Geographic information system based roadway construction planning

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Abstract: The planning process for roadway construction involves a large amount of information on design, construction methods, quantities, unit costs, production rates, and site conditions. Therefore, it is very important to acquire, manage, and process the necessary information efficiently to produce a rigorous construction plan. The geographic information system (GIS) is a very effective tool for integrating and managing various types of information, including spatial and nonspatial data, required for roadway construction planning. This paper proposes a GIS-based system for improving roadway construction planning with its “interactive space scheduling” and “operation level planning” functions, which are supported by the integration of various data required for planning. The proposed system can assist construction planners in a unique way by integrating design and construction information and creating modularized design elements for space scheduling in real time using its interactive space scheduling function. In addition, operation level planning on earthwork can be conducted via the ability of the system to analyze haul routes in three dimensions and selecting the best equipment combination. It is expected that the proposed system could improve the efficiency of roadway construction planning.

Key words: geographic information system (GIS), roadway construction planning, information integration, space scheduling.

1. Introduction

The planning process for roadway construction involves a large amount of information on design and construction. Construction schedules have to be developed based on the work quantity and the production rates of the selected construction methods. Cost estimation as a part of the planning process also requires obtaining and combining work quantity from the design data and the unit cost data. Although some portion of roadway construction plans can be performed at the activity level, with construction activities based on standard construction methods and crew data provided by estimating references such as Balboni (2004), or through a company’s own historical record, operation level planning should also be performed for certain construction activities. Operation level planning, as opposed to activity level planning, involves the selection of resources such as equipment, labor, and material to perform construction activities that take into account construction site conditions and other factors that could affect construction productivity (Halpin and Woodhead 1998).

Various types of information are required for roadway construction planning, and different sources and (or) tools are currently used to deal with them, as shown in Table 1.
is the responsibility of the planner to acquire, manage, and assemble the necessary information from various sources to produce a construction plan. For example, the operation level planning of earthmoving operation would require that the planner obtain the quantity of earthwork from computer-aided design (CAD) data, determine remotely located loading and dumping sites based on maps and associated geological site information, and select proper equipment based on equipment performance charts to finally come up with unit cost and production rate of the earthwork activity. The compiled unit cost and production rate data and the information on the job conditions should, in turn, be saved in a historical construction database for future reference of earthwork activities of similar conditions. Therefore, there is a need to create a tool to acquire, manage, and assemble the necessary information for planning of roadway construction more efficiently to make better and timely decisions on how to complete a construction project. Information technology (IT) can be the solution to this problem.

The roadway design process has benefited greatly from IT via the use of CAD–CAE (computer-aided engineering) tools. As a result, most design data are created and stored electronically; however, the full potential of these data is not being used in construction planning. In recent years, especially in the building and industrial construction field, there has been great improvement in the integration of design and construction information to use the digitized or CAD data at the construction planning stage (Yau 1992; Marir et al. 1998; Cheng and Yang 2000). These approaches mostly deal with data modeling and (or) design of database management systems (DBMS) to connect design data and construction data under a digital environment. CAD platforms that can manage the integration of nongraphic construction data are also in use (Koo and Fischer 2000; Bentley Systems Inc. 2001). Visualization tools for dynamic construction processes became very valuable to planners by providing them with intuitive information and enabling them to make better plans and decisions for construction. The reason why such approaches are usually applied to building and industrial facilities is due to the modularized nature of the component data used in their construction, such as columns, beams, and pipes, which makes the integration of design and construction information more feasible without creating too much additional work for the sake of information integration. On the contrary, these approaches don’t seem to be very attractive to the roadway construction arena. This is mainly due to the difficulty of using roadway data to create modular design components that can be linked to construction information such as unit cost and production data for a certain construction plan. This also means that creating a new design component rather than selecting, assembling, and (or) decomposing an already modularized design component is necessary to accommodate changes in roadway construction plans. Furthermore, roadway construction planning, especially the earthwork portion, generally involves operation level planning aspects that deal with construction resource and site information intensively. This makes tools such as discrete event simulation programs, which explore various combinations of construction resources (Halpin and Riggs 1992; Shi and AbouRizk 1997), more attractive to planners of roadway and other heavy construction.

The geographic information system (GIS) is an excellent platform to develop an automated and IT-based tool for construction planning due to its strong capability of integrating and managing various types of information, such as spatial and nonspatial data, required for roadway construction planning. Attempts to utilize digitized design data for construction planning via GIS have also been made in the roadway construction field recently (Hassanein and Moselhi 2002). A GIS-based system for improving roadway construction planning is presented in this paper. The proposed system improves the roadway construction planning process in a unique way with its “interactive space scheduling” and “operation level planning” functions, which are supported by the integration of the data required for the planning of roadway construction. The proposed system can improve the planning process by integrating design and construction information within the system and creating modularized design elements for space scheduling in real time using its interactive planning capability. The operation level planning function of the system is designed for the earthwork portion of roadway construction and is based on the three-dimensional (3-D) analysis of haul routes and the equipment selection procedure. It is expected that roadway construction planning can exploit IT more with the GIS-based paradigm suggested by this study. Three major work sections of roadway construction including pavement, earthwork, and drainage and other items were considered for this study.

### 2. GIS-based information integration for roadway construction planning

Generally, the GIS is defined as the skills, processes, and tools to store, query, modify, and analyze geographic–spatial data and related information to refine pertinent information and aid in decision making. Unlike traditional paper map information, digital map information stored in GIS can be utilized repeatedly, so various types of refined information can be generated by querying and handling both spatial and related nonspatial data. Similarly, roadway design drawings created in a digital environment such as CAD data can also be regarded as digital map information. CAD drawings are converted to GIS formatted files and used for construction planning purposes by integrating them with other types of spatial and nonspatial information in the proposed system.
2.1. Overall structure

The overall structure of the proposed system is schematically illustrated in Fig. 1. The system provides two important planning functions: interactive space scheduling and operation level planning. These two functions are supported by the information integration capability of the system. Two-dimensional (2-D) CAD drawings with the roadway geometry design information are converted to several shape files, which are a type of GIS formatted file, according to geometry such as points, lines, and polygons. The converted shape files contain spatial feature attribute tables with the shape features. Digital topographic maps and aerial photographs of the construction site and the surrounding area are also fed into the system and overlapped on the shape files to provide visual feedback to the planner.

Activity level planning is performed with the interactive space scheduling function. The spatial features identified or created by the interactive space scheduling function of the system are integrated with nonspatial attributes such as activity assemblies, unit costs, production rates, and other pertinent construction data. The system then generates a table containing activity lists with quantities, costs, and durations. This table can be connected to commercial scheduling software such as Primavera™ and MS-Project™ for the critical path method (CPM) scheduling. After CPM scheduling (for example, calculation of early start date and early finish date), the date information is returned to the system and connected to corresponding design elements by the system, enabling visualization of the activity sequences.

The operation level planning function of the system is designed for earthwork planning only. It is often difficult to use the production rate and the unit cost of standardized equipment combination for earthwork from estimating references because of various site conditions. Therefore, this system function lets the user identify haul routes for earthwork, and it recommends the best earthwork equipment combination along with the calculated cost and duration for earthwork based on 3-D analysis of the work site and equipment information integration.

2.2. Spatial attribute table

CAD drawings utilized for the planning process are 2-D layout drawings that provide the plan view of the construction elements. The construction elements of typical roadway design drawings are included in Table 2. As shown in Table 2, three major work sections are considered: pavement, earthwork, and drainage. These construction elements in CAD drawings are represented by geometric types such as points, lines, and polygons. The construction elements of work sections are classified and stored in separate shape files according to their geometry. For example, a pavement area in CAD drawings represented by lines is adjusted and converted to a pavement shape file with polygon geometry for area calculation. The spatial attribute tables are automatically generated after CAD drawings are converted to GIS-formatted shape files. The tables contain both conventional feature attributes, such as object identification number, area, and length, and shape features such as the coordinates of the
shape components. This set of data along with user input (e.g., pavement thickness) become the base information for work quantity takeoff.

2.3. Nonspatial attribute table
Additional data not included in the spatial attribute tables are required for generating activity lists with calculated quantities, durations, and costs and determining the best equipment combination for earthwork. The nonspatial attribute tables are composed of information about construction activities and equipment. The “activity assembly” table contains the detailed activity lists associated with the graphic objects of the shape files. The “activity information” table contains the unit cost and the production rate data used to calculate cost and duration of activities based on the work quantity of the design information. The “equipment information” table is used when deciding on the best equipment combination and calculating cost and duration for earthwork. Further details on the nonspatial attribute tables are included in subsequent sections.

2.4. Planning process
Figure 2 shows the planning process with the proposed system. The planner conducts the activity level planning with the interactive space scheduling function for pavement, earthwork, and drainage based on standard crew data. The order of activities is arranged by the precedence relationship input by the planner. For earthwork, the planner can further decide whether operation level planning would be required. If operation level planning is performed, the activity list table is updated with cost and duration data obtained from the operation level planning. Upon acceptance of the activity list, the generated activity list table and the earthwork resource information table become the output of the planning system.

3. Interactive space scheduling

3.1. Space scheduling and activity lists generation
Buildings and industrial facilities such as plants can be easily modularized into components such as columns, beams, and pipes, which makes the connection between modularized design elements and associated construction information within a digital environment convenient. Roadway design components are not easily modularized, however. The proposed system, therefore, provides an interactive space scheduling function with which the planner modularizes roadway design data in real time. This function has an important meaning in that the planner is able to divide 2-D roadway graphic objects in real time and connect them with construction information to create activity lists for the modularized construction elements. After activating a shape file of interest such as pavement, the planner can divide the graphic objects directly as shown in Fig. 3. The system then identifies the intersected region as a new graphic object, which enables the system to generate activity lists, quantities, and costs by connecting the divided graphic objects and nonspatial attributes as shown in Fig. 3.

A graphic object selected by the planner is connected to one of the construction elements with activity assemblies. The activity assembly table contains the activity lists that can be associated with the graphic objects of the shape files. For example, as shown in Fig. 4, the activity assembly table shows that the polygon which represents “concrete pavement” has two construction activities, namely “aggregate base” and “concrete.” The system aids the process with various construction element options so that the planners can easily connect the graphic object with the proper activity assembly. The construction element is the key field that provides the connection between a graphic object and an activity assembly. Detailed data such as unit cost and production rate in the prepared activity information table are used for estimating cost and duration of activities. All of the generated information is allocated to a new table. Figure 4 shows the process of quantity takeoff, cost estimation, and calculating duration of activities.

Figure 5 shows a GIS map screen of an example roadway with all the construction elements activated. The planner can activate construction elements of interest only. As shown in Fig. 6, the planner can create a modularized design element.
instantly by selecting the pavement portion. Two construction activities of pavement activity assembly are then created with duration and cost information.

The generated activity lists can be directly transmitted to commercial scheduling software. After finishing detailed CPM scheduling, the planner can get a detailed schedule ta-
ble including the start date and the finish date of activities. This detailed schedule table is connected again to the spatial attribute table of the graphic objects by the system to visualize and analyze activity sequences. The system demonstrates activity sequences by changing the color of graphic objects based on the date criterion input by the planners. The planners can then review the sequences intuitively in real time; if there is something wrong with the sequences, the planners can modify the detailed schedule immediately. Figure 7 shows an example screen of the activity sequence visualization. The aforementioned spatial and nonspatial information is integrated by the system modules customized in ArcMap Visual Basic Application with the ArcObject library. The details on the development environment for system implementation are given in Sect. 5.

3.2. Space scheduling for earthwork

Planners have to consider earth volume when they divide an earthwork area with the space scheduling function. The system calculates cut or fill volume between two successive stations based on the mass diagram and lets the planners plan on cross-haul, spoil-bank, borrow fit, etc. Typical CAD-based roadway design output includes the mass-haul diagram and the cut–fill boundary. Therefore, the mass-haul diagram was utilized instead of extending the system functionality for earthwork volume calculation based on 3-D terrain analysis. The mass-haul diagram information can be easily stored in the system by inputting the station and cumulated earth volume data.

The space scheduling method described previously is also applied for earthwork. The planner activates the cut–fill boundary as the earthwork construction element. The planner then selects the earthwork area with the user polygon as shown in Fig. 8. In case the planner defines a volume-balanced area, the system provides balanced volume and average haul distances. The planner is then able to connect equipment information to the graphic objects so that the cost and duration for earthmoving can be calculated. In other cases it is necessary to waste excess cut material at the spoil-bank or borrow deficit from the borrow-fit. The system, then, offers the planners an excess or deficit volume to complete operation level planning, including haul route planning.

4. Operation level planning on earthwork

An earthmoving plan involves making many decisions, such as selecting equipment, determining equipment combination, and route planning. The proposed system supports the decision-making process with the operation level planning function for earthwork based on a 3-D analysis of digital topographic maps. This system function is achieved through the use of three modules. The first is the “module for 3-D analysis of haul route,” which conducts 3-D analysis of haul route grade and provides the planner with haul distance, speed, and time. The second is the “module for calculating equipment production,” which calculates the productions of loading and hauling equipment. The third is the “module for analysis of duration and cost,” which calcu-
Fig. 6. Example of space scheduling.

Fig. 7. Activity sequence visualization.
lates the duration and cost required for earthwork. In this paper, hoes and trucks are considered for operation level planning on earthwork as typical loading and hauling equipment. Figure 9 shows input and output data flow of three modules for operation level planning on earthwork. Details on the input and output data and the equations of each module are described in the following sections.

4.1. Three-dimensional GIS data model triangulated irregular network (TIN) and aerial photographs

A triangulated irregular network (TIN) is a vector data structure that depicts geographic surfaces as contiguous non-overlapping triangles. It is represented by triangles, with each triangle face having an approximate slope, aspect, and surface area. The irregularity of the triangles comes from the...
scattered nature of the \((x, y, z)\) points used as a background elevation source. TINs not only provide the system with the basic materials for a 3-D analysis of haul routes but also have a good visual effect for the planning system. The system also takes aerial photographs. The photographs are overlaid on the spatial feature data. The photograph and TIN, along with the spatial and nonspatial data of the proposed design work, are intended to provide the planner with an immediate and intuitive understanding of on-site and local conditions. Therefore, the planner is able to complete operation level planning on earthwork with visual feedback of on-site conditions by using the three modules.

4.2. Module 1: 3-D analysis of haul route

The planner is expected to draw haul routes or select one of the existing roads for hauling equipment with the interface of the proposed system. The system automatically generates the profile graphs of haul routes as shown in Fig. 10 based on the “3-D analysis of haul route,” and the system identifies points with slope changes to determine the varying grades of the haul route with eq. [1] and Fig. 11:

\[
\text{grade}(n) = \frac{\Delta Z(n)}{\Delta D(n)} \times 100
\]

where grade\((n)\) is the grade of the \(n\)th slope (in %); \(\Delta D(n)\) is the horizontal difference in the \(n\)th slope; and \(\Delta Z(n)\) is the vertical difference in the \(n\)th slope.

Haul speed is determined by rolling resistance (wheel resistance), which depends on the surface condition of haul routes and wheel types, and grade resistance, which is determined by the slopes of the original ground. Haul speed is a function of total resistance, which is the sum of rolling resistance (\%) and grade resistance (\%) (Peurifoy and Schexnayder 2002):

\[
\text{total resistance} = \text{rolling resistance} + \text{grade resistance}
\]

The system calculates the time required for hauling based on the average haul speed (in km/h) and the average return speed (in km/h) acquired from the total resistance – speed tables that are prepared based on the performance handbooks of equipment dealers (Caterpillar Inc. 2000).

4.3. Module 2: calculating equipment production

Truck cycle time is the sum of load time, haul time, return time, and wait time. While load time, dump time, and return time are not likely to change, haul and return times are susceptible to haul distance, meaning haul and return times are the key factors that determine truck cycle time. Haul distance and speed are required to calculate haul time. Thus, the planner can identify haul distance and speed through the system’s 3-D analysis of haul route and calculate truck cycle time, \(C_{\text{mT}}\) (in minutes):

\[
C_{\text{mT}} = \text{load time} + \text{haul time} + \text{dump time} + \text{return time} + \text{wait time}
\]

The planner is expected to choose loading and hauling equipment and to input percent swell, shrinkage, and wet density into the computer system. The system subsequently
calculates productions of equipment based on eqs. [4] and [5] and presents the number of trucks required to keep the loading equipment working at capacity based on eq. [6]. The cycle time of hoes under average conditions is in the range of 17–24 s (Peurifoy and Schexnayder 2002). Truck production $Q_T$ (in m³/h) is calculated as

$$Q_T = \frac{60 \cdot q_t \cdot f \cdot E_T}{C_{mT}}$$

where $q_t$ is the truck capacity (in m³), $f$ is the percent swell and shrinkage, and $E_T$ is the truck efficiency. Hoe production $Q_H$ (in m³/h) is calculated as

$$Q_H = \frac{3600 \cdot q_h \cdot K \cdot f \cdot E_H}{C_{mH}}$$

where $q_h$ is the hoe capacity (in m³), $K$ is the hoe fill factor, $E_H$ is the hoe efficiency, and $C_{mH}$ is the hoe cycle time (in seconds). The number of trucks required $N$ is calculated as

$$N = \frac{Q_H}{Q_T}$$

4.4. Module 3: analysis of duration and cost

Module 3 calculates the required duration and cost of earthwork for each route with earth-volume data and the results of equipment production calculated by the previous modules based on eqs. [7] and [8]:

$$\text{duration} = \frac{V_e}{(Q_H \times 8)}$$

where duration is the integer in days required to finish the earthwork, and number $V_e$ is the earth volume (in m³); and

$$\text{cost} = \text{unit cost of equipment combination} \times V_e$$

where cost is the cost in Korean won required to finish the earthwork, and the unit cost of equipment combination is given in won/m³.
The planner is then able to select a preferred equipment and route combination among various options based on the calculated duration and cost of each equipment combination.

4.5. Example analysis

An example of route and equipment selection for earthwork is presented in this section to demonstrate the system’s operation level planning capability and explain the details of the module calculation. We assume that excess earth is disposed from the construction site at point A to the spoil bank at point B, and two routes (route 1 and route 2) are considered as shown in Fig. 12. Table 3 shows the assumptions in relation to the road conditions and the rolling resistance for the analysis.

Figures 12 and 13 show the result of module 1 (module for 3-D analysis of haul route). As indicated in Table 3 and Fig. 12, route 1 is a poorly maintained earth way, and route 2 is a street with smooth concrete passing through the city area to the spoil bank. The planner can immediately recognize the vertical profile of each route from the graphs in Fig. 12. In the case of route 1, the average speed is calculated at 20.22 km/h, and it takes 28.40 min to haul and return. In contrast, the average speed of route 2 increases to 42.81 km/h and the duration is reduced to 19.16 min. Although the distance of route 2 is longer than that of route 1, the total time of route 2 is less than that of route 1 because route 1 has a greater grade resistance and rolling resistance than route 2.

Production of hoes and trucks is calculated in module 2 (module for calculating equipment production). This module requires several user inputs such as percent swell and shrinkage and wet density of soil. The system calculates the production of each piece of equipment with the input data and the result of module 1. As shown in Fig. 14, production of the hoe and truck is 72.58 and 11.99 m³/h, respectively, when a 0.7 m³ hoe and 15 ton dump truck are selected as the loading and hauling equipment and route 1 is considered. The module also calculates and presents the number of trucks per hoe to keep the hoe working at capacity, based on eq. [6].

Figure 15 is the result screen of module 3 (module for analysis of duration and cost of route and equipment combination). The planner can consider the available combinations of loading and hauling equipment. For this case study, three hoes and two dump trucks of different capacity were considered. Therefore, a total of six combinations of equipment are available for each route. Based on the number of trucks per hoe to keep the hoe working at capacity and the equipment production result by module 2, cost and duration of the equipment combination required to finish the earthwork are calculated, taking the considered routes into account. In this example, route 2 with a 2.0 m³ hoe and 20 ton dump truck would be the best choice because of the shortest duration.

Table 3. Assumptions for example analysis.

<table>
<thead>
<tr>
<th>Route name</th>
<th>Route condition</th>
<th>Rolling resistance (%)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Route 1</td>
<td>Earth, poorly maintained</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>Route 2</td>
<td>Smooth concrete</td>
<td>1</td>
<td>Along city area street</td>
</tr>
</tbody>
</table>

Fig. 13. Result of module 1 (3-D analysis of haul route).
and the lowest cost. The duration and cost results shown in Fig. 15 are based on the utilization of one hoe. The planner can select the number of hoes and consider the available workspace. The production of equipment combination increases in proportion to the number of hoes because the number of trucks per hoe to keep the hoe working at capacity applies to each hoe for equipment balance.

5. System implementation

A working prototype system has been developed under a Windows™ environment. The basic components of the system are ArcGIS, ACCESS, and MS-Project, which support functional modules of the system with their own fundamental functions. The user can communicate with the components of the system through custom interfaces, including forms, pop-up menus, and pull-down menus developed using Visual Basic for Application (VBA).

The system architecture shown in Fig. 16 is established at three main levels: application user level, function construction level, and data provision level. In the data provision level, all source data such as design drawings and construction information tables are prepared and adjusted for the
The CAD design drawings are converted to shape files, and the tables are constructed and stored in a standard dBASE file format on ArcGIS, which is GIS software to make maps, query data, analyze spatial relationships, and edit feature shapes and attributes. In function construction level, user interfaces and several functional modules such as interactive space scheduling and operation level planning modules are built on VBA by customizing some functions provided by ArcGIS. VBA works as an integral component of the desktop ArcGIS applications with the ArcObject library. The user can display converted CAD design drawings on the interface and handle and analyze shapes and attributes with the functional modules provided by the system at the application user level. It is also possible to directly connect the output information tables of the system to and from MS-Project™ for detailed CPM scheduling and activity sequence visualization.

6. Conclusion

This paper demonstrates that spatial manipulation, three-dimensional analysis, and information integration capability of GIS can be effectively used for roadway construction planning. The proposed system provides the planners with an interactive space scheduling function with which the planners can divide 2-D roadway graphic objects into construction stage modules so as to conduct quantity takeoff and calculate duration and cost of construction elements. It is also possible to conduct operation level planning for earthwork with the proposed system based on the capability of the system to perform 3-D analysis of haul routes and equipment selection. Planners can identify haul speed, cycle time, and productions of hauling equipment using contours from digital topographic maps in a GIS environment. In addition, the system’s visualization function enables the planners to review the construction plans intuitively and immediately by querying the graphic objects. The application of the system is designed for the roadway portion of highway construction projects. Future extensions to the system could include system features that extend functionality to structures such as bridges and tunnels. A four-dimensional (4-D) system might be utilized for bridge structures along with the proposed system because a 4-D approach is more appropriate for structures that are composed of modules. GIS might also be a platform for 4-D applications in the near future with the growing capability of GIS in 3-D manipulation. In that case, a stand-alone GIS system for the planning of roadway and structural portions of highway projects altogether could be considered.

References


