Network Analysis in Geographic Information Systems

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ABSTRACT: Many spatial relationships can be described as linear networks using a common database structure stored in a geographic information system (GIS). Pathfinding and allocation procedures built into a GIS can be used to create highly realistic models of flow through these networks. In a GIS environment, a single data model can be use to analyze linear networks representing streets, waterways, telephone lines, and other related phenomena. Several other functions of a GIS facilitate network analysis. Map digitizing and editing procedures support creation of the cartographic portion of a network database. A relational database management system supports assignment of flow-control attributes to network cartography. Finally, the GIS environment makes possible interactive graphical implementations of pathfinding and allocation procedures, which are easy to use and produce models easy to interpret.

INTRODUCTION

We seem often to ignore the degree to which the world is organized into networks. Most of our personal movement and the delivery of all that we consume occurs within vast systems of connected linear channels. Whether these systems are tangible, such as streets and telephone lines, or elusive, such as microwave relays, each may be described as a line graph and a set of constraints that dictate paths of flow across it.

A line graph is a two-dimensional mathematical figure composed of links representing linear channels of flow and nodes representing their connections (Figure 1). This abstraction is the common basis for all analysis of flow through networks. A line graph alone, however, is not sufficient to simulate realistic flow, because it implies that movement is possible along any connected path and that costs of movement are determined solely by path length.

Although path length is always a component of travel cost, flow in actual networks is constrained by rules related to the nature of the flow they conduct. In an electrical network, flow is governed by physical laws, such as resistance, that make some paths preferable to others. In a street network, flow is influenced by physical laws, but dominated by legal restrictions.

Although the rules controlling flow differ among network applications, all such rules add to the cost of travelling along or between links. In a street network, for example, travel costs along a link are a function of its length and speed limit. Between-link travel costs result from traffic signals and congestion. Flow-control rules affect the flow along and between particular links differently. Therefore, to model flow through any real network, each component of the line graph that represents it must be assigned a travel cost that reflects both geometric and flow characteristics.

Two fundamental flow analyses are commonly applied to network databases to answer various operational questions. The first analysis is termed "pathfinding." Its object is to determine the minimum-cost path through a network between a given origin and destination (Figure 2). The second is termed "allocation." In allocation, every link of a network is assigned to the nearest (minimum travel-cost) of several centers located on the network (Figure 3).

The pathfinding procedure is used to determine an optimum route between a known origin and destination. Optimization does not necessarily imply a minimum distance solution. Rather, an optimum path considers all of the components of travel cost, those of travel along links as well as between links. Pathfinding is often used to determine the best route to an unfamiliar destination. In other applications, pathfinding is used to evaluate the locations of origins and destinations by considering the path between them. For example, does the shortest path from a quarry to a construction site pass through quiet neighborhoods?

The allocation procedure is used to determine which of several centers is closest to each network link in terms of minimum travel cost. This procedure is used to assign each link in a network to its proximal center, thereby defining service areas. Given these assignments, center locations may be analyzed by examining characteristics of the links assigned to them. For example, how many houses are located closest to a particular fire station?

The algorithms used to perform pathfinding and allocation are well established and have been in widespread use since the 1960s (Moore, 1957; Dijsktra, 1959). A GIS implementation of these algorithms provides rapid and interactive analysis of real networks. It also allows users to manage the results of analysis procedures, making them useful for decision support.

NETWORK ANALYSIS WITH A GIS

A system for automating network models must manage coordinate data defining a line graph. It must also permit association of travel costs with each link, and with every connected pair of links. Operationally, this requires a geographic information system comprised of generic software procedures. Such a system makes network analysis feasible for a variety of applications. Because GIS procedures operate on a highly abstracted model of network, they can be applied to any particular line graph using any particular flow contraints. In this context, pathfinding and allocation are simply additional methods of viewing spatial relationships.

The ARC/INFO GIS, for example, stores a network as a set of line features with associated attributes. The line features consist of coordinate pairs and an explicit indentification number. Attributes of these features are stored in a table within a relational database management system (DBMS). Records in the table also contain explicit indentification numbers that relate them to a particular feature. Whenever the coordinate information for a network is modified, perhaps by the addition of new features, the attribute file in the DBMS is automatically updated.

One important contribution of a GIS environment to network analysis is the power a DBMS offers for calculating realistic flow constraints. The travel cost associated with each link, even though interpreted as a single value, can be thought of as the product of attribute modeling of various items within the DBMS. For example, the travel cost of an ice cream truck through a street network is a function of distance traveled and operating cost, offset by the profit to be gained by sales. To assign travel cost to a particular link, a value is generated based upon its length, multiplied by some factor for vehicle operating cost and a similar factor for labor. The expected sales receipts are subtracted

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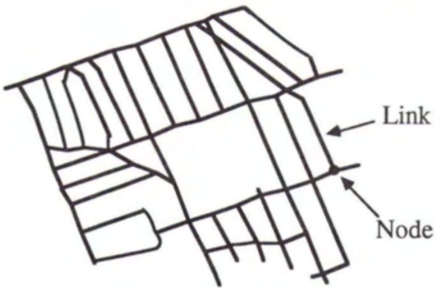

FIG. 1. A line graph is composed of links representing linear channels of flow and nodes representing their connections.

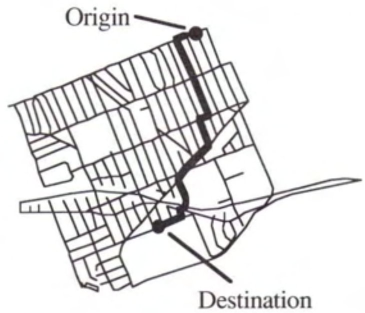

FIG. 2. A pathfinding procedure determines the path through a network, between an origin and destination, that minimizes total travel costs.

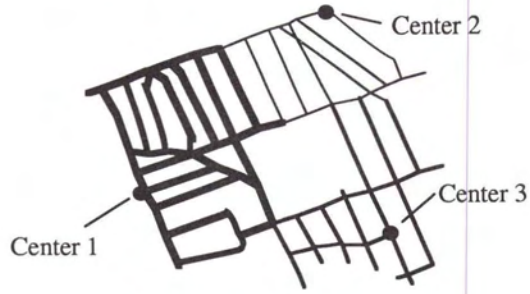

FIG. 3. An allocation procedure assigns each link of a network to one of several centers by determining the minimum cost path to each center.

from this calculated cost. This yields a value that represents the true benefit of travel along the link. Applying a pathfinder analysis to a network coded in this manner produces a path that maximizes profit.

The expected sales receipts used in creating the single travel cost attribute might themselves be the product of attribute modeling. For example, characteristics of the population living along a street network might be used to predict the spatially distributed demand for a particular good. This modeling attributes to produce new attributes, which then become the flow contraints for network analysis, is made practical because of the DBMS and its tight coupling with the line graph in a GIS.

Just as a GIS supports network creation and attribute coding, it provides invaluable support to the analysis environment itself. Network analysis systems not integrated with GIS have traditionally operated in batch mode, with the locations of origins and destinations preselected by node identification number and laboriously encoded in program data statements (Rushton, 1973). In a GIS, however, analysis proceeds interactively with full graphic display. Origin and destination locations can be entered using a cursor or mouse, or as street addresses which are automatically assigned geographic coordinates. Interaction in network analysis provides the user with an opportunity to experiment with many alternative origin/destination scenarios, to evaluate their results visually and mathematically, and to use the results of one analysis run to guide specification of the next.

For example, a user may wish to choose from among several sites for a new electric power substation. With a GIS-based allocation procedure, he could select and evaluate a few different locations, to gain quickly a general understanding of the impact of a new substation on the power distribution system. He could then use this new understanding to evaluate the few sites that seem likely to satisfy the complex constraints of his selection. Detailed analysis results for only these sites need be considered.

Detailed results of network analyses are stored in a GIS as additional attributes of the network database. In pathfinding, each network link may be assigned the identification numbers of the paths to which it belongs, along with its distance from those paths' origins. In allocation, each link may be assigned cumulative travel costs and the identification number of the center to which it was assigned. Links may also be assigned the identification number of the link that precedes them in a path to their assigned center. These linked identification numbers can be used to generate directions from a link to its assigned center (e.g., "Travel 3600 feet on Eureka Street, turn left to Clarke. . ."). Furthermore, service centers may be assigned characteristics of the links assigned to them in an allocation.

APPLYING GENERIC NETWORK TOOLS

The programs that comprise a GIS are often structured as a toolbox of generic operations upon a common spatial database. This requires GIS users to design an analysis project as a coherent series of steps, each invoking a particular software tool. Each of these steps transforms a database toward the state in which it contains the answer to some operational question. The network analysis procedures for pathfinding and allocation appear as steps in projects that answer three broad classes of questions:

(1) What is the best path between an origin and a destination?
(2) Where should I locate a service center?
(3) Which center serves a particular link?

Each of these questions is discussed below as an application of

WHAT IS THE BEST PATH BETWEEN AN ORIGIN AND A DESTINATION?

This question is sometimes states as "How do I get there as quickly as possible?" This is the form of the question for emergency services dispatching. In shuch an application, "rapidity of response" is equivalent to "best." In other applications a best path is constrained by potential benefit, as in the ice cream truck example, or as would be a sightseeing excursion. In still others, a best path is constrained by risk avoidance, whether the risk is congested traffic or overloaded electrical circuits.

The best path question is solved by establishing some attributes in the database that model the desirability of traversing each link. The network line graph and these flow control attributes are submitted to the pandfinding procedures along with origin and destination locations. The procedure then determines and displays an optimum path, which the user may accept and save to database, or modify to produce and evaluate a less optimal path.

GIS pathfinding or allocation procedures.

WHERE SHOULD I LOCATE A SERVICE CENTER?

The nature of service centers varies with application (e.g., fire stations, polling places, electrical substations, telephone wire centers, and water treatment facilities). The characteristics of centers as they relate to a network, however, are simple and constant.

All centers have a capacity for the demand that is distributed through the network. This might be a maximum number of concurrent telephone calls that a wire center can manage, or the maximum number of students in a school, or a number of fire-prone structures that can be protected by a single fire station. All centers also have a limit to their service range. This limit may be the five-minute response goal of an ambulance service, or the drop of pressure to zero in a water pipe over distance from a pumping station.

The question "where should I locate a center" is solved with a GIS by evaluating alternative locations. A network and a set of centers are specified to the allocation procedure, which determines the nearest center, in travel cost terms, for every net-

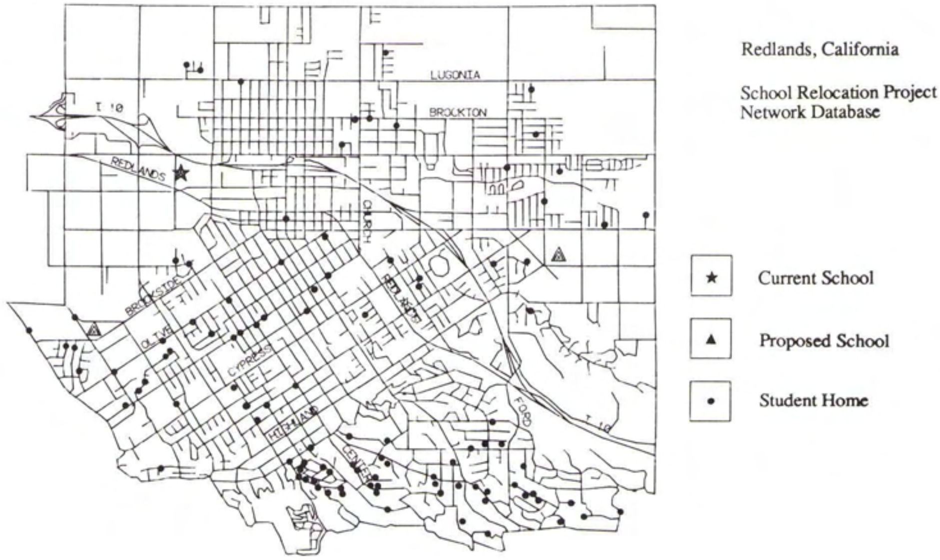

FIG. 4. Redlands, California network database.

TABLE 1. TRAVEL-TIME TO SCHOOL IN CURRENT AND PROPOSED LOCATIONS

	Mean (minutes)	Maximum (minutes)
Current location	4.8	7.6
Proposed East Site	5.1	9.2
Proposed West Site	5.5	9.9

TABLE 2. OVERALL TRAVEL TIME TO NEAREST SCHOOL. TWO SCHOOL ALLOCATION MODEL.

	Mean Time (minutes)	Assignment of Students	
		Existing School	Proposed School
Current and East Site	4.1	84	54
Current and West Site	4.4	90	48

TABLE 3. OVERALL TRAVEL TIME TO ASSIGNED SCHOOL. CONSTRAINED ALLOCATION MODEL.

	Mean Time (minutes)	Assignment of Students	
		Existing School	Proposed School
Current and East Site	3.9 Minutes	113	25

work link. In a GIS, the results of an allocation may be listed and considered immediately. A decision might then be made to move or modify a center and repeat the procedure. Working iteratively, an appropriate center location can quickly be found.

WHICH CENTER SERVES A PARTICULAR LINK?

This question is often answered by retrieving information created by an earlier allocation run from the database. One of the results of allocation is a set of attributes that specify to which center link is assigned, the travel cost to reach that center, and the path to follow toward it. These results, once stored, allow data associated with a link to be assigned to a center. A common application of this procedure is the assignment of voters to polling places. Each link is allocated to a polling place, then a list of voter addresses is matched to address ranges associated with each link. These two processes create database relationships that associate each voter with a polling place, and can be used to notify the voter where to go to vote, the distance to their polling place, and how to get there. Similar applications involve assignment of commuters to bus stops, and of grocery stores to warehouse service areas.

In an interesting variant of the "which center" problem, a subset of the network is sought containing only those links necessary to serve some other her set of links. A telephone company, for example, may wish to identify links in their distribution network that are required to serve the company's largest business customers. These links are candidates for service improvement, using fiber-optic technology. To identify the network subset, an allocation would be performed, assigning all links to their proximal wire center. The results of the allocation, particularly the "previous link" item, would then be manipulated to traverse the network from each large business customer location to a wire center. As the network is traversed, each link encountered is identified as an element of the network subset needed to reach businesses.

A RESEARCH EXAMPLE

In October, 1986 Environmental Systems Research Institute conducted a project to evaluate two proposed sites for relocation of a private primary school in Redlands, California. The methodology of this project provides interesting examples of network analysis techniques applied to actual decision support.

The first step in this project was to determine the travel time for each student from his or her home to the current location of the school. This was accomplished by creating a network database using the ARC/INFO GIS. This database contained linear features representing a street map of Redlands (Figure 4). Each link of the network was assigned a travel time value, calculated from its length and speed limit. Every link-to-link turn was also assigned a travel-time value, based upon its angle and the types of streets meeting at an intersection. For example, left turns were assigned more delay than right turns, and turns off of highway overpasses were prohibited by assigning them extreme travel costs.

The locations of students' homes, and of the current and proposed school sites, were determined by matching their street addresses to address ranges associated with each network link. The database was then manipulated to summarize the number of students living along each link of the network. That value was saved as a link attribute.

The ARC/INFO allocation procedure was used to determine the average and maximum travel-times for all students to the cur-

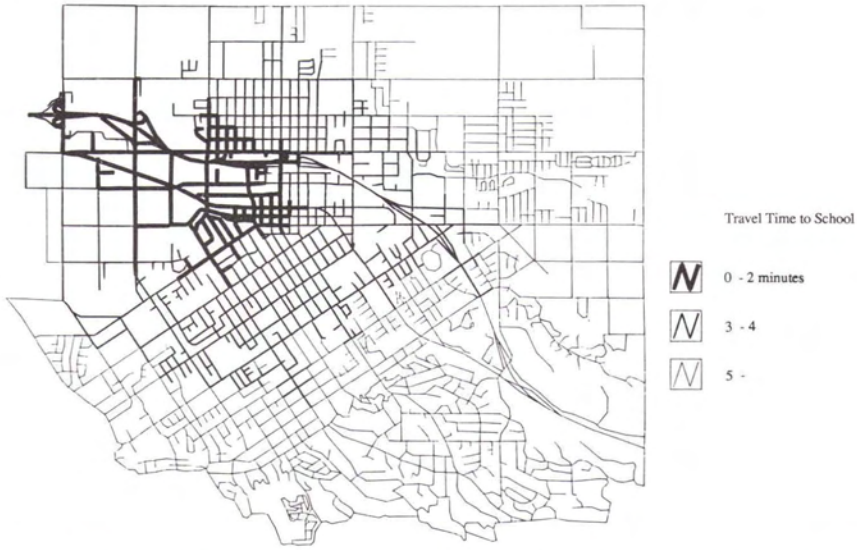

FIG. 5. Travel time to the current school location is determined for each link using allocation analysis.

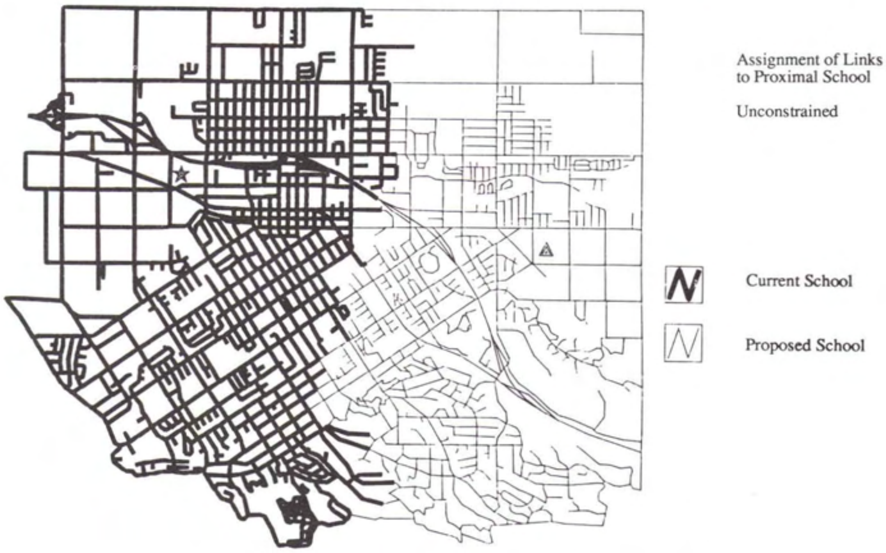

FIG. 6. Each link is assigned to the nearest center.

rent school site. In this analysis, the current school site was specified as a lone center, without capacity or limit constraints. All links in the network were allocated to the center, yielding a travel-to-school time for each link (Figure 5). This value was modeled with the number-of-students link attribute to determine the average and maximum travel-times for all students. The allocation procedure was repeated for each proposed school site to evaluate the impact of relocation to either site on overall student travel-time (Table 1).

The project also considered the possibility of maintaining the current school site, and developing one of the proposed sites as a secondary facitlity. To evaluate this scenario, a series of allocation analyses were performed, each using the current school site and one of the proposed sites as centers. In these allocations, each school competed for students by "capturing" those nearer to itself than to the other.

In the first pair of two-school allocations, each student was assigned to his proximal school (Figure 6). This assignment would reduce overall travel-time if either proposed site were developed (Table 2). In these proximal assignments, however, the secondary site was allocated so many students that the existing school was left underpopulated. The allocation model used for the two-school scenario was, therefore, modified with a capacity constraint to limit the proportion of total enrollment that could be assigned to a new school.

The two-school allocation procedures were repeated several times, using different capacity constraints for the new school in each iteration. By evaluating the results of each allocation run, and by varying capacity constraints interactively, the project analyst was able to identify an assignment of students to school that reduced overall travel time and preserved the enrollment base of the primary facility (Figure 7, Table 3).

CONCLUSIONS

By integrating pathfinding and allocation procedures with a toolbox-style GIS, their analytical power can easily be applied to many databases. Successful integration of network analysis tools depends upon a concise and generic model of networks and the flow through them. Given this model, the data management and display functions of a GIS can be used to create, manage and analyze any network. This makes feasible the use of network analysis in a variety of applications.

One limitation of the GIS approach to network analysis is its assumption that a network maintains its original flow characteristics during an allocation of pathfinding session. An urban

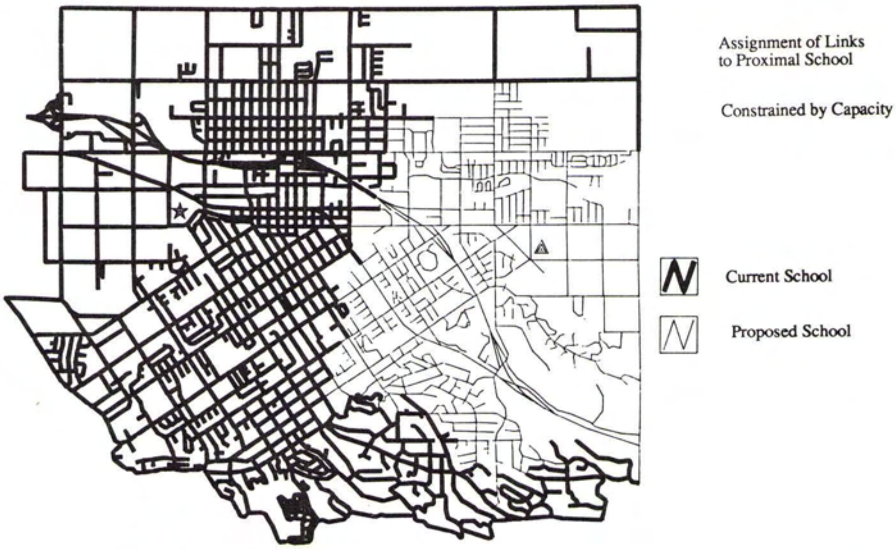

FIG. 7. A capacity constraint is added to an allocation to limit the number of students assigned to a secondary facility. Appropriate values for constraints are determined by interactive analysis.

rush-hour, with ephemeral and influential patterns of congestion, is not well modeled with a GIS.

To overcome this limitation, a system might permit flow-control characteristics of a network to be specified as functions of several variables. These variables would include those in the database as well as those available only during the analysis session, such as the instantaneous volume of flow across a link. An improved system might also integrate graphic editing functions with network analysis. This would allow users to modify network geometry, to pose "what if" questions essential to planning, without interrupting their network analysis session.

The interactive session is the essence of the GIS approach to network analysis. Although algorithms exist for mathmatically determining optimal location, they are not widely used in GIS. They are not used because actual planning decisions are constrained by the availability of certain properties for center locations. Furthermore, optimization techniques presume that their criteria are complete. They arrive at a solution without providing intermediate results that help a user comprehend the complex patterns of spatial interactions that occur within a network. The GIS approach is to regard network analysis as one of many techniques for examining spatial relationships. In that context, a GIS is successful when it provides knowledge to its user, and when it makes available the tools needed to answer the questions raised by that new knowledge.

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