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Management of Spatial Information For Construction Planning and Design Using Geographical Information Systems (GIS)

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ABSTRACT

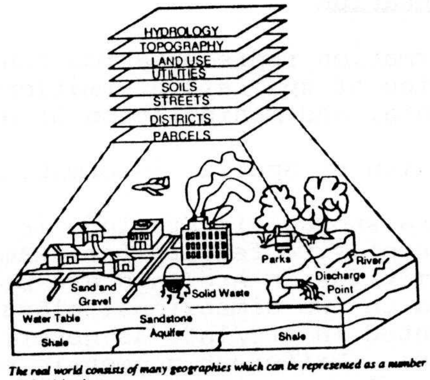
Geographic information systems (GIS), a technology for spatial data analysis which is widely used in geology, appears to have significant potential in construction applications. GIS as well as computer-aided design (CAD) are two computerized systems widely used in engineering design and spatial management. Currently, CAD is the most popular tool in geometric model creation. However, due to the poor capability in analysis, CAD is limited to be a design and drafting tool. GIS, an evolutionary technology in spatial information management, seems to have potential in solving this problem. The purpose of this paper is to illustrate the feasibility of applying GIS in potential construction applications. The applications of GIS can achieve the following objectives: 1. Integration and organization of ill-structured information , 2. Automate spatial analysis, 3. Improve efficiency of construction planning, 4. Improve project control, 5. Improve the quality of construction plan and design , and 6. Reduce paper work and improve the eases of accessibility and modification of information.

1. INTRODUCTION TO GIS AND ITS FUNCTIONALITY

1.1 Introduction

Geographical Information System (GIS)

Geographical Information System (GIS) is a set of tools to store, retrieve, output, manipulate, and analyze spatial data[6]. GIS defined by Environmental Systems Research Institute (ESRI) is a computer system capable of holding and using data describing places on the earth's surface (see Figure 1)[2]. Not only is GIS a computer system for creating maps with different scales, projections, and colors, but also an analysis tool to link spatial data with geographical information about a particular feature on a map. The primary advantage of a GIS is that it allows you to integrate locational information with thematic information and identify the spatial relationships between map features.



The real world consists of many geographies which can be represented as a number of related data layers.

Figure 1 The Definition of GIS (ESRI,1989)

GIS combines CAD with a relational database management system (DBMS) and stores the descriptive information as attributes of the graphical features. The following example illustrates GIS in a construction context. A construction site can be divided into blocks by access roads and railroads. In this case, the actual visual representation of the blocks will not yield much information about it. To obtain information about the landuse, such as its area or construction schedule, the user can query the database. In addition, the user can create a display symbolizing the landuse according to the type of information that needs to be shown. A GIS can also use the stored attributes to compute new information; for example, to calculate the duration of an activity based on the start and finish date of the activity stored in the database or determine the total labor requirement of a speciality.

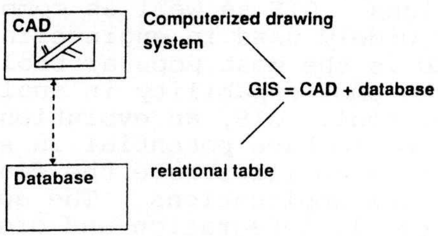


Figure 2 Arc/Info Definition

ARC/INFO

Arc/Info is the standard GIS software developed by ESRI. GIS - Arc/Info is a one-to-one linkage between a map feature and a data record [3]. Arc/Info's name is derived from the capability of the software to represent locational data (Arc), and thematic data (Info) as shown in Figure 2. The Arc/Info geographic information system was the first GIS to incorporate interactive graphic capabilities with a relational database management system (DBMS) [1]. Arc/Info is based on a generalized definition of a GIS [4]. It integrates spatial modeling, database management, spatial analysis, and computer graphics into a software environment for managing geographic features [5]. Arc/Info is a full scale, commercially available, vector-based GIS. It utilizes a topological and relational data model where not only map features are stored, but also their relationships to each other.

1.2 Arc/Info functions

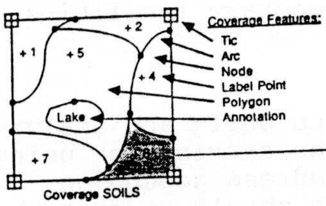
The basic functions of Arc/Info are discussed in this section. These functions are: (i) information representation, (ii) spatial operations, (iii) network analyses, and (iv) adding functionality.

1.2.1 Information Representation

The fundamental information representation functions of Arc/Info enables the efficient representation of spatial information, the integration of locational and thematic data, and manipulation of attributes in data layers.

Efficient representation of spatial information

The basic unit of data storage in Arc/Info is a coverage. It contains information about one type of site feature for example roads, railroads, or buildings. The basic primitives in Arc/Info are points, lines, and polygons. These primitives are based on two dimensional planar graph theory. All the site features are represented in Arc/Info as generic geometric entities; lines, points, and polygons. Different geometric entities are separated and stored in different feature layers. For example, roads which can be all represented as line features are stored in an line coverage. Likewise, buildings can be all represented as polygons and are stored in a polygon coverage.



Feature Attribute Table SOILS.PAT

RECNO	AREA	PERIMETER	SOILS#	SOILS-ID	SOIL	CLASS	SUITABILITY
1	-36.0	24.0	1	0	—	—	—
2	3.0	9.0	2	1	A3	113	HIGH
3	2.5	8.5	3	2	C6	95	LOW
4	15.0	15.0	4	3	B7	212	MODERATE
5	4.0	8.5	5	4	B13	201	MODERATE
6	2.0	4.5	6	5	Z22	86	LOW
7	5.5	12.0	7	6	A6	77	HIGH
8	4.0	7.0	8	7	A1	117	LOW

Figure 3 Schematic representation of a coverage, with some of the possible feature classes, and a feature (polygon) attribute table (ESRI, 1989).

Integration of locational and thematic data

Due to the lack of database linkage in most CAD applications, engineers are limited by the system constraints of aggregating and distributing databases between graphical and nongraphical attributes. Arc/Info solves this problems by providing fully integration with dBASE database management files. This nonredundant data model greatly reduces the amount of processing power needed to perform operations. To facilitate the integration of data, every feature in a coverage is linked to a record in a relational table called the feature attribute table (FAT). Arc/Info will generate the basic feature attribute table automatically when a spatial feature is created. Additional fields can be added to this table to represent the thematic information. The data represented in the coverages can be manipulated by functions such as criteria matching and relational join.

Querying and manipulation of information

Arc/Info provides two types of queries, namely aspatial and spatial query. For example, asking "What is the traffic condition of the access road?" is an aspatial query. The answer does not require the stored of spatial data; nor does it describe where the places are in relation to each other. Conversely, spatial query asks questions about spatial information and relationship between the attributes. For example, "What is the shortest route with minimal impedance between two points on a construction site?" and "Is the building's location on the left or right hand side of an access road?" are spatial queries.

As mentioned above, Arc/Info creates and maintains the connection between the spatial feature and feature attribute table automatically. The connection is established by sharing a common attribute. This concept can be applied to joining two tables if they share a common attribute. Once a connection is established, the related tabular data file can be maintained and update separately. Further, a look up table can also be used to extend the database and reduce the size of the table. Using the functions of query and data manipulation, Arc/Info can extract and merge data and identify the information which meet the criteria set by the user.

1.2.2 Spatial Operations

Performing geographical analysis is what makes GIS different from digital mapping systems. Each coverage contains basic information required for analysis. To generate the additional information required to make planning decisions, it is necessary to identify the spatial relationships between the various features. Arc/Info allows users to determine spatial relationships by providing the following functions; (i) topological overlay, (ii) Buffer generation, and (iii) feature extraction and merging. Topological overlay functions for example, can be used to identify the intersections of access roads and overhead. Buffer generation functions can be used to identify the areas adjacent to the permanent facilities and access roads. Feature extraction functions can be used to extract the occupied areas such as permanent facility locations, trees, ponds, and rivers from a construction site and identify the available areas for locating temporary facilities.

1.2.3 Network Analyses

Arc/Info's has a set of tools which can be used to build and analyze networks. The following three types of analyses can be carried out using these tools (i) allocation, (ii) routing, and (iii) address geocoding. Allocation analysis is used to determine how resources should be distributed between various centers in a network. It is also used to determine the nearest center for each link in the network. Route analysis determines the path of least impedance for the conveyance of resources. Based on a specified start point and end point within the network, the routing procedure determines the path of least impedance between them. Optionally, the points through which a route must pass, and barriers to the resources can be defined. Address geocoding permits the association of address information with a geographic location. This feature can be used to create natural references to the various features in the network.

1.2.4 Adding Functionality

Arc/Info contains internal development languages which can be used to incorporate additional functions. Two languages, the Simple Macro Language (SML) and Arc Macro Language (AML) are available. SML is available with the PC-Arc/Info while AML is available with the workstation version. Both languages offer high level programming capabilities such as expression evaluation, handling of input/output, and directing program flow of control. In addition, Arc/Info can communicate with external programs at two levels: (i) command level, (ii) data level. A hardware platform which supports multitasking is required to support communication at the command level. In this case both Arc/Info and the program will run simultaneously and the functioning of the program will be controlled by commands issued from Arc/Info. Conversely the program can control the commands issued by Arc/Info. This interface can also be used to communicate with software packages such as spreadsheets, database management systems, and expert systems. Communicating at a data level does not require the simultaneous execution of the software packages. In this case, a data file acts as the communication media. The data file acts like a blackboard to/from which each software writes/reads the information. As Arc/Info stores information in a standard dBASE file format, communication at a data level can be established easily.

2. DEVELOPMENT OF GIS APPLICATIONS IN CONSTRUCTION

GIS can help engineers understanding of construction design and planning processes by providing powerful modeling techniques that have not previously been available. Based on the functionalities of GIS, the rest of this paper addresses the feasibility of applying GIS in the following construction problems.

2.1 Construction Site Layout Of Temporary Facilities

Problem Description

Construction temporary facilities (TF) are facilities located on site to support construction activities. The objectives of site layout of temporary facilities are to locate facilities to optimize manpower travelling, material and equipment handling, travel distance, traffic interference, need for expansion and relocation, and locate support facilities near to support activities.

To achieve the objectives, project manager has to consider the characteristics and spatial constraints of the site and collect information from different resources such as A/E engineering, general contractors, subcontractors, and superintendent etc. Each party has his own interests and concerns. Therefore, how to organize and analyze the collected information efficiently and make tradeoffs between the interested parties becomes a decision for the project manager.

Problem Attributes

The primary concern in site layout is to identify and determine suitable area to locate the right TF. Spatial features summarized in Table 1 are coverages used to represent the plant site. To identify the relationships of the coverages and determine the potential areas to locate TF, criteria such as distance, adjacency, position, accessibility, and space have to be considered. Road traffic condition and area congestion are required to minimize traffic conflicts. To identify the available areas, landuse status such as "open" or "occupied" is determined. The construction schedule has to be considered to determine when the TF is required and design TF over time. The features and attributes required to select suitable areas are summarized in Table 1.

Table 1: Features and Attributes for Temporary Facility Site Layout

Feature	Attributes
Access Roads	Layout, Width, Lanes, Surface, Traffic Condition, Road type (Permanent vs. Temporary)
Railroads	Railroad Layout, Railroad type(Permanent vs. Temporary)
Landuse	Layout, Landuse Code, Landuse Status, Area density, Accessibility
Undergrounds	Layout, Width, Construction Schedule, Type(Sewer, Elect. etc.)
Plant Structures	Layout, Construction Schedule, Code(Can or can't be used as TF) Type(Cover/noncover)

Current Approach

Sketches, templates and two dimensional scale models are three two dimensional physical models commonly used for layout display. Sketches as well as drawings are basic tools to communicate ideas among the parties involved throughout the life time of the project. Templates and 2-D scale models are cut-out cardboards which can be used to visualize the object configurations and move around on the model to identify the satisfying layout. Three dimensional scale model is another alternative to represent the site layout.

Modeling in GIS

All of the physical models discussed above are visual representation of the site which wouldn't yield much thematic information about it. For example, physical models can represent the relative locational relationship among the objects but not the dimensions of the objects and distances in between. Especially when layout drawings or information come from different parties it is hard for people to show all of the information together efficiently and identify the relationship between the drawings.

Comparing with physical models, Arc/Info represents the spatial information efficiently and is easy to be modified. Arc/Info can also help project manager to organize and analyze the information that comes from different interested parties. Each drawing from different resources can be treated as a coverage. Related thematic information is attached to each coverage. With the manipulation of the coverages such as data query, polygon overlay, buffer generation, and feature extraction, Arc/Info can identify the potential areas that satisfy all of the criteria set in searching. Next is an example to illustrate the operations.

First, locate TF in the areas adjacent to the access roads and away from the work areas which are next to the permanent facilities (PF). In this case, the user buffers access road and PF coverages and then erases the PF buffer from the access road buffer coverage. Second, manipulate the landuse coverage using query and data manipulation functions to select areas which are available and can be used to locate TF. Then, by intersecting the result coverages derived from the previous two operations, potential sites can be identified. Likewise, further analysis of the potential sites can be done to identify the optimal site. Once the solution is obtained, the user can save it as a coverage. This dynamically generate coverage is used to represented an occupied space during a certain period of time for later design.

2.2 Material Allocation And Distribution

Problem Description

On large industrial sites, work areas that require the same material can exist at different locations. In such cases, the material is stored in more than one location as determined by the site layout. The quantity of materials stored at any given stage of the schedule should be adequate to meet the demand for construction and at the same time should not tie up the capital in excess inventory. In addition, if the routes selected aids the quick delivery of the material with minimal interference with other activities, the overall productivity of the project will be enhanced.

Problem Attributes

To optimize the inventory level at each storage facility, the material demand from each workface has to be forecast. The quantity of materials required at a workface and the schedule of construction is required to determine the material demand at each storage facility. To select the optimal route for delivering the material to the workface, the layout of the roads, the road properties and the location of the storage areas and the work areas have to be known. The features and the attributes required to make the decisions are presented in Table 2.

Table 2: Features and Attributes for Material Allocation and Delivery

Feature	Attributes
Roads	Layout, Grade, Surface, Traffic
Storage Areas	Location, Capacity, Material Type
Work Areas	Location, Material Quantity, Installation Schedule

Modeling in GIS

For this problem, the spatial attributes consist of the location of storage areas, work areas and the layout of the roads. The thematic attributes mainly consist of the road properties, material properties, and construction schedule. The basic capability of Arc/Info to represent the integrated information, its capability to communicate with external software and its network analyses features can be used to model the attributes and develop solutions to this problem

2.3 Planning Access For Large Vehicles

Problem Description

Planning access routes for large vehicles within a construction site is an important consideration in the development of an effective project execution plan. Large vehicles are used to transport either construction equipment such as cranes, or preassembled modules of the plant such as piperacks and process columns. Of these, the transport of the preassembled modules tend to be more critical because of their larger size.

Preassembled modules form an integral part of the process equipment needed for the operation of a plant. The average dimensions of prefabricated process columns are 100 to 200 ft in length and 10-15 ft in diameter. These columns usually weigh between 200-400T.

For new projects, the delivery of the preassembled equipment occurs after the construction phase of the project is well underway. For retrofit projects, the plant already exists and is usually congested. If the project execution has been well planned, there will be no hindrances to transporting the module to its installation location within the site. Any hindrance to transportation can result in rework to the facility or the modules. This can be expensive and delay the project.

Problem Attributes

The primary concern in planning an access route is to determine and avoid features on a site that can obstruct a vehicle. The obstructions to a vehicle can either prevent it from traveling on a road or impede the progress of the vehicle.

The features and the attributes required to determine obstructions are summarized in Table 3. To determine the best accessible route (i) the factors that prevent the progress of the vehicle should to be avoided and (ii) The factors that impede the vehicle should be minimal.

Table 3: Features and Attributes for Planning Access

Feature	Attributes
Roads	Layout, Width, Pavement Capacity, Surface, Grade, Traffic
Turns	Road Layout
Overheads	Layout, Height, Installation Schedule,
Undergrounds	Layout, Depth, Design Stresses, Installation Schedule
Plant Structure	Layout, Installation Schedule
Vehicle	Length, Width, Height, Weight, Steering Kinematics, Axle/Tire Type

Modeling in GIS

It can be seen from Table 3 that the representation of locational information and thematic information is essential for planning access. Thus, Arc/Info provides an ideal environment for developing the information model. Further, the spatial analysis capabilities of Arc/Info can be used to establish the relationships between the potential paths and obstacles needed to determine the paths accessible to the vehicle. Finally, the network representation and route analyses' capability of Arc/Info, can be used to represent the impedance of the accessible segments of the road network and analyze the road network to determine the route of least impedance.

2.4 Hazard Evacuation Plan

Problem Description

A hazard evacuation plan is developed to evacuate people from an incident area in order to minimize the damage occurred. Further, in addition to avoid the potential secondary events and hazards, a plan for evacuation of proximity people not in the immediate area has also to be developed. A hazard evacuation plan includes identification of incident location and type of incident and appropriate actions and evacuate routes to take. Different project characteristics have varying incident potential. According to the type of potential incident, specific action for evacuation has to be taken. Currently, computer monitoring systems are used in some of the dangerous and pollutant industry to locate the incident location. Once an incident happens, an isobar diagram will be generated to identify the incident location, radius of impact, speed of spread, and routes and actions of evacuation.

Problem Attributes

Plant layout including site boundary, permanent objects, and utilities is required in developing a hazard evacuation plan. For the identification of evacuation routes, on site and off site access roads layout are also needed. A map of plant location and adjacent villages can be used to evacuate proximity people not in the immediate area. Weather such as wind direction and speed are an important index in a hazard evacuation plan. Local government regulations and police strategy in handling hazard conditions have to be considered. Worker characteristic and distribution of site information needs to be provided. Knowledge of potential hazards and actions to take when a hazard occurs are crucial in the development of a hazard evacuation plan. The features and attributes required to develop a hazard plan are shown in Table 4.

Table 4: Features and Attributes for Temporary Facility Site Layout

Feature	Attributes
Access Roads	Layout, Width, Lanes, Surface, Traffic Condition
Location map	Layout, Population Density, Weather
Landuse	Layout, Worker Distribution/Density
Undergrounds	Layout, Width, Construction Schedule
Plant Structures	Layout, Potential hazards

Modeling in GIS

As mentioned above, these computer monitoring systems are very delicate, costly and hard to be maintained. GIS is an alternative to achieve the objective with less cost and easy to be maintained. Using GIS with expert system integration, a diagnose of an incident can be generated and right actions can be suggested and taken. GIS with generation of an isobar diagram can show the incident location, radius of impact, and routes of evacuation graphically. Then with the integration of an expert system, the system can diagnose the incident, provide information such as worker density in the hazard area and what kind of worker, identify the speed of spread, and suggest the right actions and routes to evacuate.

2.5 Construction Schedule Monitoring

Problem Description

During construction, a project manager may want to overview the percentage of completion of the project and have the progress information shown on the plant drawings. For example, mark the entities of the drawings in different colors to represent the activity status. Completed activities for instance, are colored in black, activities in progress in blue, and activities haven't start in red. Most of the time, this process is done manually. To automate the process, first engineers can integrate the plant drawings which are designed in the design phase using CAD with a schedule monitoring database. Second, manipulate and update the database to represent the current project progress. Last, show the results with different symbols and colors on the drawings.

Problem Attributes

A pilot plant drawing is required to overview the project in all. Then, based on the work breakdown structure (WBS), a series of drawings are used to monitor the activity progress on a certain level. Information such as precedent and successor activities, start and finish date, actual start and finish date, free and total floats, and required resources are attached to each entity on the drawings. The features and the attributes required to monitor the project progress are listed in Table 5.

Table 5: Features and Attributes for Schedule Monitoring

Feature	Attributes
Plant structures	Layout, Construction Schedule/Sequence, Actual start/finish date, Free/Total float, Required Resources
Main Activities	Drawings, Construction Schedule/Sequence, Actual start/finish date, Free/Total float, Required Resources
Landuse	Layout, Landuse Code, Landuse Status
Undergrounds	Layout, Construction Schedule/Sequence, Type(Sewer, Elect. etc)

Modeling in GIS

All of the drawings to monitor the activity progress can be represented as coverages. Each primitive in a coverage contains thematic information of activity precedent and successor activities, start and finish date, actual start and finish date, free and total floats, required resources, and percentage of completion. By querying and manipulating the data of the coverages, Arc/Info can retrieve, calculate, and update the information and represent the project progress efficiently. This approach of using GIS can be thought as a graphical WBS integrated with a schedule monitoring system.

2.6 Equipment Location

Problem Description

It is important to place major construction equipment such as cranes in a position at which it can be of maximum utility. Tower cranes should be located in a position where it can effectively serve the required areas during the project at minimum transport cost. Specialized heavy lift cranes, should be located in a position from which a maximum number of heavy lifts can be performed safely.

Problem Attributes

The information required to position a tower crane is based on the location of areas to be served by the crane, the quantity of materials to be transported and the characteristics of the crane. The positioning of heavy lift cranes are based on the pick and place locations of the loads, the characteristics of the crane and the layout of the surrounding structures.

Modeling in GIS

The information required for determining the optimum location of a tower crane can be integrated and represented using the basic capabilities of Arc/Info. The programs required to calculate the optimum location can be written using Arc/Info's macro language. Positioning a heavy lift crane ideally requires the representation of 3 Dimensional space. This is beyond the current capabilities of Arc/Info. But for most cases, representation of the constraints in 2 Dimensions is sufficient to determine a suitable location for the crane. In addition to representing the information the spatial analysis capabilities can be used to determine the spatial relationships between the potential positions and the pick and place locations.

3. EVALUATION OF GIS (Arc/Info) FOR CONSTRUCTION APPLICATIONS

The representation and integration locational and thematic information is fundamental for developing a computer based tool for planning construction activities. The ability of Arc/Info to create efficient information representation is a key to the development of a integrated planning database. In addition to representing information, the other features of Arc/Info permit the development of custom applications with a minimum investment in time and programming effort.

The primary drawback of Arc/Info for construction applications is the lack of 3D representation of space. Planning for many construction activities are based in 3D space. The lack of this capability limits the applicability of Arc/Info.

4. SUMMARY

GIS is a powerful tool for the representation and integration of spatial and non-spatial information. Further, it can be used for querying, analyzing and manipulating the represented information. It is widely used in many areas such as environmental management and transportation planning, but is yet to have any significant impact on the construction industry. This paper introduced the concepts of geographic information systems and discussed how some common problems in construction can be modelled using GIS.

The original idea of applying GIS in construction planning and design was derived from the author in solving spatial management problems of laying out construction temporary facilities [6]. Through recent researches at the University of Texas at Austin [6][7], the new concept is proven to be applicable and has potential in construction applications.

ACKNOWLEDGEMENT

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