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A COMPUTER-AIDED DECISION SUPPORT SYSTEM FOR MAKING LOCATIONAL DECISIONS

Prepared by
The University of Iowa
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MIDWEST
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A COMPUTER-AIDED DECISION SUPPORT SYSTEM FOR MAKING LOCATIONAL DECISIONS

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PREFACE

This report is the product of a first-year research project in the University Transportation Centers Program. The Program was created by Congress in 1987 to "contribute to the solution of important regional and national transportation problems." A university-based center was established in each of the ten federal regions following a national competition in 1988. Each center has a unique theme and research purpose, although all are interdisciplinary and also have educational missions.

The Midwest Transportation Center is one of the ten centers; it is a consortium that includes Iowa State University (lead institution) and The University of Iowa. The Center serves federal Region 7 which includes Iowa, Kansas, Missouri, and Nebraska. Its theme is "transportation actions and strategies in a region undergoing major social and economic transition." Research projects conducted through the Center bring together the collective talents of faculty, staff, and students within the region to address issues related to this important theme.

This particular project was carried out by an interdisciplinary research team at The University of Iowa's Public Policy Center. This center is a reflection of the University's renewed commitment to applied research that seeks to advance the public interest. The Center's projects generally involve close interaction with decision makers and resource people in both the public and private sectors.

The project is central to the Midwest Transportation Center's theme in that it develops a readily usable computer-based support system for making decisions regarding the location of public facilities. The principal investigator was Gerard Rushton, Professor in the Department of Geography. Also on the interdisciplinary research team were Marc Armstrong, Assistant Professor in the Departments of Geography and Computer Science; Brian Dalziel, a doctoral student in Geography; Suranjan De, an Assistant Professor in the Department of Management Sciences; Paul J. Densham, a doctoral student in Geography; Panos Lolonis, a Research Fellow in the Department of Geography; Rex Honey, Associate Professor in the Department of Geography; and Joel Horowitz, Professor in the Departments of Geography and Economics .

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TABLE OF CONTENTS

FIGURES

SECTION 1
INTRODUCTION: SPATIAL DECISION SUPPORT SYSTEMS

Project Purpose

This project developed a computerized system to support decisions about how to locate facilities that serve rural areas while minimizing transportation costs. Our work is based on the premise that transport systems should be efficient—that is, the lower the total transport costs, the better the transportation plan is. The computerized system integrates transportation databases with algorithms that specify efficient locations and allocate demand efficiently to service regions; the results of these algorithms are used interactively by decision makers. They can introduce or relax constraints and reject solutions on the basis of their informed judgments about what will work.

This spatial decision support system is suited to solving semistructured problems—those in which decision makers do not know at the outset what criteria are relevant, what their appropriate weights are, or what the site-specific constraints are. Using the system, decision makers can vary the objectives they specify for the transportation plan and immediately see the resulting patterns for locating facilities on system-generated maps.

We developed documentation for the system so that others could apply it to estimate the transportation and route requirements of alternative locations and identify locations that meet certain criteria with the least cost. We developed and tested the system on two transportation-related problems in Iowa, and this report uses these applications to illustrate how the system can be used. More generally, the project demonstrates the type of support that decision makers need in making locational decisions.

Spatial Decision Support Systems

Patterns of economic development and population growth change the demand for transportation. This observation has an obvious consequence: planning for development should be closely linked to transportation decisions. The National Transportation Policy Statement (1990) concluded that changing demographic and economic conditions "require continuing improvements in analytical techniques and supporting data to permit planners and other professionals to anticipate transportation needs and design long-term investments and short-term operational enhancements to meet those needs." This project contributes to that goal by improving the class of analytical techniques known as "spatial decision support systems" (SDSS).

Spatial decision support systems integrate transportation network data and socio-economic data with analytic models; these models estimate transportation demand under different spatial patterns for locating economic activities. With ongoing input from experts on local or regional conditions, the constraints on the acceptable solution are modified until a solution is generated that these users deem acceptable and practicable. What makes these support systems work are the availability of appropriate real data and the interaction with decision makers.

Until recently, appropriate spatial databases did not exist. In the past year, however, the Census Bureau's TIGER files have made available a detailed topological description of the U.S. road network. These off-the-shelf databases incorporate the digital line graphs from the U.S. Geological Survey's 1:100,000 map series; they can be pre-processed to any level of generalization and thereby tailored to use for specific applications. Each road segment in the TIGER file contains a descriptor field which specifies the type of road (e.g., four-lane divided, neighborhood street). Analysts can select only those roads that are pertinent to a given project, eliminating unnecessary data. For example, in state-level analyses, federal, state, and county roads would be included and neighborhood roads eliminated. Users can add more accurate data and encode additional features. These databases will radically alter the spatial data infrastructure for transportation planning in the future.

In addition, before they could deal with the exigencies of real data, decision support systems awaited more sophisticated software systems and improvements in analytical techniques. Geographical information systems have recently enhanced their network mapping and analysis functions, and new data storage structures have been linked to the architecture of desktop and workstation computer technology, making possible the development of truly integrated transportation planning and analysis capabilities. Some of this progress can be seen in informal working groups on geographic information systems within several state departments of transportation.

SECTION 2

TRANSPORT-RELATED USES OF THE SPATIAL DECISION SUPPORT SYSTEM: TWO EXAMPLES

To briefly illustrate how the SDSS can be applied to locate facilities that have significant impacts on transportation demand, we offer two examples. The first is a problem faced by the Iowa Department of Transportation (Iowa DOT) in replacing its system of smaller vehicle maintenance garages with fewer, larger facilities. The second problem is that of restructuring the administration of services provided to school districts, taking into account travel times between school districts and service centers.

Relocating Highway Maintenance Garages

In 1987 the Iowa DOT decided to develop a long range plan for reorganizing its highway maintenance garages. This system has a large number of facilities—about 130 located across the state—and was designed when equipment was smaller and less powerful than it is today. Some garages had been modernized in recent years to make them suitable for modern road maintenance equipment, but many others would require capital investments. On the demand side, needs for road maintenance had shifted since these garages were built. Clearly, the maintenance system would be more efficient if some garages were relocated, some closed, and others modernized. Which locations should be selected for investment and which closed, and how much could efficiency be improved by relocating facilities? These were important questions both to the Iowa DOT and communities affected by facility expansion or closure.

We applied a prototype of the decision support system described below to this problem. The DOT specified the amount of maintenance work required on each segment of highway served by a particular maintenance garage, and these data were entered into the system. The results indicated which garages should not be relocated under any circumstances and where new garages could be located. The Iowa DOT also specified objectives that the location plan should meet; for example, that all roads requiring maintenance be within 20 miles of a garage. The maintenance division of the Iowa DOT used the system to determine different scenarios for upgrading, relocating, and closing garages. At the end of the planning period, the Iowa Legislature required that hearings be held on the subject of highway maintenance throughout the state and on the Iowa DOT's plans for facility reorganization. The decision support system played a key role in the public discussions that ensued as alternative scenarios were examined.

Reorganizing Iowa's Area Education Agencies

In 1986, the Iowa Legislature mandated that the state's 15 Area Education Agencies—which provide special services to students in 433 districts—be restructured and reduced in number. At the invitation of the task force charged with redrawing agency boundaries, we applied the spatial decision support system to this problem. The state legislature wanted each agency to serve enough students to justify a range of specialized services while keeping each service center within a reasonable travel time from the school districts it served. The optimal student numbers and travel times, as well as the optimal number and location of service centers, were unknown.

We applied the SDSS in a series of consultations with task force members, who were able to modify the constraints they imposed on the solution and see the resulting maps almost immediately. In examining tentative solutions, they were able to discuss what criteria a practicable solution had to meet and how to trade off performance standards relating to these criteria. The informed judgment of these experts determined what solutions were feasible. Figure 8, on page 28, illustrates the type of map the system generated. This map is also the one adopted by the Iowa Department of Education and submitted to the Iowa Legislature for approval. A fuller discussion of our role in the district definition process is presented in Section 7.

SECTION 3
TRANSPORTATION ISSUES AND LOCATIONAL DECISION-MAKING

Suppliers incur transport costs as they produce and distribute goods and services, and consumers incur costs as they meet their needs for these goods and services. Decisions that affect where suppliers and consumers locate will affect the demand for transportation. In rural states like Iowa, many activities are becoming more geographically centralized as they locate to reduce total transport costs. A number of forces contribute to this location/relocation process:

1. changes in the demand for goods and services related to changes in tastes and preferences;
2. changes in the numbers of people, their spatial distribution, and their demographic characteristics;
3. changes in the scale for efficient production of suppliers; and
4. changes in the transportation infrastructure.

Research has discovered four processes of location and relocation that minimize transportation costs in the system as a whole (Ghosh and Rushton, 1987). Each of the four location processes is the basis of a heuristic algorithm (known as a location-allocation algorithm) that can determine approximately where facilities would locate in order to minimize the total transport costs incurred if people used the closest facilities.[1] Although relevant studies are rare (e.g., Gregg, Mulvey, and Wolpert, 1988), sufficient evidence exists that many decisions to locate or relocate are suboptimal and that better decisions would create significant transport savings. This project assumes that locational processes can become more efficient if decision makers have analytic support from a system like the SDSS.

Here we describe the four processes for location or relocation of economic activities that reduce transportation costs to a minimum.

1. **The Alternating Location-Allocation Algorithm.** If, through time, activities relocate to serve their market area with the least total transport cost and if the boundaries of market areas adjust so that their demands are served by the supplier who can serve them with least transport costs, then suppliers and the markets they serve will be

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[1] This problem, known as the p-median problem, is defined formally in Section 5.

located so that total transport costs in the system are approximately minimum (Maranzana, 1964; Cooper, 1963).

2. **The Vertex-Substitution Algorithm.** If, through time, facilities move from the location where people would incur the least increase in transport costs as a result of the removal and if the facility moves to the eligible location where most transport costs would be saved as a result of the move, then suppliers and the markets they serve will be located so that total transport costs in the system are approximately minimum (Teitz and Bart, 1968).

3. **The Greedy Add Algorithm.** If, through time, facilities are added to locations where the most transport costs would be saved, then suppliers and the markets they serve will be located so that total transport costs in the system are approximately minimum.

4. **The Greedy Drop Algorithm.** If, through time, facilities leave locations where the users would incur the least increase in transport costs as a result of the removal, then the remaining suppliers and the markets they serve will be located so that total transport costs in the area are approximately minimum.

Taken together, these algorithms indicate that four types of decision-making behavior, when followed repeatedly, create location patterns for a given number of facilities that approximately minimize total transport costs. This realization is the theoretical basis for a decision support system that identifies efficient location patterns. In practice, however, decision makers are generally constrained by site-specific considerations and have personal knowledge of local conditions that influences their judgments about possible locations. This project recognizes that decision makers need decision support to solve various pieces of the problems, rather than a set of optimizing algorithms that purports to give the "correct" solution. We develop this argument in the next section.

SECTION 4

THE PROTOTYPE SPATIAL DECISION SUPPORT SYSTEM: AN APPROACH TO SOLVING SEMISTRUCTURED PROBLEMS

A rich theoretical and applied literature has studied how to determine the number and location of central facilities that serve a geographically dispersed population. In conventional approaches to this problem (Love, Morris, and Wesolowsky, 1988; Brandeau and Chiu, 1989), decision makers describe to analysts their objectives and any constraints on realizing these objectives. In a computer laboratory, the analysts then formally specify the problem so that location-allocation models can generate an optimal solution. These conventional practices recognize that decision makers understand the problem in its real context and that this understanding is essential to solving the problem—but they remove decision makers from the solution stage itself. This project develops instead a system that supports interactive decision making, providing feedback to decision makers about the patterns of locations that different sets of criteria produce.

Location problems are difficult to solve for many reasons. The relevant data describing the geographical environment may not be available. Spatial data are constantly changing and are never completely known; many geographical details are known only to the decision makers. In addition, decision makers are often unable to completely specify and quantify their objectives. Many locational problems are therefore semistructured (Alter, 1977; Hopkins, 1984), the type of problem to which spatial decision support systems like the one described here are best applied. These problems meet one or more of the following conditions.

1. **A comprehensive set of relevant criteria is not known at the outset.** Instead, decision makers discover relevant criteria as they discuss the merits and problems of proposed solutions.
2. **The weights to be assigned to criteria are not known.** Decision makers need to know how the characteristics of the system change as the weights assigned to criteria change.
3. **Site-specific constraints are not fully known.** Decision makers need to know the consequence of imposing these constraints before approving a plan based on such constraints.

In our example of restructuring Iowa's Area Education Agencies, described in Section 7, all three of these conditions applied. The project team agreed with decision makers that our prototype SDSS should allow them to combine their knowledge of the service operation with general knowledge from location theory and related methods of locational analysis. The criteria that are applied to an actual location problem are, of course, specific to that problem, but the methods of applying criteria in any real application arise from more general theories and methods of locational analysis. The prototype SDSS reflects our belief that a system of analysis can integrate these general concepts with decision makers' rich domain-specific knowledge and apply them to the solution of spatial problems.

SECTION 5

A SPATIAL DECISION SUPPORT SYSTEM FOR REGIONALIZATION

Spatial decision support systems encourage users to explore the semistructured problem as they interact with the software programs and see the maps it generates (Densham and Rushton, 1988). Although semistructured problems cannot be solved using structured approaches alone, important elements within them can be solved as structured problems using conventional modeling techniques. When components of the problem have been solved, decision makers must evaluate the results obtained from the models and then make decisions about elements of the problem that cannot be structured. Experience has shown that a straightforward application of mathematical modeling often fails to capture important dimensions of spatial problems, because they contain aspects that cannot be represented in a form suitable for optimization algorithms.

A typical SDSS consists of a database, a suite of spatial data processing models, and a set of procedures for generating displays and reports that summarize alternative solutions (Armstrong, Densham, and Rushton, 1986). The database is often a simple repository of locational data and descriptions of entities; the spatial processing models are most often optimization models. These components are combined to provide an interactive and participative decision-making environment. The basic set of modules composing the SDSS are:

1. the database;
2. spatial analysis models, including
    a. data transformation utilities or file management,
    b. software that determines the shortest paths through a transportation network and that prepares the distance data for input to optimal location algorithms,
    c. a heuristic location-allocation program that can solve all the objective functions in Hillsman's (1984) unified linear model, and
    d. software to reallocate demand to meet user-defined constraints; and
3. visualization software, including
    a. a report generator that provides the user with statistical information about characteristics of solutions and
    b. mapping software.

Each component is shown in Figure 1 and is described below in greater detail.

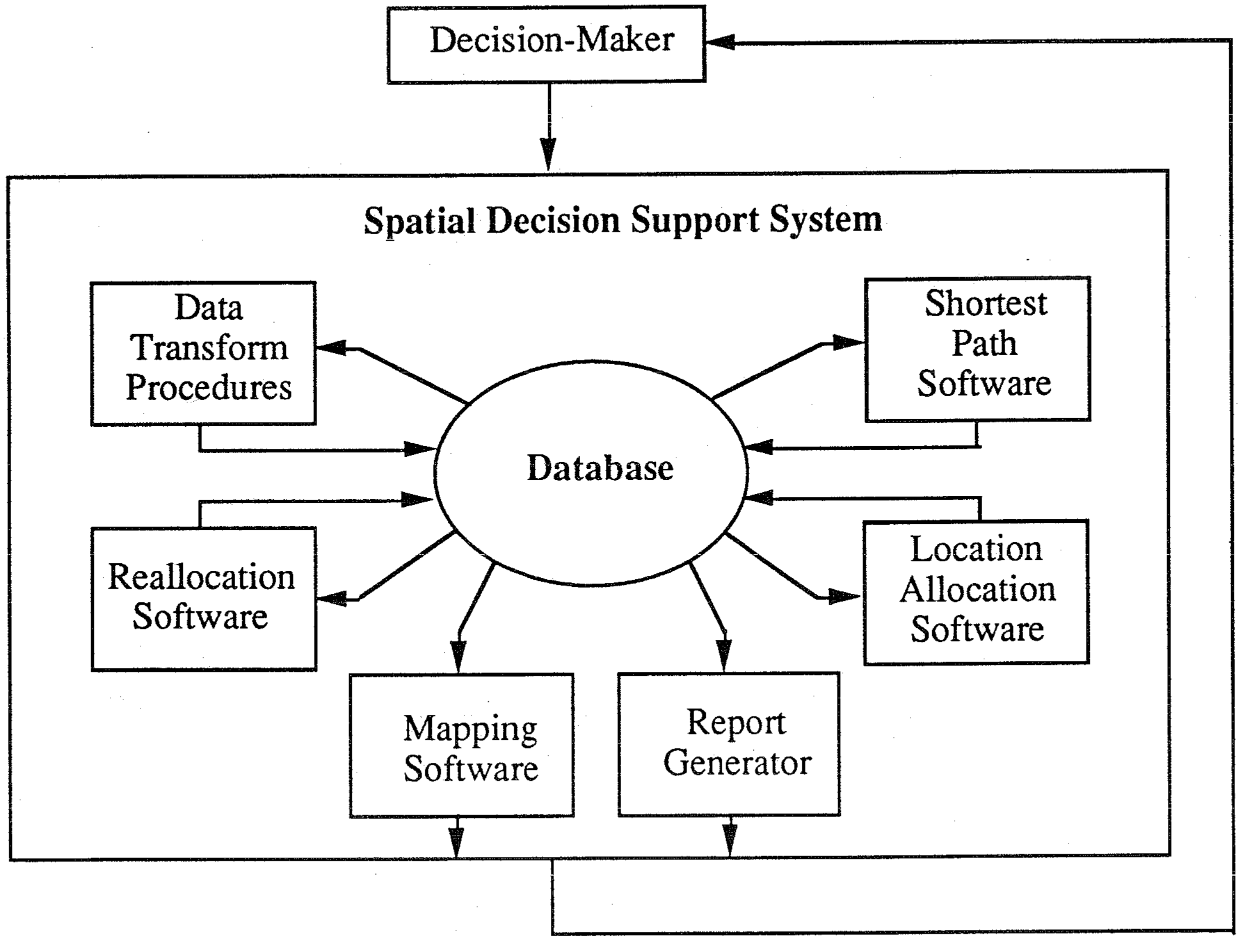


Figure 1
Architecture of the SDSS

Database

The database provides information about the amount and location of demand, candidate sites for supply of services, and linkages among places (i.e., the transportation network or a surrogate). Decision makers must identify the candidate sites and in some cases they may constrain certain sites to be centers in the solution. Demand may be represented by a population variable, although analysts often wish to identify and specifically measure the segment of the population that is likely to require services. The complex geography of real environments is abstracted by assuming that demand nodes interact through a set of links which approximates a transportation network (e.g., Hillsman, 1980; Goodchild and Noronha, 1983; Densham, 1990).

While this method of representation has often been applied to aggregated demand, the SDSS applies it to disaggregated data. The production of graphic displays also requires access to a database.

Data Transformation Utilities

Procedures written in Pascal reformat data to ensure that output from each module is compatible with other parts of the system. For example, procedures have been written to reformat output from the location-allocation models so that it can be displayed by cartographic software. Other utility procedures compute polygon centroids and prepare files for analysis.

Shortest Path Software and Distance Editing Procedures

A shortest path module generates a data set containing minimum weighted distances between each demand node and all candidate locations that might serve it. These distances are then used by the location-allocation software to optimize objective functions. The program uses a version of an algorithm developed by Dijkstra (1959) to find shortest distances between demand nodes and candidate locations.

Distance data can take the form of a full distance matrix, but such an approach is inefficient for storage and processing, particularly when centers serve only part of the region in question. Instead the SDSS uses two kinds of data structure: demand strings and candidate strings. For each demand site a demand string lists all candidate sites and their costs of serving it. For each candidate site a candidate string lists all demand sites that it might serve and the costs of serving them. This reciprocal storage structure reduces the amount of searching that must take place and thereby speeds the execution of location-allocation models (Densham, 1990). Both demand strings and candidate strings are incorporated in an additional structure—the allocation table—that is used to implement the location-allocation software in the SDSS (Armstrong et al., 1990; Densham, 1990).

Location-Allocation Software

The location-allocation software, a Pascal implementation of a heuristic vertex substitution algorithm (Teitz and Bart, 1968), solves the p-median problem. The p-median problem minimizes the total distance of demand from the closest of p centers in the system. It can be formulated in the following way:

$$\text{Min } z = \sum_i \sum_j x_{ij} c_{ij}, \text{ where}$$

z = the total distance of demand from the closest of p centers in the system;

x_{ij} = 1 if demand node i is allocated to facility j, 0 otherwise;

$j = 1, 2, \ldots, p$; and

c_{ij} = the metric of interaction.

The metric of interaction can take various forms including distance, transportation cost, or travel time. If the objective is to minimize distance, for example,

$$c_{ij} = w_i d_{ij}, \text{ where}$$

w_i = the amount of demand to be served at the ith location, and

d_{ij} = the distance from the ith to the jth location.

Further constraints are placed on this formulation to ensure that all demand is allocated to a facility and that a node has a facility before it can provide service (Hillsman, 1984, p. 307).

The c_{ij} coefficients are edited so that an appropriately coded algorithm for the p-median problem can be used to solve for a variety of locational objectives (Hillsman, 1984). The prototype system can solve for the following locational objectives.

1. **The p-Median Problem.** Find p locations and the areas they serve to minimize average travel distance subject to a maximum distance constraint.

2. **The Maximal Covering Problem.** Find p locations so that a maximum amount of demand is within distance s of its closest location.

3. **The Set Covering Problem.** Find the minimum number of locations so that all demand is within distance s of the closest of the selected locations.

The software is menu-driven, and the user can select among the functions described above, other commonly used objective functions, and two functions not available, to our knowledge, in any other geographical information and analysis system. These functions—one which adjusts regions to meet demand requirements and another which controls boundaries of regions—are described in the next two sections. Both functions were also important in solving the second problem described in Section 2.

Adjusting Regions to Meet Demand Requirements

Many regionalization problems require that all regions achieve a minimum size, as measured by demand. This requirement is often translated into a requirement that regions be compact, achieving either an equal or some minimum amount of demand (e.g., Weaver and Hess, 1963). Political redistricting, for example, is a special case in which regions must have populations of approximately equal size. The ADJUST procedure in the SDSS uses a replicable, objective method for political redistricting, rather than subjectively swapping small areas between contiguous districts, as most commercial GIS software seems to do.

The ADJUST procedure is a two-stage solution process. In the first stage, it assigns each unit of demand to its closest facility and computes the total demand served by that facility. In the second stage, it reassigns surplus demand to facilities that did not reach their demand requirement. This reassignment has the following steps:

1. Find the region with the largest deficit.
2. Compute P = a * D, where

   P = amount of deficit to be covered in current iteration;

   a = user-specified proportion of deficit to be reassigned in current iteration; and

   D = demand deficit of current region.
3. If the total reassigned demand is less than P, then
   a. identify the demand unit assigned to a region with a surplus for which the per capita increase in distance would be least if it were re-assigned to the center with the largest deficit;
   b. assign that unit to the center with the deficit;
   c. update assignment of demand for each region; and
   d. continue until reassignment exceeds P, or no improvement can be made during an iteration.

4. Process the region with the next largest deficit of demand.
5. Iterate until all regions meet the demand requirement, no improvement can be made, or the increase in distance through reassignment is larger than the decision maker is willing to accept.

The principle behind this heuristic algorithm is that, as demand is reassigned from regions with surpluses to regions with deficits, the increase in distances in the system should be minimized. The iterations allow the decision maker to monitor the increase in distance that any unit area incurs as it is reassigned to a deficit region; distances increase monotonically as the algorithm proceeds to meet the minimum demand requirement.

Controlling Boundaries of Regions

A procedure was developed to perform location-allocation analyses when the study area is divided into two or more districts. The problem is to identify the number, the locations, and the service areas of facilities in each district for a predefined total number of facilities, while minimizing the costs of providing service (ReVelle and Elzinga, 1989). The data necessary to solve this problem are the total number of facilities which must be located, the cost of serving each demand location from each candidate location, an arbitrary initial solution, and the demand and candidate locations that are enclosed by each regional boundary. The last piece of information specifies the set of candidates that can serve each demand location.

The problem is solved with existing optimization procedures which modify the costs (c_{ij}) of serving the demand site from the center when they are in different districts. Specifically, if a candidate site is across the district boundary from a demand location, a large penalty value is added to the c_{ij} coefficient. Accordingly, when the object is to minimize costs, allocating demand in one district to a candidate site in another district causes the value of the objective function to increase substantially and forces the algorithm to search for less costly alternatives within the district. This technique is conceptually simple, enables analyses to be performed quickly, and works with both exact and heuristic algorithms; as a result, it is more efficient than other techniques described in the literature (ReVelle and Elzinga, 1989).

Display Generation

The mapping component of the SDSS uses commercial software to generate displays used by decision makers. In the prototype system the software (Atlas™) generates several kinds of thematic maps, including choropleth and dot distribution maps. To show the relationship between service demand and supply, we have also created a procedure for generating "spider" maps (Charest-Berglove and McKeagney, 1983; Allard and Hodgson, 1987). For each solution, these maps display the locations of facilities and the allocation of demand to those facilities. The results of the location-allocation models also can be displayed as chorochromatic maps of the regions that would result from the solutions, with each region assigned a color that differentiates it from its neighbors. The system works especially well when two computers are linked: one machine can perform analyses while the other displays maps and prepares reports, or each machine can display a different solution for decision makers to compare and evaluate.

Hardware Environment

The system is implemented in an IBM PC (and compatible) environment using DOS. For the problem described in Section 4 a Hewlett-Packard RS 25 (Intel 80386, 80387, 25 mhz) and an IBM PS/2-80 (Intel 80386, 80387, 16 mhz) were used. Each system uses a VGA display for generating maps and graphs, and hardcopy output is produced by a HP LaserJet II printer. The computer systems can exchange data through a high speed communication link that connects their parallel ports.

SECTION 6
USING THE SDSS IN DECISION MAKING

The prototype SDSS can address a variety of location problems, including the location of public or private sector facilities, political redistricting, the location of school facilities and definition of their attendance areas, and regional aspects of public administration. In the SDSS environment, decision makers apply their expertise by revising the criteria and constraints that they apply as they search for a solution. The system allows them to explore the nature of their problem in two ways. First, they can specify criteria and constraints and find the corresponding optimal administrative centers and their boundaries. Second, they can examine results and discuss among themselves the implications of adopting a plan generated by the system. As a result of discussions in which they apply their domain-specific knowledge to the problem, decision makers frequently formulate new criteria or respecify the same criteria with different constraints. In addition, they may reject solutions that perform poorly on the criteria they select or that fail to satisfy them for other reasons that are not part of the system.

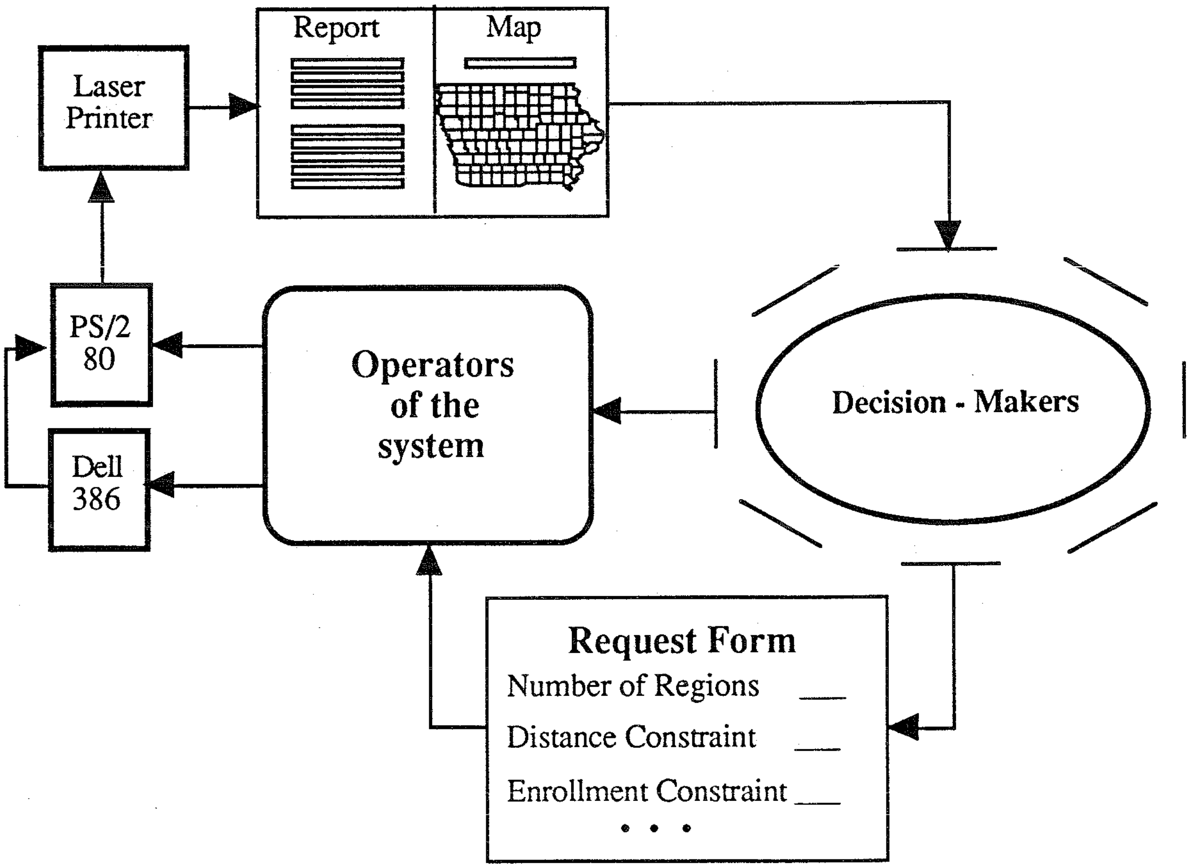


Figure 2
The Decision Making Environment

The system is more flexible and supports decision making better than optimization programs because the location-allocation software is in an interactive system with other software modules. Because we are continuing to develop the prototype analysis system, we have not yet adapted it for use by people who are unfamiliar with its methods of locational analysis. Most decision makers are untrained in the methods of multi-objective optimization and therefore require an analyst to work with them to establish a logical framework for generating and evaluating alternatives. If, for example, a decision maker wanted to introduce many place-specific constraints when defining eligible service locations, the analyst might advise against doing so at first, in order to estimate the cost of the constraints in terms of decreased system performance.

In the example problem described in the following section, we worked closely with the decision makers as they developed and evaluated alternatives, to ensure that system performance was as transparent as possible. By closely observing the decision-making process, we were able to improve the organization of the system for future use.

SECTION 7

INTERACTIVE DECISION MAKING: APPLYING THE SDSS TO THE GEOGRAPHICAL REORGANIZATION OF IOWA'S AREA EDUCATION AGENCIES

In this section we describe in detail one instance in which the SDSS was applied, so that we can illustrate a unique and important feature of the system: its interaction with the domain-specific expertise of decision makers as they formulate a problem and search for a feasible solution. That instance is redrawing the boundaries of Iowa's Area Education Agencies.

Area Education Agencies (AEAs) in Iowa "are primarily service agencies for local school districts" (Iowa Department of Education, 1987, p. 11). Each of the 15 AEAs provides to the public school districts within its boundaries special education support, media, and other services for students in public and nonpublic schools. For example, twice each week books, films, and other educational materials ordered by teachers are delivered from each AEA regional office to schools in its service area. Speech clinicians, psychologists, social workers, and other specialized personnel travel a regular itinerary to serve students. Thus, the placement of AEA offices and the designation of the schools each one will serve has significant transportation implications for the state.

The 1986 session of the Iowa General Assembly passed a law stating that the State Board of Education should restructure area education agencies, and merged area schools, with a specific emphasis on combining the Area Education Agencies (Iowa Department of Education, 1987). The 1987 session of the General Assembly amended the 1986 legislation (Iowa Department of Education, 1987) by specifying that

> the state board shall develop plans for redrawing the boundary lines of area education agencies so that the total number of area education agencies is no fewer than four and no greater than twelve. . . . The plans relating to the area education agencies and merged area schools shall be submitted to the general assembly not later than January 8, 1990 (p.3).

The intent of the plan is to "assure more productive and efficient use of limited resources, equity of geographical access to facilities, equity of educational opportunity within the state, and improved student achievement" (Iowa General Assembly, 1986). In response to this mandate, the State Board of Education appointed seven workgroups to review services provided by the Area Education Agencies. The workgroups were Distance Learning, Instructional/Educational Services, Operational Relationships, Delivery System Structure, Library/Media Services, Management Services, and Special Education. The Delivery System Structure Workgroup was charged with

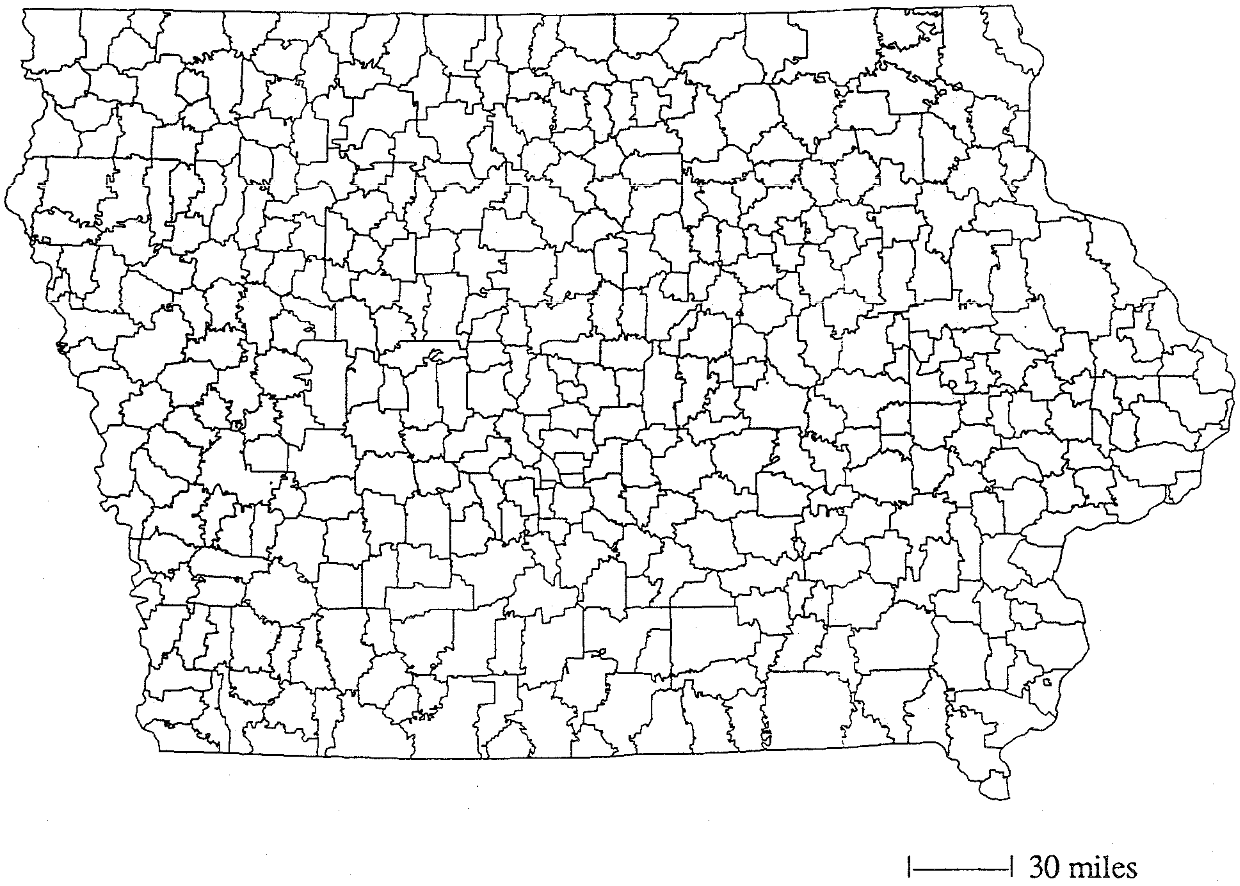
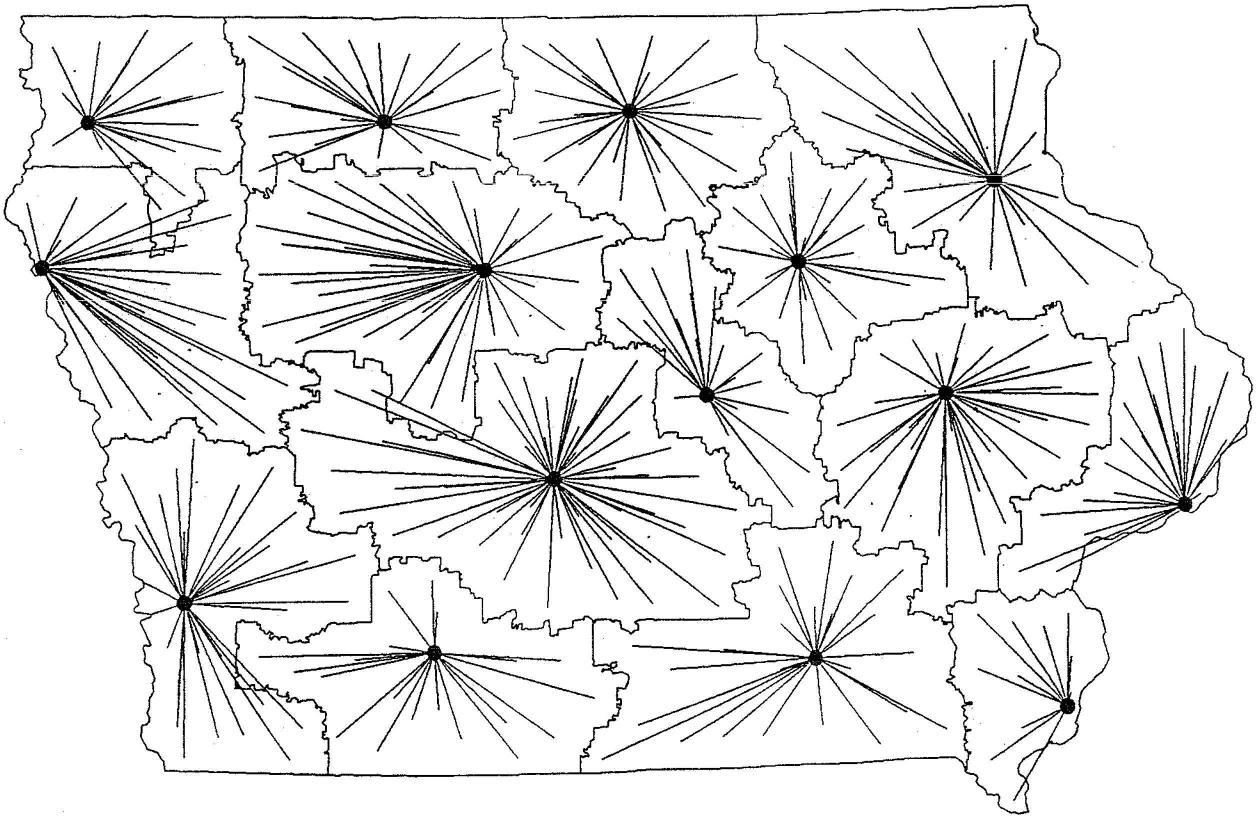


Figure 3
Iowa School Districts

coordinating the results of the other six and making recommendations to the State Board of Education for restructuring the regions.

There are 433 school districts in Iowa (Figure 3) in 15 AEA regions. There are large differences between regions in the number of students served and in the average and maximum distances from service recipients to the AEA regional offices. In 1988, the smallest region had 12,344 school children, the largest 108,963 (Figure 4). Since resources are allocated according to the number of students served, regions with small enrollments cannot offer specialized services at levels similar to those offered by regions with large enrollments.

Such differences in accessibility can be found for many service delivery systems in Iowa. Though commonly perceived as a rural state, Iowa now has a large urban population and the urban areas have better access to services. The feeling still runs deep in Iowa, however, that people



A straight line indicates assignment of a school district to an AEA center.

● AEA center

|——| 30 miles

Figure 4
Current Area Education Agency Regions

should not be disadvantaged by their rural location. Most decision makers would agree that a service delivery system should be equitable, not only efficient. The need for geographical restructuring is evident.

Following discussions with the Iowa Department of Education in May 1989, we were invited to a meeting of the AEA Delivery System Structure Workgroup in Des Moines, Iowa, in July 1989. The chairman of the Workgroup, asked us to consider the following questions before the meeting:

1. How do geographical and transportation elements relate to the number of AEAs to be determined?

2. How do population density and the location of metropolitan areas and dominant communities relate to the determination of the number of AEAs and the regions they serve?
3. Should existing AEA facilities and boundaries be respected as much as possible or should boundary planning start from the beginning?
4. How do current and potential sites for central offices and satellite offices relate to the determination?
5. How can boundary lines be established that encompass compact territory, provide for equitable services statewide, and define governmental units that will last well into the next century? (Ghan, 1989)

While the general problem of determining the number of regions, their centers, and their boundaries seemed straightforward, in fact it was not. Legislation determined the minimum (four) and maximum (12) numbers of regions, but little else. Furthermore, the questions above indicate that several aspects of the problem were not clearly defined. The relationships among the questions were unknown, as were the specifications of formal criteria for modeling and for constraining solutions. The problem as posed by the chairman, therefore, was semistructured.

We worked with the chairman to specify several criteria of interest to the Workgroup. In this prototyping phase, we progressively changed important features of the analysis system as we got reactions from the user (in this case, the chairman) and evaluated those reactions. Before meeting with the 22 member Workgroup, we prepared a set of alternative solutions to demonstrate the capabilities of our prototype system and to provide the Workgroup with information about criteria that might ultimately play a role in an adopted plan. We discussed with the Workgroup the geographical representation of the problem, the kinds of analyses that would be required, and the way in which the analyses would be implemented. These discussions led to important decisions, discussed below, about how the problem would be specified and represented in the SDSS, described below.

Geographical Representation

The Workgroup considered various approaches for solving the AEA problem, approaches which differed in the unit of analysis. One plan proposed that existing AEA regions be used as a set of building blocks out of which the solution would be constructed. It was clear, however, that simple mergers would create large distances between the new centers and the places they served, distances that would translate into long travel times for providing student services. Because of this problem and because school districts are a more meaningful level of aggregation for AEA services, we suggested that the school district be the unit of analysis (Figure 3).

A base map provided by the State Board of Education delineated the borders for each of the 433 school districts in the state as of 1989. This map was digitized so that the SDSS could produce maps showing the assignment of districts to regions. From this outline map, the coordinates of the centroid of each district were calculated to serve as a demand node. We used an areal centroid, rather than one weighted by the internal distribution of pupils within each district, because the coordinates of the locations of schools and their associated enrollments were not available to us. These centroid coordinates were also used to compute distances among the districts; we adopted a Manhattan metric (Love, Morris, and Wesolowsky, 1988, p. 5) because of the generally rectilinear configuration of Iowa's road network.

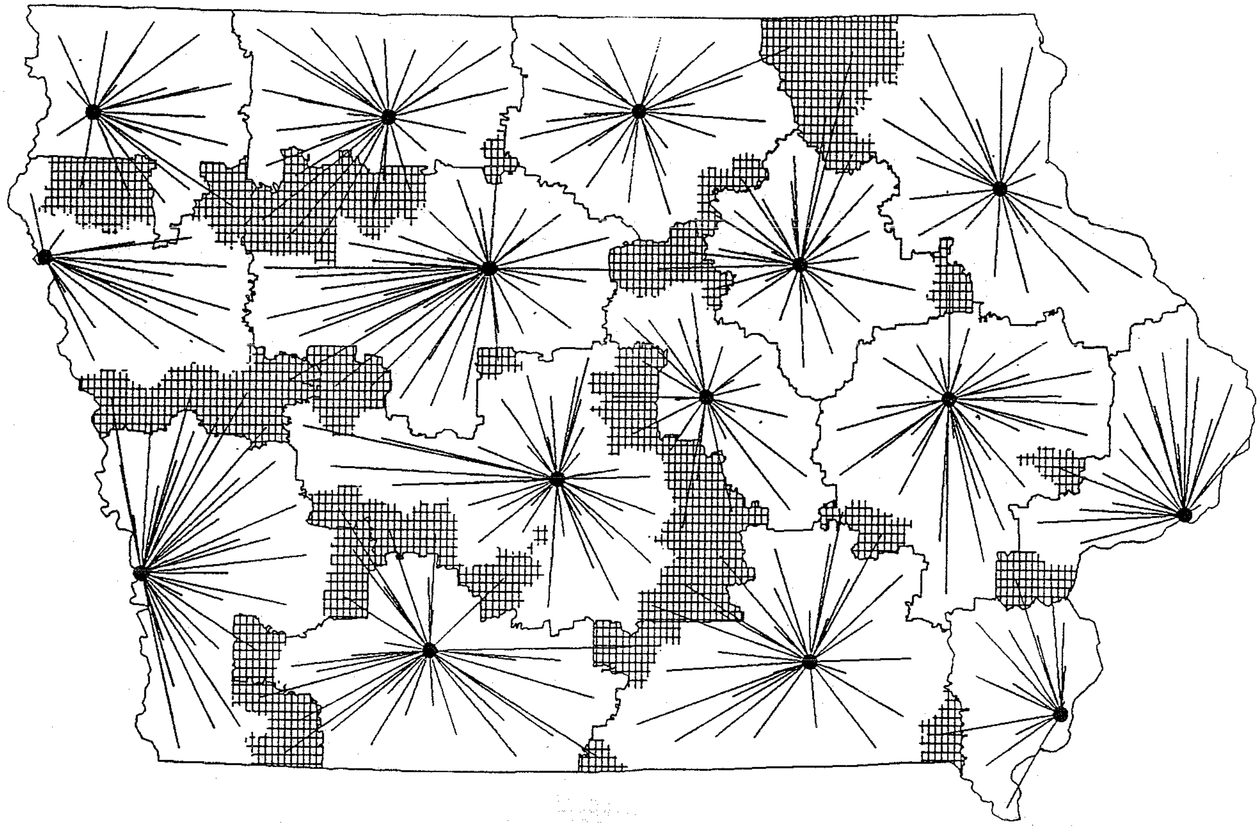
Demand Weights

The measure of demand was the total public and private enrollment for each school district in 1988 (data obtained from the State Board of Education). Enrollment is an appropriate measure because AEAs provide services not only to children but also to teachers, whose numbers are proportional to student enrollment. For the analyses, the enrollment weights were assigned to the school district centroids.

System Capabilities

The system is designed to allow decision-makers to examine the results of analyses that use different parameters of the decision criteria. In the AEA analyses, we varied the number of centers, the maximum distance from service centers to school districts centroids, the minimum enrollments served by each center, and the candidate places from which the centers had to be selected.

The system could depict each solution on a separate map or more than one configuration on a single map. In the latter case, for example, the map could display both the current assignment of school districts to AEA centers and the configuration that would result from assigning districts to their closest (proximal) AEA (see Figure 5). The software also allows decision makers to compare the solutions arrived at under different objectives. In a p-median solution (Figure 6) the 15 AEA centers are located so that the average distance between school districts and their nearest service



A straight line indicates the assignment of a district to the closest center. Shaded areas indicate districts currently served by a center other than the closest one.

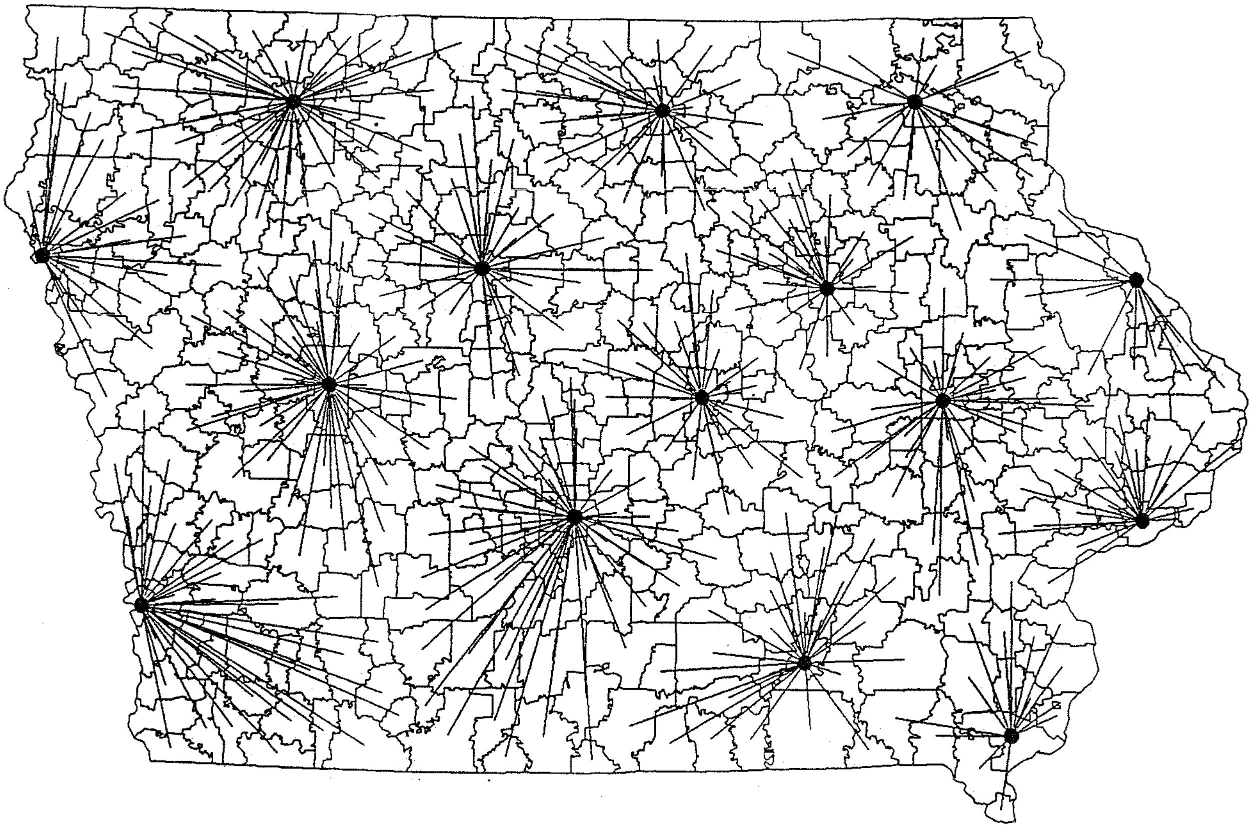
● AEA center

|——| 30 miles

Figure 5
Differences Between the Current AEA Plan and a Proximal Assignment of Districts to Their Nearest AEA Service Center

center is minimized. In Figure 5 the service centers remain in their present location, whereas in Figure 6 some centers are relocated.

As constraints are added to a solution, patterns of location change. One particularly important criterion for the AEA Workgroup was minimum enrollment. Figure 7 depicts how a solution will differ from the p-median solution if the centers remain the same in both solutions but one has the added constraint that each center serve a minimum enrollment of 25,000 students. The shaded areas represent schools that the ADJUST algorithm (see Section 5) transferred from surplus regions (those with more than 25,000 students) to deficit regions (those fewer than 25,000 students). Those school districts transferred would not be served by the closest center.



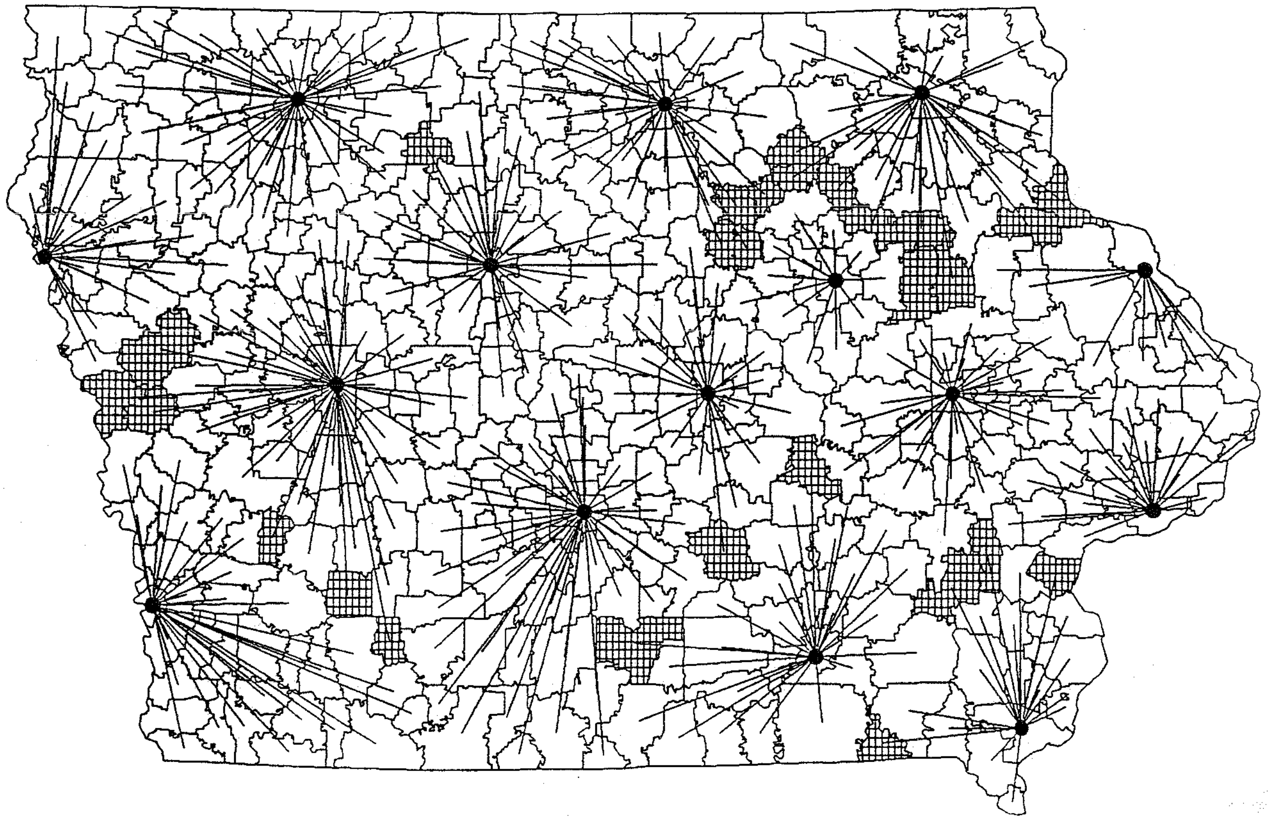
A straight line indicates the assignment of a district to the closest center.

● Center

I———I 30 miles

Figure 6
A p-Median Solution (p=15) in Which Average Distance Between School Districts and Service Centers is Minimized

As the criteria and constraints are varied, some aspects of the semi-structured problem take on an importance that the decision maker did not originally recognize. The set of criteria form a solution space with the results of different analyses occurring at discrete points in this space. By examining the degree to which performance on one criterion improves when performance on another criteria is allowed to become worse, decision makers can make trade-offs between the two criteria.



A straight line indicates the assignment of a district to a center. Shaded areas indicate districts served by a center other than the closest one.

● Center

|———| 30 miles

Figure 7
Difference Between the p-Median Solution Shown in Figure 6 and One That Has a Minimum Enrollment of 25,000 Students

System Application

In July 1989 we met with the Iowa Department of Education's Delivery System Structure Workgroup in Des Moines, where we described our approach and provided several real-time illustrations of the kinds of analyses that the SDSS could provide. We explained that the SDSS could

1. vary the number of candidate sites,
2. specify a maximum travel distance between AEA centers and the school districts they serve,

3. specify a minimum enrollment for the AEA service area,

4. define a set of places to be candidates for AEA service centers,

5. require some locations to be sites, and

6. allocate any specific school districts (or all districts) to particular service centers.

We used the dual computer setup (described earlier) to demonstrate the different configurations of regions and their assigned school districts that could result from different specifications of the problem. After evaluating several analyses of the problem and discussing the results, the Workgroup was able to see the kinds of solutions that were possible. Members asked for additional analyses during the meeting, specifying a particular set of criteria and constraints. Although they continued to wrestle with competing objectives and constraints, some of which proved to be mutually exclusive given the geographical distribution of children and places in Iowa, they were able to focus on the more highly structured aspects of the problem.

At the close of the meeting the Workgroup voted unanimously to use the analysis system to continue their search for a solution to the AEA geographic restructuring problem. We invited a subcommittee of the Workgroup to the Public Policy Center at The University of Iowa in September 1989 to spend a day discussing the problem, to use the analysis system to investigate alternatives that interested them, and to search for the alternatives that might best meet their criteria for reorganization.

Before the September meeting numerous requests were forwarded to the committee chair, who passed them along to us for analysis. After evaluating the preliminary solutions to the problem, the Workgroup were particularly interested in the following criteria.

1. **Preventing distances travelled to provide services from becoming excessive.** After seeing the long distances in many of the computed solutions, especially those which met minimum enrollment thresholds, (Figure 7, for example), members concluded that solutions in which many children were farther than 100 miles from a center were unacceptable. They believed that a staff member who had to travel more than 100 miles would not be able to provide sufficient service for one work day.

2. **Having enough enrollment, and therefore budget, to employ specialized staff to provide appropriate services.** After seeing the small number of students in some regions, especially in the western two-thirds of the state, many members

concluded that solutions in which there were fewer than 35,000 students in any region were unacceptable.

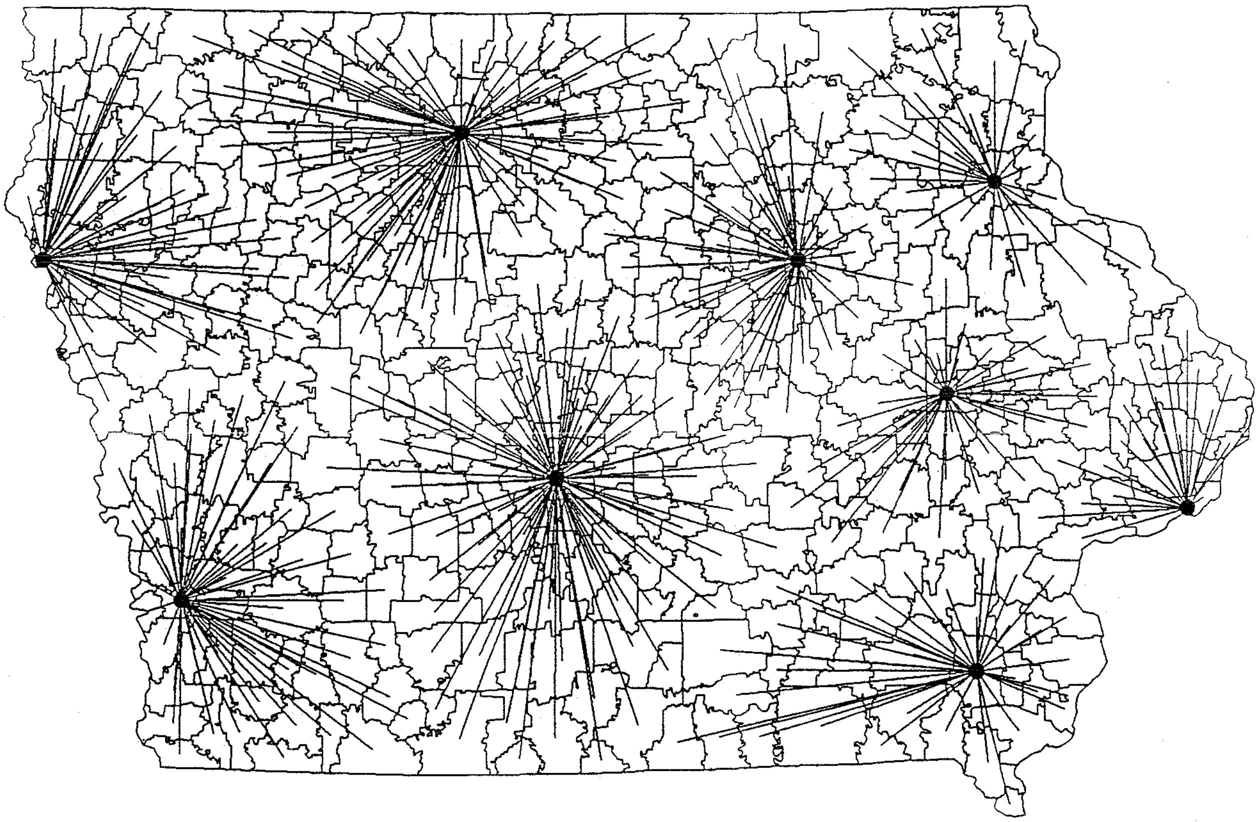
3. **Minimizing change to the current system.** After seeing that many solutions did not include some current regional centers in which large capital investments had been made, many members concluded that solutions which excluded some current regional centers were unacceptable.

At the September meeting, which lasted about six hours, a subcommittee of three persons used the SDSS. Again, a two-computer configuration generated solutions and displays concurrently. The hardcopy display and report generation capabilities of the system also facilitated discussion of the relative merits of alternative solutions. Each iteration of the process took approximately ten minutes, and therefore the solution space could be interactively examined in near-real-time. Committee members were encouraged to formulate requests or suggest values for criteria using a standard form that allowed specification of

1. number of centers,
2. fixed centers,
3. distance constraints,
4. minimum enrollment, and
5. fixed assignment of school districts to centers.

We illustrated the flexibility of the system by providing one set of analyses varying the number of centers, holding other factors constant, and another set of analyses varying other factors and holding the number of centers constant. As members of the Workgroup began to formulate additional requests to explore the decision space, varying the number of regions between nine and 12 was a key point of inquiry. (Note that they did not explore numbers as low as four—he minimum under the legislative mandate—since they saw that travel costs and travel times would become excessive.) They quickly established other primary criteria—the minimum enrollment in a region, the maximum distance to receive services in a region, and the proportion of children farther than a given distance from the service center—and spent the remainder of the session exploring these variables and their interactions. For example, enrollment thresholds were applied to ensure that each region would have a large enough population to sustain a specialized, highly qualified staff.

Following the September meeting, the Workgroup made two recommendations to the Department of Education, one for 12 centers and regions with a minimum enrollment of 30,000 students, the other for nine centers and regions with a minimum enrollment of 40,156 students (Figure 9). In this nine center regionalization, which was adopted by the Department and submitted to the Iowa Legislature for approval, the five regions of eastern Iowa have smaller areas than the four regions in west and central Iowa. This difference reflects the greater population densities of the eastern part of the state. School districts in south-central Iowa, although farther from a service center than in the current system would be served by centers with much larger enrollments than in the current system.



A straight line indicates the assignment of a district to a center.

● Proposed center

|———| 30 miles

Figure 8
The Solution Chosen by the AEA Workgroup

SECTION 8
CONCLUSIONS

If public and private enterprises make locational decisions that enable transportation costs to be kept to a minimum, we will have better service systems in the public sector and stronger enterprises in the private sector. These decisions can be supported by computer systems that are designed to provide information to decision makers about alternative solutions to locational problems.

People untrained in methods of locational analysis can understand the purpose of optimizing methods, but may not see how they could use the methods in a systematic way to search for a solution. We favor the use of an analysis system to generate interesting alternatives that decision makers can discuss as part of the process they use to define the problem to be solved. After applying our system to the reorganization of AEA regions in Iowa, we contend that decision makers are more likely to reach a consensus when they use an analysis system to generate a set of possible solutions and then evaluate the relative merits of each. When evaluating alternatives, decision makers discover new issues that must be considered (Hopkins, 1984).

The SDSS approach does not force semistructured problems prematurely into a structure; instead, it is an interactive approach to defining, formulating, and solving problems. This approach could apply to a wide range of problems in regionalization and location selection.

Improvements in transportation databases and systems technology have removed impediments to applying decision support to transportation problems. Using the road networks database, the decision support system can calculate real distances between places and integrate these data into programs for determining shortest paths, solving location-allocation problems, and allocating demand to meet user-defined constraints. The optimizing methods in the software will determine how service delivery systems can be made more efficient and transportation costs reduced. The visual displays, based on digitized maps of road networks that are becoming available, will make the effects of optimizing solutions based on different criteria immediately apparent to users.

Practical examples of where a spatial decision support system would be useful in transportation planning and management include:

- **Route maintenance**

  Find the number of locations and the placement of maintenance equipment and personnel so that service is maximized for any given quantity of available resources or so that the fewest resources will be needed to provide a given quality of services.

- **Highway inspection stations**

  Find the number of locations and the placement of highway inspection stations so that the necessary inspections can be provided at least cost.

- **Emergency medical services**

  Find the number of locations and their placement for the different levels of life support for medical emergencies.

- **Maternal and child health.**

  Find the set of hospitals that should be designed as Level II hospitals so that all women will be within 30 minutes travel time of such a hospital.

- **Disaster relief**

  Find the number of places and their locations for storing provisions to be used in local or national emergencies.

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