ding, Densham, and Armstrong, 1992); a new hill-shading algorithm (Ding, 1992; Ding and Densham, 1994); and the generation of Delaunay Triangulations and Thiessen Polygons (Ding, 1993).

Another research thread has been to examine how parallel processing can be integrated with commercial GIS to improve human computer interaction by reducing solution times and improving visualization. The parallel shortest path algorithms developed during the project have been integrated into the prototype SDSS for locational analysis described above. New location-allocation algorithms are being developed for this SDSS that form part of the modelbase management system described above and run in several parallel processing environments (Densham, 1993). Genetic algorithms for location selection and other types of problems also are being investigated (Dibble and Densham, 1993) and implemented in parallel processing environments. To improve visualization in SDSS, research also been undertaken on visual interactive modeling environments (Densham, 1994). This work has provided a framework for the investigation of how a core set of representations can be used to support query, analysis and display in a parallel processing, SDSS environment (Densham and Armstrong, 1993).

A SDSS for Exposure-Effects Analysis of Contaminants in the Lower Great Lakes

The Environmental Protection Agency is funding a three-year project at Buffalo for "Development of a Geographically-Based Ecological Modeling Framework for Exposure-Effects Analysis of Contaminants in the Lower Great Lakes." There are six co-principal investigators: four from the Great Lakes Program and College of Engineering - J.V. DePinto (Project Director), J. Atkinson, R.R. Rumer and S. Taylor - and two from NCGIA - Hugh Calkins and Paul Densham. Total funding of $1,643,005 covers the period July 1991 to June 1994. This project is developing a SDSS which integrates a suite of exposure-effects models with a GIS (ARC/INFO).

To date, a prototype system has been developed which links two models to ARC/INFO (DePinto *et al.*, 1994) to study the Buffalo River. A series of research problems have been addressed in the development of this prototype. First, the models use a three-dimensional (3-D) representation of a water body. A 3-D data structure has been developed and programmed outside ARC/INFO to complement its 2-D representations. Second, to facilitate movement of data and results among the GIS and the models, a data management interface has been developed which uses standardized data representations. Third, to maintain lineage of data, model parameters, and model results, a scenario manager has been designed and implemented. This manager fulfills several roles: it records who used which data, with which parameters and which models, to generate a particular set of results - a scenario; it enables users to jump into a scenario part-way through, either their own or someone else's to change only those parameters or data which they wish to investigate; and, third, it ensures that users undertake all necessary steps in the generation of a scenario so that all required inputs by the models are provided.

Work over the next year will extend the system to other study areas, and it will refine the

3-D data structure and its associated operations. The scenario manager will be extended to cover more models and to accommodate modeling of more than one watershed in a scenario (i.e. modeling all five Great Lakes as a system with interacting models for each lake). This project has made extensive use of workstations and software donated by Sun Microsystems and Environmental Systems Research Institute.

Rural Services Planning in India

A project supported by the India International Fund is contributing to the research agenda of Initiative 6. This project, led by Gerard Rushton (University of Iowa) and Vinod Tewari (Indian Institute of Management at Bangalore), focuses on the development and testing of a SDSS for improving access to rural services in India. Links have been established between the project, NCGIA Buffalo (Paul Densham), and the National Informatics Centre (New Delhi). An international meeting of experts was held in New Delhi in August, 1991, organized by Tewari, Rushton and Densham. This meeting brought together academics, officials and planners from Indian central and district government and agencies. This group was asked to evaluate the system, to make suggestions concerning its further development, and to identify sites for field-testing. Currently, a microcomputer-based prototype system is being field-tested at several sites in India. Papers have been presented on this project, and demonstrations of the prototype system have been made, at: *Symposium on Microcomputers for International Development*, The Institute for African Development, Cornell University (1991), 1991 Fall Meeting of ORSA/TIMS (2), and the National Informatics Centre (New Delhi, 1991).

Habitat Maintenance

Richard Church (NCGIA, Santa Barbara) and Julia Jones (Oregon State University) received a grant from the U.S. Forest Service to research issues related to the conflict between harvesting and habitat protection and management. The main objective of this research project is to develop a methodology that can be used to rate patches of forest in terms of their importance in meeting objectives of habitat and species protection and harvest goals. This is a particularly important issue for the Forest Service in the Pacific Northwest in dealing with the issue of protecting Spotted Owls. A prototype rating process will be tested within a U.S.F.S. GIS system for a ranger district in the Pacific Northwest. This project started on September 30, 1991.

Management of Urban Waste Heat

The Hitachi-funded project at UCSB to develop decision-support tools for urban waste heat management is now in its third year of funding. The team, which consists of Goodchild, Church, graduate students Sorensen, Cova, Lemberg, and Takeyama, and Hitachi researchers Oka and Embutsu, has developed models of heat loss from underground pipes and spatio-temporal

development of the urban heat island. The former will be built into a decision support system for location of district heating and cooling systems. The latter were incorporated into a cellular-automata-based modeling system during the summer of 1993 (Embutsu, Goodchild, Church, Takeyama, and Baba, 1994). An existing, public domain cellular automata modeling package is being extended to handle more general spatio-temporal modeling, and linked with a neural net package for model calibration. The extended package will be distributed through the NCGIA Software Series.

Data Models for Distributed Navigable Databases

At UCSB, Caltrans, the California state department of transportation, has funded a project to develop improved data models for map databases for IVHS (Intelligent Vehicle Highway Systems). The project has focused on three aspects: definition of the requisite components of an IVHS map database; extension of the traditional planar link-node structures to handle non-planar and other pathological cases, and topological information on lanes; and examination of the design and implications of distributed databases. The research has resulted in a report (Church *et al.*, 1994) and research papers (Cova and Goodchild, 1994; Gottsegen, Goodchild, and Church, 1994).

RESEARCH PRODUCTS AND DELIVERABLES

Newsletter

One of the most important products of the Initiative was the newsletter edited by Bruce Ralston (University of Tennessee). This newsletter kept researchers across the world informed about research on SDSS, the evolution of existing and the development of new university courses in SDSS, and what vendors were doing to add SDSS capabilities to their products.

LADSS

The Locational Analysis Decision Support System (LADSS) is a product of the Initiative. Written by Paul Densham (1992), the system is a microcomputer-based system for solving location-selection problems. The system integrates a series of model solvers with utility and other programs under a push-button, interactive flowchart interface. LADSS includes an on-line tutorial and comes with instructions on how to link the system to a database management system and graphics display software or to a GIS. LADSS is distributed through the NCGIA Software Series; to date, over 40 copies have been sent to universities and corporations world-wide.

GEOLINEUS

During 1993, NCGIA released a new version of David Lanter's (1990, 1991) Geolineus package for lineage analysis to academic users. The new version incorporates several features developed during Initiative 6, and also is available in the NCGIA Software Series.

ESRI-NCGIA Project

A joint research project between Environmental Systems Research Institute (ESRI) and NCGIA (Densham) has led to the incorporation of location-allocation modeling capabilities in the NETWORK Module of ARC/INFO version 7.0. In beta release at the time of writing, this version of ARC/INFO will make location-allocation methods accessible to a wide range of potential users. The capabilities of the NETWORK Module are similar to those of LADSS (see above) with the addition of integrated graphical display and database management functions. Densham reported on the development of this module during a meeting held at the University of Lancaster, U.K., during June of 1993 entitled *Spatial Analysis in ARC/INFO*.

GEOCELLULAR

This package was developed with funding from Hitachi America Ltd. It extends the cellular automata model of space-time processes to geographically differentiated landscapes, and allows the user to specify a range of boundary conditions. Data is obtained from GRASS, and the capabilities of GRASS are used for display. It will be made available in the NCGIA Software Series.

EXTERNAL FUNDING

Research Grants Awarded

CALTRANS: "Distributed navigable database design and implementation issues"; $135,000. PIs: **Goodchild** and **Church**.

ENVIRONMENTAL PROTECTION AGENCY: "Development of a Geographically-Based Ecological Modeling Framework for Exposure-Effects Analysis of Contaminants in the Lower Great Lakes"; $ 1,643,005. PIs: DePinto, Atkinson, **Calkins, Densham**, Rumer and Taylor. July 1991 - June 1994.

ENVIRONMENTAL SYSTEMS RESEARCH INSTITUTE, Redlands, CA: "Location-Allocation Modeling with ARC/INFO's Network Analysis Module"; $ 5,650. PI: **Densham**. January 1990 - December 1990. (Award includes site license for 5 copies of the Sun

SPARCstation version of ARC/INFO: educational discount price of $ 43,400.)

HITACHI AMERICA, LTD.: "Cooperative research between Hitachi America Limited and NCGIA"; $ 120,000. PI: **Goodchild**, CoPIs: **Anselin** and **Church**. April 1992 - March 1993.

HITACHI AMERICA, LTD.: "Hitachi Resident Researcher Program, Year 2"; $ 150,000. PI: **Goodchild**, CoPIs: **Anselin** and **Church**. April 1993 - March 1994.

HITACHI AMERICA, LTD.: "Hitachi Resident Researcher Program, Year 3"; $ 130,000. PI: **Goodchild**, CoPIs: **Anselin** and **Church**. April 1994 - March 1995.

MANUFACTURERS AND TRADERS' BANK, Buffalo, NY: "Locational Analysis of Bank Retail Functions"; $9,000. PI: **Densham**. August 1989 - June 1990.

NATIONAL SCIENCE FOUNDATION (SES-90-24278): "Improving Human-Computer Interaction in Locational Decision-Making"; $ 99,810. PIs: **Densham** and Armstrong. June 1991 - December 1992.

U.S. FORESTRY SERVICE: "Spatial decision support systems for forest plan implementation and update"; $ 80,959. PI: **Church**. April 1992 - July 1993.

U.S. FORESTRY SERVICE: "Spatial decision support systems for forest plan implementation and update"; $ 27,000. PI: **Church**. October 1992 - September 1993.

Equipment and Software Grants Awarded

CALIPER CORPORATION, Newton, MA: Two copies of GisPlus Software; retail value of $20,000. PI: **Densham**. April, 1991.

ASSESSMENT

This section of the report examines Initiative 6 using the five criteria established by the NCGIA Board of Directors.

How is the research agenda different from when the Research Initiative started?

The original proposal to NSF identified four objectives for Initiative 6:

1) Design GIS data structures to support decision systems.

2) Develop methods for effectively structuring spatial search algorithms within a GIS framework.

3) Classify spatial search problems and identify gaps in current models.

4) Produce and test prototypical user interfaces.

Compared with these objectives, the research agenda developed at the Specialist Meeting is broader in scope. In addition to these original objectives, which fall into the second section of the research agenda on modeling and data in SDSS, elements concerning decision-making processes, the technology and implementation of SDSS, and a consideration of user requirements and organizational issues were added.

A second area of change has been in the incorporation of research on environmental problems and SDSS. This broadening of the research agenda reflects, primarily, the pressing nature of problems in this area and, secondarily, the availability of external funding. Indeed, five of the nine research grants awarded to support Initiative 6-related research are for three projects in the environmental area. One conclusion to draw from this shift in application focus is that the research agenda developed for Initiative 6 is robust and has implications for SDSS in general as well as for those systems used to address problems in location, retailing and marketing in particular.

To look beyond the horizon of Initiative 6, a panel session was organized for the 89th Annual Meetings of the Association of American Geographers, held in Atlanta, GA., in 1993. Both Initiative leaders and three participants in the Specialist Meeting (Armstrong, Iowa; Ralston, Tennessee; Rushton, Iowa) presented their views of what the new research issues are in SDSS. A journal article developing these presentations has been prepared and will be submitted shortly.

What do we know now that is new?

The areas in which new contributions have been made have been grouped under four themes below: frameworks and architectures for SDSS; modeling and implementation strategies for SDSS; visualization and user interfaces; and metadata, lineage and error propagation.

1) Frameworks and architectures for SDSS

- *Integration of GIS and modeling in support of planning*: One area of application that is closely related to location, retailing and marketing is that of planning. Although planners use spatial information and spatial analysis, they typically are not decision-makers *per*

se. We have learnt that linking GIS and quantitative methods for planning can enhance the ways that planners access, manipulate and use information (Batty, 1990a, 1990b, 1991; Smith, 1990). We have also learnt that planning can inform the design of GIS because the representations of space used in GIS do not correspond well to those used by planners (Couclelis, 1991).

- *Evaluations of GIS for supporting modeling*: A second research theme has been to understand the suitability of existing GIS for supporting models in different domains. Examinations have been made in the context of location models used by planners (Batty and Harris, 1992), environmental problem-solving in general (Goodchild, 1993), and water quality models in particular (DePinto *et al.*, 1994).

Together, these two threads provide insights into the design criteria of the next generation of SDSS.

2) Modeling and implementation strategies for SDSS:

- *Equitable vehicle routing models*: A considerable body of research has been carried out into spatial search strategies that yield equity in vehicle routes, where equity is measured in numerous different ways (Dutton, Batta, and Karwan, 1991; Gopalan, Batta, and Karwan, 1990; Gopalan *et al.*, 1990; Sivakumar and Batta, 1991; Sivakumar and Batta, in press; Sivakumar, Batta and Karwan, 1993; Sivakumar, Batta, and Karwan, forthcoming). The resulting model formulations can all be integrated with standard GIS database and display capabilities.

- *New location models and algorithms*: Several new location models, or reformulations of existing models, have been developed (Bloxham and Church, 1991; Church, Current, and Storbeck, 1991; Prasad and Batta, 1993; Schoepfle and Church, 1991; Weaver and Church, 1991). Two new heuristic location-allocation algorithms also have been developed (Densham and Rushton, 1992b; Dibble and Densham, 1993).

- *Linking models with commercial GIS:* Several of the Initiative's research projects have looked at linking different kinds of models with commercial GIS and have documented the problems encountered and how to resolve them (Densham, 1993; Dibble and Densham, 1993; Ding and Fotheringham, 1991; Ding, Baveja, and Batta, 1994; Willer, 1990). In addition, research has investigated new forms of linkage that currently are very difficult to implement with the existing hooks in commercial GIS (Densham, 1994).

- *Modelbase management*: Work on structuring models for use within SDSS has focussed on heuristic location-allocation algorithms (Densham and Rushton, 1992a, 1992b). One

approach to modelbase management was used to implement *LADSS* (Densham, 1992). This approach was also used to investigate the role of object-oriented programming languages for implementing a modelbase of location-allocation algorithms (Armstrong, Densham, and Bennett, 1989). This approach was subsequently refined to support the embedding of location-allocation models in ARC/INFO's NETWORK Module.

- *Decomposing spatial problems into parallel processes*: We have learnt how to decompose some spatial problems onto one class (multiple-instruction, multiple-data) of parallel processing computers (Armstrong and Densham, 1992; Densham, 1993; Ding, 1993; Ding and Densham, 1994).

3) Visualization and user interfaces:

- *Corridor location problems*: Church, Loban, and Lombard (1992) have developed a user interface for exploring spatial alternatives for a corridor location problem. This interface links representations (displays) of different spaces of interest to the decision-maker. This research shows that linked windows can be highly effective in transmitting information to a SDSS user and in providing access to modeling and analysis tools.

- *Visualization of results from location-allocation models*: We have learnt that there are numerous ways to visualize locational information at each stage during decision-making, including the output from location-selection models, using cartographic displays (Armstrong *et al*., 1991; McKinney, 1992). These displays are core components of a user interface for locational modeling (Armstrong, Densham and Lolonis, 1991) and can be used as the primary representation for interacting with the system (Densham, 1994). In this latter role, however, there are numerous differences between the geometrical, topological and thematic data used in modeling and display that must be resolved before such interfaces can be implemented (Densham and Armstrong, 1993). Such problems are not confined to locational modeling and must be addressed in most domains of modeling.

- *Visualization of urban spatial structure*: A second set of findings that merge cartographic displays with a user interface are derived from experience with integrated land-use transportation models (Batty, 1992; Batty and Xie, 1994a,b). These findings suggest that land-use modellers also tend to use abstracted topological representations, rather than the full geometrical and topological representations employed by cartographers, and that these differences must be resolved in linking models and graphics.

4) Metadata, lineage and error propagation:

- *Aggregation errors in linked spatial models*: We have confirmed earlier findings that

aggregation errors can have considerable effects on the solutions to location-selection algorithms (Fotheringham, Densham and Curtis, 1994). From extensions to this research we have learnt that aggregation errors are propagated through sequences of spatial models: these findings result from an application of a cohort component model followed by a location-allocation model. These findings suggest that the sensitivity of models to aggregation and other effects must be better understood if users are to be able to interpret scenarios that are generated by suites of linked spatial models.

- We have confirmed the findings of others that representing metadata and lineage in GIS is not a trivial undertaking (Lanter, 1990). Progress in this area has been made, however, with the development of a set of methods and displays for documenting an application's source data, transformations, and input/output specifications (Lanter, 1990, 1991, 1993). These methods are implemented in the GEOLINEUS system distributed as part of the NCGIA Software Series.

- In a GIS, the lineage and metadata of coverages, layers or themes must be tracked and recorded. In a SDSS, these procedures must be extended to include the parameter values and other information associated with models. Furthermore, system users often wish to generate a scenario and then modify it to yield a series of derivatives. Providing these capabilities requires the use of a scenario manager that acts both as an interface to the system's capabilities and a lineage and metadata repository. A prototype scenario manager has been built for a system that integrates water quality modeling with a commercial GIS (DePinto *et al.*, 1994). Research continues into the best way to structure and implement the scenario manager in this system.

What recommendations does NCGIA have to promote further advances in knowledge in this area?

One offshoot of Initiative 6 has been the Research Investigation entitled *Parallel Computation and GIS*, led by Paul Densham and funded by a grant from NSF (SES-9024278) to Densham and Marc Armstrong (Iowa). This Investigation focuses attention on the role of parallel computation in improving human interaction in locational problem-solving. Several papers resulting from this Investigation have been published and more are in preparation. The findings to date show that while parallel processing can have tremendous effects on both the size of problems that can be addressed and the throughput of computer systems, these problems must be carefully decomposed to exploit both their own characteristics and those of the computer. Further research in this area is badly needed: parallel processing personal computers and workstations are now available and symmetric multiprocessing operating systems are nearing completion. Geoprocessing software that can exploit these computers and operating systems is noticeable by its absence from the marketplace. As modeling and analysis capabilities become commonplace in

mainstream GISs, users will want to address larger problems at better levels of resolution than are now practicable; in this context, parallel processing increasingly will be seen as one way of addressing the massive computational requirements that will result.

A second set of suggestions for advancing knowledge in this area were presented during the panel session at the Atlanta meetings of the AAG in 1993. Several of these themes have been woven into the proposal for a new Initiative. Initiative 17 (*Collaborative Spatial Decision-Making* or CSDM) was approved in principle by the NCGIA Board of Directors at its June, 1993, meeting in Buffalo. This Initiative picks up many of the threads of Initiative 6 and extends them to consider collaborative or group-based software that supports spatial problem-solving and decision-making. With an increasing emphasis on computer-supported cooperative work environments in the mainstream business software market, the single-user mode of interaction supported by most GIS and SDSS is being rendered atypical. Paradoxically, it is the very technology that has made GIS accessible and feasible for many companies and institutions (local and wide area networks of PCs and workstations with distributed processing and databases) that has enabled the move to collaborative business software. Impediments to the development of CSDM systems include:

- the design of user interfaces that will effectively support group decision-making and enable individuals to resolve conflicts;

- providing decision-makers with the means to interact with problems in near-real-time so that they may visualize the effects of making adjustments to the parameters that define the solution space of a problem;

- embedding knowledge in CSDM environments so that they can actively help decision-makers employ complex analytical and evaluative capabilities;

- designing collaborative spatial modeling tools that enable decision-makers to work in a solo mode, with one or two others, or with all members of a task force or team; and

- the incorporation of methods of decision analysis and multi-criteria decision-making in CSDM environments to enable decision-makers to evaluate their own scenarios and to comparing them with those generated by other decision-makers.

What has NCGIA learned about the Initiative process and how might the operation of future initiatives be improved?

One of the major difficulties in planning Initiative 6 was to identify representatives of government agencies who could participate in the Specialist Meeting. Although many agencies

expressed interest in the Initiative, we found it very difficult to identify people who could both contribute to the Specialist Meeting and attend. Fortunately, many of the academic and private sector participants have worked in or with government agencies on SDSS-related matters and were able to contribute their experiences at the Specialist Meeting. The selection of participants is crucial to the success of a Specialist Meeting, however, and the whole process relies on networks of contacts. Although Goodchild had well-established links in the government agencies, Densham, unlike other junior faculty leading Initiatives (Buttenfield, Initiative 3), lacked such contacts because his appointment to the faculty at Buffalo in 1988 was his first job. Consequently, the formal adoption of a core planning group for Initiative 9 and all subsequent Initiatives is an excellent idea: supplementing junior Initiative leaders with the expertise and networks of such a group ought to greatly enhance the probability of finding the right participants for a Specialist Meeting.

One of the strategies adopted in running the Specialist Meeting was not to have presentations of the participants' position papers. Although many of the invited participants were working on SDSS-related research, many of them used different terminologies and subscribed to a large range of views on what constituted a SDSS. We felt that the Specialist Meeting would founder on problems of definition and perspective if participants presented papers and the meeting was not provided with an explicit framework or context for discussion. Consequently, we decided to provide this framework by, first, narrowing the focus to adopt the definition of DSS advocated by Geoffrion and others and, second, asking participants to read four papers before coming to Santa Barbara that we hoped would provide a common view of SDSS and a framework for discussion. The Specialist Meeting began with several large-group meetings to review these papers and this framework before alternating between large and small-group discussion sessions. Although this process may seem overly confining, we believe it achieved its goal: participants discussed research issues rather than trying to defend positions adopted in earlier work. Moreover, by the end of the Specialist Meeting, it was clear that a cadre of people existed who shared an understanding of one view of SDSS and the associated research problems. Although Fotheringham (1990) pokes fun at the jargon associated with SDSS, he concludes that this cadre may have been the most important result of the Specialist Meeting.

Other Initiative Closing Reports have noted the importance of bringing researchers outside the NCGIA into the Initiative process. One approach adopted for Initiative 6 was to run a newsletter edited by Bruce Ralston at the University of Tennessee. This had two benefits: first, it was an important avenue for reporting what people were doing; and, second, it served to distance the newsletter from the Initiative leaders who, as described above, had influenced the content and course of the Specialist Meeting. We would recommend that other Initiatives adopt a similar forum for keeping researchers in touch with each other.

The active research phase of Initiative 6 was three years in length, rather longer than the 2

year period of most other Initiatives. Furthermore, many of the projects falling under the aegis of Initiative 6 are still in progress. In part, this time-scale reflects the considerable overhead involved in designing and implementing prototype systems that link GIS and GIA. Another reason is the delays incurred in securing external funding for research activities. Although Initiative 6 has been successful in garnering outside funding, this has inevitably resulted in delays to and deviations from the planned schedule. Leaders of future Initiatives should consider this lag effect when compiling their own research schedules and try to find a balance between projects that can commence immediately and those that require external support to be viable.

What contribution has the Initiative made to GIS education?

A number of graduate theses and projects contribute directly to the Initiative 6 research agenda. At Buffalo, four graduate degrees have been completed to date. David Willer (1991) and Jim McKinney (1992) have completed Master's degrees entitled, respectively, *A spatial decision support system for bank branch location*, and *The visualization of solutions to location-allocation models*. Two students have graduated with Ph.D.s: Yuemin Ding (1993) wrote a thesis entitled *Strategies for parallel spatial modeling on MIMD computers*; Michael Gould (1993) undertook research on *Map use, spatial decisions, and spatial language in English and Spanish*.

Course materials have been developed and distributed to assist in teaching the concepts and applications of SDSS. Gould and Densham (1991) compiled a bibliography of papers and theses in the areas of DSS and SDSS which is distributed as an NCGIA Technical Report. The *Locational Analysis Decision Support System* (Densham, 1992) is also distributed by the NCGIA, in its Software Series, and has been adopted for use in SDSS courses by over 20 universities worldwide. Densham and Gerard Rushton (The University of Iowa) and Marc Armstrong (The University of Iowa) organized a workshop entitled *Spatial Decision Support Systems: Principles and Applications* which was presented at the 88th Annual Meetings of the Association of American Geographers, April 18th - 21st, 1992, San Diego, CA. During this workshop, Densham and Rushton distributed syllabi for their respective courses in SDSS.

Several conferences with a strong SDSS component were held during the active period of Initiative 6 (NCGIA personnel on the organizing committees are indicated by boldface type):

1) *Second International Conference on Computers in Urban Planning and Urban Management*. Organizers: **M. Batty** (NCGIA, Buffalo), R.E. Klosterman (University of Akron), I. Masser (University of Sheffield) and L. Wiggins (Massachusetts Institute of Technology). July 6th - 8th, 1991, Oxford, UK.

2) *First International Conference/Workshop on Integrating Geographic Information Systems and Environmental Modeling*. Organizers: **M. Goodchild** (NCGIA, Santa Barbara) and Brad Parkes

(ASCI Corporation). September 15th - 18th, 1991, Boulder, Colorado.

> The conference attracted specialists at the interface between GIS and modeling. The Steering Committee solicited presentations, case studies, and discussants from among the various research communities working in these fields. These issues were addressed during a three-day symposium. The symposium focussed on the modeling of physical processes, complementing Initiative 6's focus on location, marketing and retailing. A second conference was held in Breckenridge, CO in September, 1993, and a third is planned in Santa Fe, NM, in January 1996.

3) *International Meeting of Experts on Spatial Analysis and Spatial Decision Support Systems in Rural Service Planning.* Organizers: Vinod Tewari (Indian Institute of Management at Bangalore), Gerard Rushton (The University of Iowa), and **Paul Densham** (NCGIA Buffalo). August 1991, New Delhi, India.

> This meeting brought together academics, officials from Indian central and state government and agencies, and planners to evaluate the use of spatial analysis and spatial decision support systems in rural service planning. The meeting was followed by presentations on a prototype system at the National Informatics Centre, New Delhi.

Conference sessions presenting Initiative 6 research were organized for the following meetings:

1) Two special sessions on SDSS at the 88th Annual Meetings of the Association of American Geographers, 1992, San Diego, CA.

2) A special session on spatial decision support systems at GIS/LIS '92, 1992, San Jose, CA.

3) A panel session entitled *Spatial Decision Support Systems: a Review and Future Directions* at the 89th Annual Meetings of the Association of American Geographers, 1993, Atlanta, GA.

Presentations on Initiative 6 research were made at the following venues:

1989   5th New York State GIS Meeting; National Science Foundation; GIS/LIS '89.

1990   86th Annual Meeting of the Association of American Geographers; Fall Meeting of the Operations Research Society of America and The Institute of Management Scientists.

1991   Symposium on Microcomputers for International Development: New Applications in Planning and Management, Cornell University; Spring Meeting of the Operations

Research Society of America and The Institute of Management Scientists; San Diego State University; Annual Meetings of the Urban and Regional Information Systems Association; National Informatics Centre, New Delhi, India; First International Conference/Workshop on Integrating Geographic Information Systems and Environmental Modeling; Environmental Systems Research Institute Forum, Redlands, CA; Fall Meeting of the Operations Research Society of America and The Institute of Management Scientists.

1992   The Center for Tomorrow, State University of New York at Buffalo; 5th International Spatial Data Handling Symposium; 4th International Conference on Applied Demography; Fall Meeting of the Operations Research Society of America and The Institute of Management Scientists; United Nations, New York.

1993   Institute of British Geographers Annual Conference; 89th Annual Meeting of the Association of American Geographers; NYNEX Science and Technology (1993); Spatial Analysis in ARC/INFO, Lancaster University; The University of Iowa (1993); Auto-Carto 11; GIS/LIS '93; Second International Conference/Workshop on Integrating GIS and Environmental Modeling, Breckenridge.

ANNOTATED LIST OF NCGIA PUBLICATIONS FROM INITIATIVE 6

Refereed Journal Articles

Armstrong, M.P., S. De, **P.J. Densham**, P. Lolonis, G. Rushton, and V.K. Tewari (1990) A knowledge-based approach for supporting locational decision-making. *Environment and Planning B* 17(3): 341-364.

The paper describes a system for providing decision support to people who make locational decisions in which the domain-specific knowledge of users is combined with the general problem-solving strategies, techniques, and mathematical models of locational analysts. A metaplanner interacts with users to generate scenarios which describe the general problem-solving strategy to be pursued. These scenarios are organized into a series of tractable problems which are solved in a subproblem-solver module consisting of location-allocation and other analytical models. The system enables decision-makers to examine systematically the results of a series of analyses leading to a desired solution.

Armstrong, M.P., and **P.J. Densham** (1990) Database organization strategies for spatial decision support systems. *International Journal of Geographical Information Systems* 4:3-20.

The selection of a data model is an important step in designing a spatial decision support system (SDSS). A methodology for SDSS conceptual database design is developed using the Entity-Category-Relationship approach. To accommodate this conceptual structure in database management software, a review of available data models is made and the authors select the hybrid extended network model. To illustrate their methodology, the authors design a logical database structure for a locational analysis SDSS.

Armstrong, M.P., and **P.J. Densham** (1992) Domain decomposition for parallel processing of spatial problems. *Computers, Environment, and Urban Systems* 16(6): 497-513.

The authors contend that spatial models often are not used to their fullest potential because they have massive computational requirements. Existing workstations and microcomputers often must solve these models in batch mode and, consequently, decision-makers are unable to explore and resolve complex spatial problems in an interactive and graphical environment similar to that provided by general-purpose business software. Parallel processing can solve spatial models at high speed, however, greatly decreasing turnaround times and enabling decision-makers quickly to see the results of revising parameters and criteria. To reap these benefits in a parallel processing environment researchers must recast modeling procedures from their existing sequentially-oriented form to one in which parallelism can be exploited. This process, referred to as domain decomposition, is a fundamental enterprise in parallel spatial modeling. Domain decomposition for spatial problems can be structured by a set of general principles which are described and illustrated using an example from location-allocation modeling.

Armstrong, M.P., **P.J. Densham**, P. Lolonis, and G. Rushton (1991) Cartographic displays to support locational decision-making. *Cartography and Geographic Information Systems* 19(3): 154-164.

A functional taxonomy is developed to describe the kinds of maps that can be used by decision-makers when they must change the locations of activities to serve distributed demand. Locational maps, demand maps, supply maps, allocation maps, and delta maps can be used for a variety of purposes during all three stages of the decision-making process: problem research and definition; the generation of alternative solutions; and selecting a course of action. Implementations of these display types are described. Finally the authors argue that in a visual interactive modeling environment, linkages between the objective space of mathematical models and the graphical space of cartographic displays will enable decision-makers to select more appropriate analytical models and to intervene and change their decision criteria.

Armstrong, M.P., G. Rushton, R. Honey, B. Dalziel, P. Lolonis, S. De, and **P.J. Densham** (1991) Decision support for regionalization: a spatial decision support system for regionalizing service delivery systems. *Computers, Environment and Urban Systems* 15(1): 37-53.

The problem of finding an optimal number of regions, and service locations within each region, to serve a dispersed geographical pattern of demand is treated as an interactive location-allocation problem. Distinctive elements of the problem involve controlling the location of region boundaries, solving for multiple objectives that involve minimizing average and maximum distances to clients from central facilities, ensuring that a minimum number of clients are served in each region, and, under user-defined circumstances, using existing facilities in selected locations. The paper discusses a prototype microcomputer-based spatial decision support system and its use by members of an Iowa state government workgroup charged with developing recommendations for the geographical reorganization of educational services provided to school districts from central facilities.

Batty, M. (1991) New technology and planning: reflections on rapid change and the culture of planning in the post-industrial age. *Town Planning Review* 62(3): 269-94.

This article reviews the response of planners and the planning system in Britain to the effects of new technology during the last 40 years. During this period, planning has changed direction several times, moving from design, through systems approaches to social advocacy and political economy, while during the last ten years, its practice has been ever more pragmatic, dominated by a concern for land, a quest for enterprise, all to be achieved through bargaining and negotiating with powerful interests. Into this milieu came new technology whose short history has been equally turbulent, usually out of phase with the problems to which it has been addressed. The picture is uneven but is dominated by the development of data and information systems, thus implying rather more modest and practical uses for new technology than was originally supposed. The article concludes by identifying key problems in education and practice, and by focussing on the crucial dilemma in training a future generation of planners able to rise above the current and traditional response of rejecting any new technology out-of-hand.

Batty, M. (1992) Urban modeling in computer-graphic and geographic system environments. *Environment and Planing B* 19: 663-688.

This paper presents a prototypical visual environment that links GIS to spatial models. The elements of visualization in such an environment are first defined in terms of the model-base processes which characterize applications emphasizing data exploration, model calibration, prediction, and prescription. These processes are then concentrated through model inputs, outputs, and causal structures, illustrating the operation of various model sectors through different modes of spatial, statistical and graphic analysis. These ideas are implemented through windowing systems which mix text, numerics and graphics, and are illustrated using an elementary model of residential location of Melbourne, Australia. The operation of the model in a UNIX environment which is accessed through proprietary windows-based software is demonstrated, thus providing a platform to discuss the problems of linking conventional model-based techniques to graphics software in general, and GIS in particular. The paper is concluded with a sketch for future work.

Batty, M., and **Y. Xie** (1994a) Modeling inside GIS. Part 1: model structures and interactive graphics. *International Journal of Geographical Information Systems* 8(3): 291-307.

This is the first of two papers which elaborates a framework for embedding urban systems models within GIS. This framework is based upon using the display capabilities of GIS as the user interface to the conventional modeling process, beginning with data selection and analysis, moving to model specification and calibration, and thence to prediction. In this paper, the authors outline the structure of this process and show how these various stages, which are based on purpose-built software outside the system, are accessed and operated through the GIS. First, the authors discuss display based on thematic maps, surfaces, graphs and linked windows which are standard to any data from whatever source, be it observations, model estimates or predictions. The discussion then focuses on how various datasets are selected, how the spatial system can be partitioned or aggregated, and how rudimentary exploratory spatial data analysis enables scatterplots to be associated with thematic maps. All these functions and operations are illustrated using ARC/INFO which is applied to population data at the tract level in the Buffalo region.

Batty, M., and **Y. Xie** (1994b) Modeling inside GIS. Part 2: urban location models using ARC/INFO. *International Journal of Geographical Information Systems* 8(5): 451-470.

> In this, the second of two papers, the authors outline a series of model-based functions linked to a GIS and demonstrate their use. First, the theory of residential location models is developed using population density theory, stating continuous then discrete model forms, and calibration methods. The authors illustrate a simple pass through the complete software system, using the example of the Buffalo urban region, and show how observed data and model estimates can be evaluated through graphic display. Ways in which the system can be used to explore and fit a variety of models to different zoning systems are presented and are used to illustrate how subset selection and aggregation can be used to find models with good fit. Finally, the authors sketch an agenda for further research.

Bloxham, C.A., and **R.L. Church** (1991) The p-median scheduling and location problem. *Papers in Regional Science* 70(1): 21-35.

> With few exceptions, public-facility location models have considered facility accessibility to be solely a function of spatial distribution relative to demand. In this paper, we expand this definition to recognize a temporal component as well. A model is presented that optimally locates a given number of facilities and simultaneously schedules their operations to maximize accessibility to demand. In addition, for the special case when facilities already exist, a model is presented that focuses solely on the optimal scheduling of facility operations. Test results indicate that these models may have significant and varied implications for locational and policy analysis.

Carson, Y., and **R. Batta** (1990) Locating an ambulance on the Amherst Campus of the State University of New York at Buffalo. *Interfaces* 20(5): 43-49.

> The authors used past call-data statistics and a network representation of the Amherst Campus of the State University of New York at Buffalo to find a dynamic positioning strategy for the campus ambulance. Average response time to a call was used as a measure of performance in solving several one-median problems. These models were validated and the authors show that the location strategy selected resulted in a 6% saving rather than the predicted 30% saving.

Church, R.L., J. Current, and J. Storbeck (1991) A bicriterion maximal covering location formulation which considers the satisfaction of uncovered demand. *Decision Sciences* 22(1): 38-52.

> This paper presents a bicriterion locational covering model which explicitly considers the travel distance or time necessary to service demand not within the maximal covering distance of a facility. The model may be used to generate noninferior (Pareto optimal) siting configurations which demonstrate the inherent trade-offs between a siting scheme designed to maximize total coverage and one designed to minimize total travel time for uncovered demand to reach its nearest facility. In addition, it is shown that for any particular weighting scheme on the two objectives, the problem can be solved as a p-median problem; a problem for which several efficient solution methods exist.

Church, R.L., S.R. Loban, and K. Lombard (1992) An interface for exploring spatial alternatives for a corridor location problem. *Computers and Geosciences* 18(8): 1095-1105.

> The location of corridors of rights-of-way across a landscape for the purpose of siting a facility such as a power transmission line has been the subject of much research. Many different computerized models have been developed to address this design and layout problem. Any environmental review usually requires that alternative routes be considered. Thus, the value of a model can be measured not only in terms of determining a good solution but in supporting the search for good alternatives as well. Such problems have been posed as multiobjective programming models. This paper presents a novel user interface that is designed to help explore possible alternative corridors. This new interface allows for exploration in terms of both objective space and decision space and could be modified for other spatial decision-making problems as well.

Church, R.L., and O.B. Schoepfle (1993) The choice alternative to school assignment. *Environment and Planning B, Planning and Design* 20(4): 447-457.

Couclelis, H. (1991) Geographically informed planning: requirements for planning-relevant GIS. *Papers in Regional Science* 70(1): 9-20.

For a variety of practical, technical and theoretical reasons, GIS capabilities are not yet fully attuned to the information needs of planning. This paper focuses on one of the more theoretical sources of existing discrepancies: the differing underlying representations of space in GIS on the one hand, and in much of planning in the other. Indeed, GIS embody an absolute "container" view of space, whereas the higher-level functions of planning, along with most of regional science and human geography, treat space as "relational". It is suggested that the absolute-relative polarization could be theoretically resolved, and GIS could be made more relevant for strategic planning, through the operationalization of an intermediate conception of space as "proximal".

Densham, P.J. (1994) Integrating GIS and spatial modeling: visual interactive modeling and location selection. *Geographical Systems* 1(3): 203-219.

A variety of strategies can be used for integrating GIS and spatial modeling. These strategies can be viewed from several perspectives: the technical or programmer's perspective; the functional or user's perspective; and the conceptual perspective. Each perspective is discussed and used to evaluate software integrating location selection and GIS capabilities. When evaluated from the functional perspective, these systems are shown to support only a restricted form of human-computer interaction. GIS-model linkages that support higher forms of human-computer interaction are discussed.

Densham, P.J., and G. Rushton (1992a) Strategies for solving large location-allocation problems by heuristic methods. *Environment and Planning A* 24: 289-304.

The authors show that processing costs for the most accurate heuristic, location-allocation algorithm can be drastically reduced by exploiting the spatial structure of location-allocation problems. Their implementation strategies enable the solution of large problems (3,000 nodes) in a microcomputer-based, interactive decision-making environment. Tests on four network problems validate claims that these strategies yield solution times which increase approximately linearly with problem size.

Densham, P.J., and G. Rushton (1992b) A more efficient heuristic for solving large p-median problems. *Papers in Regional Science* 71(3): 307-329.

The Teitz and Bart (1968) vertex substitution heuristic is more robust than competing algorithms and yields solutions with properties that are necessary, but not sufficient, for a global optimum solution. All documented implementations of this algorithm, however, use a naive spatial search procedure, whereas an intelligent spatial search procedure, requiring considerably less computation to solve any given problem, is possible. An algorithm incorporating this new search procedure, called the global/regional interchange algorithm, is described. As problem size increases, proportionally larger reductions in processing costs occur.

DePinto, J.V., **H.W. Calkins, P.J. Densham**, J. Atkinson, W. Guan, and H. Lin (1994) Development of GEOWAMS: An approach to the integration of GIS and watershed analysis models. *Microcomputers in Civil Engineering* 9: 251-262.

This paper describes the design and implementation of a loosely-coupled SDSS that contains a commercial GIS (ARC/INFO) and a suite of watershed analysis models. The GIS passes data to the models via a data management interface; this interface is also used to import results into the GIS where they can be displayed. A scenario management system provides access to modeling tools and data and records which data were used by whom and to what effect.

Ding, Y., **A. Baveja**, and **R. Batta** (1994) Implementing Larson and Sadiq's location model using a geographic information system. *Computers and Operations Research* 21(4): 447-454.

      Larson and Sadiq (1983) developed and analyzed a model for locating facilities on a Manhattan plane with impenetrable barriers to travel. Their principal result was that the search for candidate facility locations can be restricted to a finite, easily identifiable set of points.   In this paper, the authors describe an implementation of Larson and Sadiq's model in the ARC/INFO geographic information system. A sample case study based on data from the Town of Amherst is presented.

Ding, Y., and **P.J. Densham** (1994) A loosely synchronous, parallel algorithm for hill shading of digital elevation models. *Cartography and Geographic Information S*ystems 21(1),: 5-14.

      An integrated hill-shading algorithm has three components that model self shading of terrain features, shadows cast by other terrain features, and atmospheric scattering. Self-shadows are detected from the relative reflectance of direct light, in a vertical direction, from surface elements. Cast-shadows are modeled by a coordinate rotation approach. Atmospheric scattering is simulated by solid angles based on a ball model.   The algorithm is decomposed into loosely synchronous parallel processes using both data parallelism and procedural parallelism and is implemented on a Transputer array. Representative results for several digital elevation model indicate that, when compared with a serial implementation, the parallel algorithm reduces solution times by over 70% when four processors are used.

Dutton, L., **R. Batta**, and M.H. Karwan (1991) Equitable sequencing of a given set of hazardous materials shipments. *Transportation Science* 25(2): 124-137.

      The authors consider the problem of equitably sequencing a series of hazardous materials shipments.   The set of routes selected is such that overall risk to the community is low and once they are all traversed, risk is equitably distributed among the zones of the community.   The objective function used is to minimize the sum of the maximum differences in risk that exist between any two zones, where the sum is taken over all the trips made. This problem is formulated both as an integer programming problem and as a dynamic programming problem. Optimal solution strategies are examined for small problems and several heuristics are proposed for obtaining reasonable solutions to large problems.   The proposed solution methods are tested on a real data set from the city and county of Albany, New York, and on randomly-generated data sets.

Fotheringham, A.S., **P.J. Densham**, and **A. Curtis** (1994) The zone definition problem in location-allocation modeling. *Geographical Analysis* forthcoming.

      Location-allocation modeling is a frequently used set of techniques for solving a variety of locational problems, many of which are politically sensitive. The typical application of a location-allocation model involves locating facilities by selecting a set of sites from a larger set of candidate sites, with the selection procedure being a function of "optimality" in terms of the allocation of demand to the selected sites. Demand data often are counts of the numbers of people living in particular spatial units. Although widely employed, a problem with using aggregated demand in location-allocation models is that the measurement of that demand is dependent on the definition of the spatial units, which, for the purposes of the modeling procedure, is often completely arbitrary. In this paper the authors examine the sensitivity of one particular type of location-allocation model, the p-median procedure, to the definition of spatial units for which demand is measured. The nature of this sensitivity is demonstrated both for the locations of facilities and for the allocation of demand to these facilities.

Goodchild, M.F. (1991) Guest commentary: geographic information systems. *Journal of Retailing* 60(1): 3-15.

Gopalan, R., **R. Batta**, and M.H. Karwan (1990) The equity constrained shortest path problem. *Computers and Operations Research* 17(3): 297-307.

This paper examines the problem of finding the shortest path on a network subject to "equity" constraints. Suggested applications for this problem include routing of a vehicle carrying hazardous materials, routing a police car through a city, and planning a politician's campaign tour. The equity constraints ensure that the route generated is fair to all the parties concerned. Results suggest that a good degree of fairness can be achieved with only a fairly modest increase in the cost of the route. A Lagrangean dual bounding approach is utilized and a heuristic is developed. Computational results are reported.

Gopalan, R., K.S. Kolluri, **R. Batta**, and M.H. Karwan (1990) Modeling equity of risk in the transportation of hazardous materials. *Operations Research* 38(6): 961-973.

The authors develop and analyze a model to generate an equitable set of routes for hazardous material shipments. The objective is to determine a set of routes that will minimize the total risk of travel and spread the risk equitably among the zones of the geographical region in which the transportation network is embedded, when several trips are necessary from origin to destination. An integer programming formulation for the problem is proposed. The authors develop and test a heuristic that repeatedly solves single-trip problems; a Lagrangean dual approach with a gap-closing procedure is used to optimally solve single-trip problems. Results are presented for an application in the Albany, New York area which suggest that a high degree of equity can be achieved by increasing modestly the total risk and by embarking upon different routes that spread evenly the risk among the zones.

Haynes, K.E., and **A.S. Fotheringham** (1990) The impact of space on the application of discrete choice models. *The Review of Regional Studies* 20(2): 39-49.

The structure of this paper is as follows. The first section outlines the implications of Independence from Irrelevant Alternatives (IIA) for modeling discrete choice processes with particular reference to the multinomial logit model. The next section focuses on the reliability of these assumptions in a spatial context. Attention then turns to two alternative paths for relaxing the IIA assumption through explicitly modeling alternative substitutability within the systematic component of utility or implicitly modeling alternative substitutability through the error structure. Throughout these latter two sections, we focus on the potential for introducing spatial effects into existing model frameworks.

Honey, R., G. Rushton, M.P. Armstrong, P. Lolonis, B. Dalziel, S. De, and **P.J. Densham** (1991) Stages in the adoption of a spatial decision support system for reorganizing service delivery regions. *Environment and Planning C* 9(1): 51-63.

A prototype spatial decision support system was used by a task force appointed by the State of Iowa to redraw the boundary lines of education service delivery regions. Details of this regionalization problem are described and key stages are identified in the task force's adoption and use of the SDSS to arrive at recommended solutions. This approach separates the policy task of setting regionalization objectives and criteria from the more technical task of locational analysis which involves searching for alternatives that meet the requirements of the policy criteria. The authors conclude that the SDSS contributed significantly to meeting the basic objectives of the Iowa Legislature.

Jamil, M., **R. Batta**, and D.M. Malon (1994) The traveling repairperson homebase location problem. *Transportation Science* 28(2): 150-161.

This paper considers the problem of locating the home base of a travelling server on a network. Calls for service arrive solely at nodes via independent, time-homogeneous Poisson processes. Calls finding the server busy enter a finite capacity queue which is depleted in a First-Come-First-Served (FCFS) manner. The server travels from his/her home base when he/she finds the system empty upon the completion of a service. The objective is to minimize the average response time to an accepted call. The queueing system is analyzed via a busy period analysis, which uses a decoupling scheme to simplify the task of optimizing the home base location. Computational experience is discussed and a numerical example is presented. Generalizations of the model also are discussed.

Lanter, D.P. (1991) Design of a lineage-based meta-database for GIS. *Cartography and Geographic Information Systems* 18(4): 255-261.

Lanter, D.P. (1993) A lineage meta-database approach toward spatial analytic database optimization. *Cartography and Geographic Information Systems* 20: 112-121.

> This work demonstrates how increasing levels of intelligence can be added to commercial geographic information systems. The lineage-knowledge representation introduced in an earlier article (Lanter, 1991) provides a basis for encoding the logic applied within specific spatial analytic applications.   This knowledge is general, reusable and extendible to solving many significant problems in geographic information processing. In this study, the lineage-knowledge representation is applied to automatically differentiate between source and derived layers, pick an optimal spatial analytic database configuration, and generate applications tailored to the contents of the spatial analytic database.

Prasad, S.Y., and **R. Batta** (1993) Determining efficient facility locations on a tree network operating as a FIFO M/G/1 queue. *Networks* 23: 597-603.

> In this article, the authors study the problem of locating a server on a tree network that operates as a FIFO M/G/1 queue. They consider an objective function which is a weighted sum of appropriate powers of the first *n* moments of the response time. The properties of the service time, travel time, and the objective function are studied and the authors identify sets of efficient facility locations. The results are illustrated with an example.

Schoepfle, O.B., and **Church, R.L.** (1991) A new network representation of a classic school districting problem. *Socio-Economic Planning Sciences* 25(3): 189-197.

> Declining and fluctuating enrollments of the last decade have necessitated changes in the sizes and locations of schools in hundreds of districts across the United States. School administrators are thus faced with the difficult and complex problems of redistricting, compounded when desegregation is at issue. Researchers have worked for two decades with variants of a linear programming districting model which minimizes total distance traveled as all students are assigned to schools which are subject to capacity and racial balance limitations. This model could aid in the construction of districting alternatives but in practice is difficult to solve with generalized solution methods due to excessive size. Network-based representations have been actively pursued because of the existence of fast special algorithms and codes. However, single-network representations have been successful in modeling only special cases of this problem. We present here a generalized network flow problem with side constraints which is a new and exact equivalent of this classic districting problem.

Sivakumar, R.A., and **R. Batta** (in press) The variance-constrained shortest path problem. *Transportation Science*.
> The variance constrained shortest path problem can be used to model any application in which the travel costs on a link are not deterministic, but follow a distribution that has a possible correlation with travel cost on other links. Both exact and heuristic solution methods are proposed.   These techniques are illustrated through a numerical example, and via computational experiments on data sets derived from a real-life routine scenario involving the transportation of liquefied-gas hazardous materials.

Sivakumar, R.A., **R. Batta**, and M.H. Karwan (1993) A network-based model for transporting extremely hazardous materials. *Operations Research Letters* 13: 85-93.

> While routing those hazardous materials that can be catastrophic when involved in an accident, it sometimes can make more sense to minimize the risk given the occurrence of an accident rather than the *a priori* risk. In this paper, the authors consider the concept of conditional risk, and propose two solution procedures. A model that minimizes the conditional risk, keeping the accident probability within a set threshold also is presented.

Sivakumar, R.A., **R. Batta**, and M.H. Karwan (forthcoming) A multiple route conditional risk model for transporting hazardous materials. *Information Systems and Operational Research*.

This paper considers the problem of developing effective routes for transporting hazardous materials for the case where the routing ends after the occurrence of the first accident. A multiple route situations is permitted, the objective being to minimize the expected risk of the first accident, with constraints on the accident probabilities, the expected *a priori* risk, the transportation cost, and the equity of risk. A column generation techniques is used to generate heuristic solutions. A brief summary of results from computational testing, based on a "real-life" hazardous materials routing scenario, is presented. Also presented is an example problem that illustrates several features of the model.

Weaver, J.R., and **R.L. Church** (1991) The nested hierarchical median facility location model. *Infor* 29(2): 100-115.

In hierarchical facility systems there are multiple levels of facilities such that each facility level provides different but related services. The specific hierarchical locational system which we model is a nested facility hierarchy such that the location of a higher level facility at a site requires that facilities of all lower levels also be located at that site. In addition, it is assumed that all demand is serviced directly by the closest facility of the appropriate level and that there are no referrals. Under the assumption that all demand is located at the nodes of the transportation network, we prove that an optimal configuration of facility nests is located at nodes. The node optimality result is used to formulate the nested hierarchical median problem as a binary linear program.

Book Chapters

Batty, M. (1990a) Information systems for planning in developing countries. In *Information Systems and Technology for Urban and Regional Planning in Developing Countries: A Review of UNCRD's Research Project*. United Nations Center for Regional Development, Nagoya, Japan: 105-236.

This paper provides a review of the UNCRD Project on Information Systems for Planning in Developing Countries, with specific reference to applications in Asia-Pacific. The review is based on the papers presented and the recommendations made at four conferences organized by UNCRD held between 1984 and 1988. Principles for information systems (IS) design and their development using information technology (IT) based on computers and telecommunications are drawn out, and comparisons between the application of such systems in the developed and developing worlds are made. After exploring the complexities of introducing IS into planning in developing countries, the author proposes an approach or model to draw out the various relationships between organization, technology, and its application in planning, and indicates how organizational structures and training programs might be designed using this approach.

Batty, M. (1990b) Informative planning: the intelligent use of information systems in the policy-making process. In H. Sazanami, editor, *Critical Success Factors: Key to Use of Information Systems/Technology in Local/Regional Planning*. United Nations Center for Regional Development, Nagoya, Japan: 307-356.

The use of information systems in urban planning over the last 20 years has changed from large-scale, integrated systems to small-scale, less ambitious systems in the present day. The author argues that the most informative way of using the new technology is in the construction of many small information systems, each dealing with different aspects of the planning task, and being integrated with each other using emergent network technologies. Characteristics and examples of information systems are described, and a series of dimensions reflected in a typology of information systems introduced. The process of using such systems informatively and intelligently is then described. These issues are illustrated in the design of a simple library system consisting of maps describing the socioeconomic conditions in the docklands area of south Cardiff (Wales, UK).

Densham, P.J. (1991) Spatial decision support systems. In D.J. Maguire, **M.F. Goodchild** and D.W. Rhind (eds.) *Geographical Information Systems: Principles and Applications*. Longman Scientific and

Technical, London 1: 403-412.

Spatial decision support systems are explicitly designed to address complex spatial problems. This paper examines the design of such systems, the types of problem to which they can be applied, and the decision-making processes they support, and discusses a framework for their implementation and subsequent evolution.

Goodchild, M.F. (1993) The state of GIS for environmental problem-solving. In **Goodchild, M.F.**, B.O. Parks, and L.T. Steyaert (eds.) *Environmental Modeling with GIS*. Oxford University Press, New York NY: 8-16.

The strengths and capabilities of GIS for supporting environmental problem-solving are documented in this chapter. Emphasis is placed on data modeling, the different types of data model supported by GIS, and how these models influence both the functionality and use of GIS for environmental problem-solving.

Goodchild, M.F. (1993) Data models and data quality: problems and prospects. In **Goodchild, M.F.**, B.O. Parks, and L.T. Steyaert (eds.) *Environmental Modeling with GIS*. Oxford University Press, New York NY: 94-103.

This chapter explores the links between data models and data quality, focussing on the differences among *accuracy*, *precision*, *resolution* and *scale*.

Monographs and Technical Reports

Church, R., D. Coughlan, T. Cova, M.F. Goodchild, J. Gottsegen, D. Lemberg, and R. Gerges (1994) *Final Report: Caltrans Agreement 65T155*. Technical Report 94-6, National Center for Geographic Information and Analysis, Santa Barbara CA.

The NCGIA/UCSB project explored three major aspects of navigable map databases: the elements to be stored in them, appropriate data models, and issues of database distribution. The sections of the report describe the major functions of IVHS, and their requirements, if any, for map databases; alternative data models, including the traditional link/node planar model and newer, more powerful models; and the design of a distributed navigable database, and the capabilities of current GIS and database management products in this area.

Densham, P.J. (1992) *The Locational Analysis Decision Support System (LADSS)*. Software Series S-92-3, National Center for Geographic Information and Analysis, Santa Barbara CA.

LADSS is a PC-based software system for locational modeling. The system consists of two components: an object-oriented, hypertext user interface; and a suite of programs implementing data manipulation, analytical and reporting capabilities. The user interface provides an interactive flowchart to access the system's capabilities, including on-line tutorial, help, and editing facilities. The analytical capabilities of LADSS include a shortest path algorithm, three heuristic location-allocation algorithms, and a statistical report generator. Problems with up to 3,000 demand nodes - all of which may be candidate facility locations - and up to 1,500 facilities can be addressed using LADSS.

Densham, P.J., and **M.F. Goodchild** (1990) *Spatial decision support systems: scientific report for the specialist meeting*. Report 90-5, National Center for Geographic Information and Analysis, Santa Barbara CA.

This report discusses the objectives of Initiative 6, documents the discussion that took place at the specialist meeting and details the initiative's research agenda. A list of participants in the Specialist Meeting is included.

Densham, P.J., and G. Rushton (1991) *Designing and implementing strategies for solving large location-allocation problems with heuristic methods*. Report 91-10, National Center for Geographic Information

and Analysis, Santa Barbara CA.

The authors show that processing costs for the most accurate heuristic location-allocation algorithm can be drastically reduced by exploiting the spatial structure of location-allocation problems. Their implementation strategies enable the solution of large problems (3,000 nodes) in a microcomputer-based, interactive decision-making environment. Tests on four network problems validate claims that these strategies yield solution times which increase approximately linearly with problem size.

Ding, Y. and **A.S. Fotheringham** (1991) *The integration of GIS and spatial analysis: the development of the STATCAS module for ARC/INFO.* Report 91-5, National Center for Geographic Information and Analysis, Santa Barbara CA.

This paper describes a spatial analysis module developed for ARC/INFO. The module calculates statistics of spatial autocorrelation and spatial association and provides graphical display of results.

Gould, M.D. and **P.J. Densham** (1991b) *Spatial decision support systems: a bibliography.* Report 91-9, National Center for Geographic Information and Analysis, Santa Barbara CA.

This report contains 24 pages of references on SDSS and DSS. The bibliography is organized in six sections: implemented systems, papers (geography/planning), papers (other), books, journals, and dissertations (1985-Present).

Harris, B. and **M. Batty** (1992) *Locational models in geographic and information and planning support systems.* Technical Report 92-1, National Center for Geographic Information and Analysis, Santa Barbara, CA.

The authors contend that, in the 1990s, one of the dominant modes of computation will be in graphics, picture and image processing. All applied fields will be affected although none more so than those areas such as spatial planning and decision-making whose modes of analysis and communication are based on maps. Already, Geographic Information Systems (GIS) are becoming widespread in management and planning, and their focus and form is beginning to affect the organization and operation of policy-making. In this paper, the authors address the problems and potential of such systems, particularly in relation to the analytical, predictive and prescriptive basis on which such planning processes are founded. Current GIS are not rooted in the sorts of function and activities which drive the planning process and the authors identify the difficulties and possibilities for developing more appropriate GIS which are sensitive to the sorts of simulation, optimization and design activities on which spatial planning is based. To this end, the authors describe the development of Planning Support Systems (PSS) in which a wide array of data, information, and knowledge might be structured, and within which GIS development must take place. The authors identify the sorts of urban systems and locational models which characterize planning and whose data demands might be accommodated using GIS. Finally, the authors identify a series of requirements which PSS must meet.

Lanter, D.P. (1990) *Lineage in GIS: the problem and a solution.* Technical Report 90-6, National Center for Geographic Information and Analysis, Santa Barbara CA.

This paper focuses on a fundamental geographic structure: the GIS application. Lineage documentation specifies an application's source data, transformations, and input/output specifications. Such information is inherently causal, communicating the theory embodied in a GIS application and the meaning of its product. A number of techniques for automating lineage information are examined. None are found to be capable of documenting data lineage.

Willer, D.J. (1990) *A spatial decision support system for bank branch location.* Technical Report 90-9, National Center for Geographic Information and Analysis, Santa Barbara CA.

This MA project describes the design, implementation and use of a SDSS to help solve semi-structured location problems that exist within the banking industry. Bank-branch location problems are complex and

often require large data sets and sophisticated modeling techniques in their solution. The paper examines the design and construction of a prototype SDSS which makes use of currently available software and hardware. The SDSS is applied to a complex, bank-branch location problem and is used by decision-makers to develop new solution strategies.

Conference Proceedings

Armstrong, M.P., **P.J. Densham**, and D.A. Bennett (1989) Object-oriented locational analysis. *Proceedings*, GIS/LIS '89, Orlando FL: 717-726.

>An object-oriented approach to the analysis of spatial data is presented. The paper begins by describing object-oriented programming, and then defines a structure of spatial and analytical objects within the problem domain of locating facilities. From these objects a set of object classes and inheritance structures is created. The spatial and analytical objects are represented using frames. A Smalltalk implementation of a heuristic location-allocation algorithm is also described.

Armstrong, M.P., **P.J. Densham**, and P. Lolonis (1991) Cartographic visualization and user interfaces in spatial decision support systems. *Proceedings*, GIS/LIS '91, Atlanta LA: 321-330.

>This paper argues that the results of analytical models must be placed in a geographical context for decision-makers to understand key spatial relationships among components of their problem. The authors present a model of a user interface which adapts to the display requirements of the user at distinct stages in the decision-making process. This interface relies on the establishment of linkages between database entities and displays to support visualization requirements.

Batty, M. (1990) Information for planning and decision-making. A paper for the *UNESCO Meeting of Experts*, Beijing, China, UNESCO, Paris, December, 1990.

>This paper discusses the role of information, the systems and technology used to process information, and the functions within the planning process which are informed by such processing. The concern is for planning in developing countries although many of the ideas originate from work in information systems and planning techniques in developed countries. The purpose of the paper is to focus discussion on proposals for alleviating problems and realizing the potential of new information technologies in planning for developing countries. A number of possible strategies for the future are identified, namely the development of information plans for the introduction of this technology, information centres, issues involved in training and the general question of appropriate software development. These proposals are then translated into recommendations for international action, and the paper concludes with some pointers to where UNESCO might best target resources for this area in the framework of its General Information program.

Chou, H.-C., and **Y. Ding** (1992) Methodology of integrating spatial analysis/modeling and GIS. *Proceedings,* Fifth International Symposium on Spatial Data Handling, Charleston, SC 2: 514-523.

>The authors argue that with growing levels of interest in the integration of spatial analysis and modeling with GIS, a methodology for efficiently designing a coupling is essential. This paper presents a taxonomy of integration from three perspectives: data sharing, modeling methods, and user interfaces. A five-stage methodology for integration is presented that is based on the principles of systems analysis and object-oriented software design.

Cova, T.J., and **M.F. Goodchild** (1994) Spatially distributed navigable databases for intelligent vehicle highway systems. *Proceedings, GIS/LIS 94, Phoenix*, ASPRS/ACSM, Bethesda, MD, pp. 191-200.

>Intelligent Vehicle Highway Systems (IVHS) are placing formidable challenges before the GIS community regarding the issues of dynamic data collection and sharing. This paper outlines the problem and reviews the requirements that are driving the need for a distributed spatial database in meeting the needs of IVHS.

A set of contemporary GIS architectures is described and evaluated regarding these requirements.

Densham, P.J. (1993) Integrating GIS and parallel processing to provide decision support for hierarchical location selection problems. *Proceedings*, GIS/LIS '93, Minneapolis MN: 170-179.

GISs enable their users to search space for locations with a given set of attributes but typically do not contain algorithms for optimizing the spatial organization of a network of facilities, especially hierarchies of facilities. In a hierarchy, the spatial organization of any one level, or layer, both influences and must reflect the spatial arrangement of facilities at other levels. Two parallel versions of a new algorithm for solving the hierarchical problem currently are being implemented: the first on a Transputer array in a host personal computer; the second on a local area network of personal computers using PCS-LINDA. The focus of this paper is on the integration of these parallel programs, and their associated processing environments, with a microcomputer-based spatial decision support system (SDSS). The addition of these parallel processing components to the SDSS, which consists of a locational modeling package and Caliper Corporation's TransCAD GIS, illustrates how multiple, heterogeneous processing environments can be used to improve human-computer interaction during problem-solving.

Densham, P.J., and M.P. Armstrong (1993)   Supporting visual interactive locational analysis using multiple abstracted topological structures. *Proceedings*, Auto Carto 11, Minneapolis, MN: 12-22.

Data structures for automated cartography traditionally have been based on either vector or tessellation models. The authors describe a set of topological abstractions, derived from a vector approach to the representation of geographic space, that were developed to support the interactive solution of location-selection problems. When augmented with an appropriate representation of geometry, these abstractions are used to generate cartographic displays that support interactive decision-making.   The advantages of this approach include: the use of the same data abstractions for analysis and display purposes; support for multiple representations of networks and, therefore, a degree of scale independence; and, finally, support for highly interactive problem-solving and decision-making because map generation can be decomposed into parallel processes.

Densham, P.J., and **M.F. Goodchild** (1989)   Spatial decision support systems: a research agenda. *Proceedings*, GIS/LIS '89, Orlando FL: 707-716.

Definitions of geographic information systems often focus on the capture, storage, manipulation, analysis and display of spatial data - implying that geographic information systems implicitly are designed to support spatial decision-making. For many spatial problems, however, geographic information systems do not support decision-making effectively: analytical modeling capabilities are lacking and system designs are not flexible enough to accommodate variations in either the context or the process of spatial decision-making. One response to these needs is the development of spatial decision support systems. The paper draws a distinction between geographic information systems and spatial decision support systems in terms of system design, the types of problem to which each can be applied, and the decision-making processes supported. Impediments to both the design and implementation of spatial decision support systems are identified and a research agenda is outlined to address these problems.

Dibble, C., and **P.J. Densham**, (1993)   Generating interesting alternatives in GIS and SDSS using genetic algorithms. *Proceedings*, GIS/LIS '93, Minneapolis MN: 180-189.

Decisions often are evaluated on the quality of the process that generated them. It is in this context that GIS and SDSS increasingly are being used to generate alternatives to aid decision-makers in their deliberations. Unfortunately, GIS and SDSS typically lack formal mechanisms to help decision-makers explore the solution space of their problem and thereby challenge their assumptions about the number and range of options available. This paper describes the use of a genetic algorithm to generate a range of feasible alternatives to location selection problems. The ability of genetic algorithms to search a solution space and selectively focus on promising combinations of criteria makes them ideally suited to such complex spatial decision problems. The authors also describe the implementation of this algorithm in a

microcomputer-based SDSS and present representative results for several location selection problems. Finally, the authors discuss the inherent parallelism of this algorithm and strategies for its decomposition that will enable it to exploit the efficiency gains of parallel processing computers.

Ding, Y. (1992) An improved method for shadow modeling based on digital elevation models. *Proceedings, GIS/LIS '92, San Jose, CA* 1: 178-187.

Three factors determine both the extent and the intensity of relief shadows on the landscape: self-shadowing, shadows cast by other terrain features, and atmospheric scattering. Equations that account for the effects of all three factors are derived and integrated into a new model of relief shading. The model has been implemented in software that can be used with Digital Elevation Models (DEM). Representative images are presented for part of a DEM and potential areas of application of the model are discussed.

Ding, Y., **P.J. Densham**, and M.P. Armstrong (1992) Parallel processing for network analysis: decomposing shortest path algorithms on MIMD computers. *Proceedings*, 5th International Spatial Data Handling Symposium, Charleston SC: 682-691.

A classification scheme for spatial problems is presented and used to develop strategies for decomposing a popular shortest path algorithm into parallel processes. Several decompositions are implemented on a four-node Transputer Array, running in a host PC. Representative results are presented for shortest path problems with a range of network sizes and characteristics.

Embutsu, I., K. Baba, **M.F. Goodchild**, and **R.L. Church** (1994) A cellular automaton modeling for urban heat island mitigation. *Proceedings, GIS/LIS 94, Phoenix*. ASPRS/ACSM, Bethesda, MD, pp. 263-272.

The impact of increased air temperature due to urbanization is getting so serious as to affect a thermally-benign environment and to increase energy use for cooling. For mitigating an urban heat island problem, two mitigation plans which incorporate a district heating and cooling (DHC) plant allocation and traffic control were proposed in this study. Effects of the plans were estimated using a heat island model consisting of a cellular automaton model and physical submodels with a geographic information system (GIS) through a case study of the city of San Jose, California.

Gottsegen, J., **M.F. Goodchild**, and **R.L. Church** (1994) A conceptual navigable database model for intelligent vehicle highway systems. *Proceedings, GIS/LIS 94, Phoenix*. ASPRS/ACSM, Bethesda, MD, pp. 371-380.

This paper describes research on appropriate data models for a navigable database to support Intelligent Vehicle Highway Systems (IVHS). This research has two main concentrations. The first is the most efficient conceptual model of a street network for the purposes of IVHS, and the second is an effective method for including representation of road lanes in the database. The first issue compares the planar model to a non-planar alternative. The second issue is important for the California transportation department who has funded the research. Because an accurate representation of lane geometry is not possible, the research proceeds with methods for describing lanes within the attribute data. This lane structure must support several types of information about the lanes including: data about the traffic flow in the lanes, possible turn directions from each lane, and connectivity between lanes at street intersections. The ongoing research is currently developing a prototype of the planar model with lane information to determine the effectiveness of the structure developed for storing lane information. If funding allows, the non-planar model will also be tested through a prototype project. This paper discusses the planar and non-planar models of the road network generally and the planar model in more detail. It concludes with a brief description of the prototype project.

Gould, M.D. (1989) The value of spatial decision support systems for oil and hazardous chemical spill response. *Papers and Proceedings*, 12th Applied Geography Conference, Binghamton NY: 75-81.

This paper examines the decision-making processes and the computing and communications infrastructure

used in oil-spill response in the U.S. The author suggests that because remediation efforts for spills are inherently ill-structured spatial problems, spatial decision support systems would be of benefit. This suggestion is reinforced by illustrating the match between spill-response decision-making needs and the functionality offered by decision support systems, especially spatially-oriented DSS.

Sivakumar, R.A., **R. Batta**, and M.H. Karwan (1992) Establishing credible risk criteria for transporting extremely hazardous materials, *Proceedings* of the International Concensus Conference on the Risks of Transporting Dangerous Goods, Toronto, Canada, April, 1992.

> A measure of risk that is more appropriate while routing extremely dangerous hazardous materials is to minimize the expected risk, given that an accident occurs. This paper introduces this alternate measure of risk, and discusses efficient solution procedures for determining an "optimal" path for a single shipment for such a hazardous material.

Smith, B. (1990) The use of geographic information systems in development planning in Latin America. *Proceedings*, Conference of Latin Americanist Geographers, Auburn AL: 272-283.

> The use of GIS in development planning in Latin America involves the role of the development planner and the nature of planning processes in Latin America. The discussion addresses 1) the role of concepts of development planners and the problems of applying Western theories and planning methods in a Latin American context; 2) Latin American development planning processes; and 3) the present and potential use of GIS in Latin America.

Other Publications

Batty, M. (1990) Comment on Harris: Planning support systems and the emerging technological environment for urban and regional planning. *Regional Development Dialogue* 11: 58-62.

> This commentary examines Britton Harris's ideas on the adoption of GIS by planners and its potential role in the development of planning support systems.

Batty, M., and T. Yeh (1990) Applications of geographic information systems to urban and regional planning. *Environment and Planning B* 17: 369-374.

> This editorial introduces a special issue of Environment and Planning B on applications of geographic information systems and spatial decision support systems in urban and regional planning.

Fotheringham, A.S. (1990) Guest Editorial: One view of a conference on SDSS: are we descended from the Golgafrinchams after all? *Environment and Planning A* 22(9): 1137-40.

> This editorial reports on the Initiative 6 Specialist Meeting.

Fotheringham, A.S. (1992) Some random(ish) thoughts on spatial decision support systems. *Environment and Planning A* 23(12): 1699-1700.

Graduate Theses

Ding, Y. (1993) *Strategies for parallel spatial modeling on MIMD computers*. Unpublished Ph.D. Thesis, Department of Geography, State University of New York at Buffalo, Buffalo NY.

> This research (part of the Research Investigation into Parallel Computation and GIS) develops strategies for decomposing spatial problems into parallel processes to run on multiple instruction multiple data (MIMD) architecture parallel computers. These strategies were used to implement parallel algorithms on a Transputer array for generating: shortest paths through a network; Delaunay Triangulations and Thiessen Polygons; and hill-shading on digital elevation models (DEMs).

Gould, M.D. (1993) *Map use, spatial decisions, and spatial language in English and Spanish*. Unpublished Ph.D. Thesis, Department of Geography, State University of New York at Buffalo, Buffalo NY.

This research studies the problem of GIS design from the perspective of map-based problem solving. A form of task analysis is applied to four spatial sub-tasks where human subjects were asked to select locations on standard topographic and tourist maps of the island of Puerto Rico. To test for possible cross-linguistic differences, data from 20 subjects in Buffalo, New York, and 22 in Quito, Ecuador, was compared using pattern and content analyses provided by SHAPA: a PC-based protocol analysis system. Results show the absence of strong problem-solving patterns in either the Quito or the Buffalo protocols. These results indicate that the encoding chosen was overly coarse and did not catch structural, cross-linguistic subtleties. It is suggested, therefore, that the user interfaces of GIS can be translated directly from English to Spanish without regard for cultural-linguistic differences.

McKinney, J.V. (1992) *The visualization of solutions to location-allocation models*. Master's Project, Department of Geography, State University of New York at Buffalo, Buffalo NY.

McKinney investigated the use of color and geometrical complexity in the depiction of solutions to location-allocation models. The focus of this research was on assessing the utility of depicting the routes linking demand and supply locations and, using hue to represent magnitude, the volume of demand traversing links in the transportation network. A survey was conducted using experts and neophytes in locational modeling. Respondents were shown six displays, obtained by sampling a three by three factorial design, and asked to complete a questionnaire for each of the six displays they viewed. Findings suggest that the expert group recognized the displays as depicting solutions to locational models and were able to deduce the information contained in the map elements. The neophyte group were unable to do so, however, and did not understand the maps until they were explained after all testing was completed. These results suggest that specialized displays of the solutions to models will be of different utility to disparate groups of SDSS users. Thus, SDSS must assist users in interpreting specialized forms of displays.

Willer, D.J. (1991) *A spatial decision support system for bank branch location*. Master's Project, Department of Geography, State University of New York at Buffalo, Buffalo NY.

This MA presents a computer-based system that is designed to help solve semi-structured location problems that exist within the banking industry. The first section of the thesis discusses new developments in locational analysis and in bank-branch location. Section Two examines the literature on Spatial Decision Support Systems with the emphasis placed on describing problems facing the banking industry and how an SDSS can be designed and implemented to help solve these problems. The third section of the thesis examines the design and construction of an SDSS: the system makes use of currently available software and hardware technologies. Section four focuses on a case study which uses this SDSS to address a complex, bank-branch location problem and to develop new solution strategies. The final section consists of an evaluation of the SDSS in solving specific location problems and the results and conclusions from the case study.