GIS-Based Cost Estimates Integrating with Material Layout Planning

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Abstract: This study is focused on developing an automated site layout system for construction materials. The system, MaterialPlan, including a geographic information system (GIS) based cost estimates system integrated with material layout planning, is a new tool to assist managers in identifying suitable areas to locate construction materials. As tabulation of all project quantities is calculated using GIS, linkages are established between the graphical features of detailed design and the related estimating quantities. Based on information regarding quantities and locations of the materials required in the project, this study identifies the suitable site to store the materials. Using the concept of ''searching by elimination,'' the system develops a heuristic approach, modeling the process of human decision making to generate potential sites for placing the materials. An objective function called the proximity index is developed to determine the optimal site. In conclusion, MaterialPlan demonstrates that GIS is a promising tool for solving construction layout problems and thus opens up a new way of thinking for the management of spatial information in construction planning and design.

INTRODUCTION

Although the construction industry has seen many major technological changes, the industry still remains highly labor intensive, decentralized, and dependent on uncertain economic and working environments. Nevertheless, many owners and contractors are making improvements in management and technology, regardless of the short-term uncertainty inherent in this industry. To stay competitive in the long run, evolutionary change must be introduced. A recent development occurring in construction management and technology is materials management, which is growing in importance and visibility. The importance of materials planning to construction costs, scheduling, quality, and operations efficiency is receiving increasing attention in the construction industry. Effective management of materials at the construction site can contribute significantly to the success of a project. This was substantiated in a series of studies related to materials management, sponsored by The Business Roundtable and the Construction Industry Institute Austin, Tex. (''Reports'' 1983; *Project* 1987). These studies stated that the most important contribution of improved materials management is toward increasing construction labor productivity, and a conservative estimate of 6–8% improvement is likely.

Progress in computerization and other automation techniques provides a great opportunity for improvement in construction materials management. Currently, the computer-aided design (CAD) system is widely used in engineering for drafting and design. As these CAD systems evolve, they are capable of generating materials requirements during the drawing phase and can be used to produce takeoff quantities. The benefit associated with this type of system is that a detailed takeoff of required quantities can be obtained directly from the CAD system, thereby eliminating the need to perform a detailed manual takeoff. However, because of the CAD system constraints of aggregating and distributing databases between locational and thematic attributes, the containing information, such as materials types, quantities, location demands, and need dates, within the system cannot be automatically extended and reused in the construction phase for material planning purposes. The geographic information system (GIS), which combines a CAD-like design program with a relational database management system for spatial data analysis, appears to have potential in solving these problems. By replacing CAD with GIS, the bill of materials (BOM) is generated based on the dimensions of the design drawings, thus incorporating a linkage of locational and thematic information. The information integrated with construction scheduling is invaluable for construction materials management and layout planning.

The concept of continuous data acquisition and life-cycle support is applied in this study to demonstrate the feasibility of using GIS for materials quantity takeoffs and continuously passing the retained information into the construction phase for materials management. The objective of site materials management is to ensure that materials are available, when required, to meet the construction schedule (Kini 1999). The primary functions of the system include purchasing, receiving, warehousing, inventory control, materials distribution, and providing efficient, low-cost transport, security, and materials storage on construction sites for project completion. The information required for materials management is not only generated by various participants in different construction phases but also stored in different forms including graphics, text, tables, or various combinations of the three. To develop materials management planning, the project manager has to continuously excerpt information from various resources and draw it on paper. Without adequate staff and time, this repetitive and tedious process is difficult for the project manager to handle properly and thus reduces the effectiveness and quality of the planning process. To solve these problems, the system MaterialPlan, including GIS-based cost estimates integrated with materials management, has been developed to assist managers in effectively organizing and continuously reusing information for materials planning.

In this study, GIS-based cost estimates integrated with materials management can be classified into two categories: (1) integration of GIS-based cost estimates with materials requirements planning (MRP); and (2) integration of GIS-based cost estimates with materials layout planning. Because of limits regarding paper length, only the second part will be the major focus and discussed in more detail in this paper.

Warehouses and lay-down areas are temporary facilities located on construction sites to support operations. Efficient material site planning includes locating facilities such as warehouses, workshops, and storage yards to optimize material and equipment handling, travel distances, traffic interference, and the need for expansion and relocation (Hegazy and Elbeltagi

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1999). The primary concern in material site layout is to identify suitable areas within which to place materials. Ideally, materials are located as close as possible to their support activities to reduce travel time. However, the task of site layout has an interactive relationship with other planning tasks such as cost estimates, scheduling development, MRP, and financial analysis. The information required for materials layout planning is ill-structured when generated in different construction phases for various planning purposes and stored in different forms. How to collect and organize information related to site planning becomes a difficult task that project managers have to accomplish. In field practice, most designers lay out materials based on experience, common sense, and adaption of past layouts to present projects. Thus, it is difficult to detect layout problems if there are no conflicts or requirements to relocate materials. Also, dollars lost because of the lack of preplanning and the inefficiency of correcting mistakes ''after the fact'' can go undetected by management (Handa and Lang 1988).

Research Purposes and Objectives

The primary purpose of this paper is to identify the feasibility of applying GIS for cost estimates and effectively extending integrated locational and thematic information into construction phases to automate planning tasks required for materials layout. Based on GIS-based cost estimates, the objective of the developed system, MaterialPlan, is to identify the areas suitable for materials storage to minimize construction conflicts and improve project efficiency. The following four subobjectives were achieved in developing this system: (1) apply GIS for quantity takeoffs and incorporate a new application method in developing computer-aided cost estimates; (2) integrate GIS-based cost estimates with construction scheduling to develop a dynamic materials requirements plan (DMRP) and effectively extend through the construction phase for materials planning purposes; (3) define the dominant variables and develop an evaluation method to identify suitable locations for placing construction materials; and (4) develop a GIS-based material layout system integrated with DMRP to replace manual methods.

Scope Definition

The system, MaterialPlan, including GIS-based cost estimates integrated with materials management, was developed to design materials site layout. A house-building construction project is selected as the case study of this approach; thus, the similar processes and flow diagrams could be adopted to other construction projects of a different nature. The usage and functions of the system are identified below:

- The proposed system works on an IBM PC 586 and uses the popular existing GIS software package Map/Info as a system model.
- For materials planning purposes, the control estimate is developed using GIS. The possible use of the system includes turnkey projects or general contractors who use GIS for quantity takeoffs.
- The work packages involved in GIS-based quantity takeoffs include structural and interior constructions. The GIS-based quantity takeoffs of structural elements include formwork and concrete. Rebar quantity is calculated using Excel spreadsheets. Using the same methodology and algorithms with appropriate modifications, MaterialPlan can be applied to most construction activities for quantity takeoffs.
- The system provides the capability to track a material layout as it changes over time.
- The system generates alternative solutions.
- An objective function has been developed to optimize the generated solutions.
- Ease of user interface, system inputs/outputs, and system transparency were considered in product development.

Considerations of temporary facility construction cost, permanent facility site arrangement, on-site material and equipment transport routing, and heavy equipment locations are beyond the scope of this study. However, it would be a worthwhile study to integrate these subjects with materials management planning to assist the project manager in the decision-making process.

GIS-BASED COST ESTIMATES

Analytical Process

This section discusses cost-estimating procedures using GIS. The procedures, as shown in Fig. 1, are classified into four steps.

Step 1: Data layer classification—The purpose of data layer classification is to determine how many layers will represent the architectural design for cost estimating. Using the object-oriented concept, the data layers, as shown in Fig. 2, are classified according to the basic design components constituting the architectural design. The basic design layers required for cost estimates include column, beam, interior wall, exterior wall, and slab. The beam geographies are further classified into main-beam and subbeam coverages.

Step 2: Coverage modeling—After creating the design geometry using AutoCAD and transferring the DXF file to a Map/Info geometric coverage, coverage modeling introduces the process of creating the topologic structure and related da-

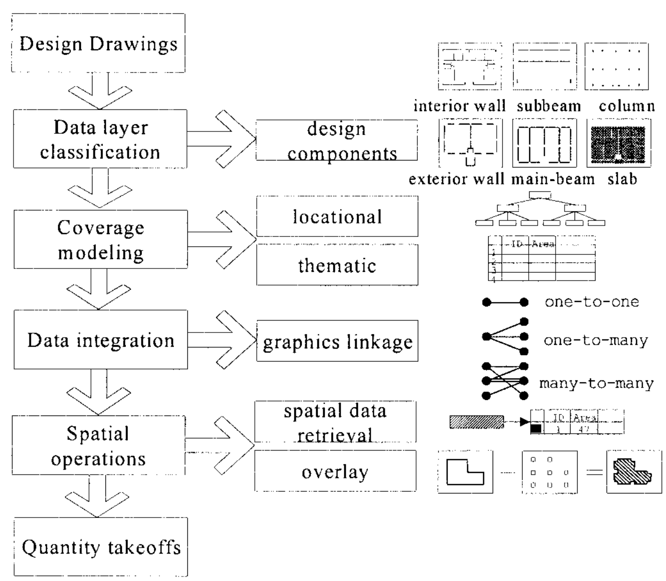

FIG. 1. GIS-Based Cost Estimates Analytical Process

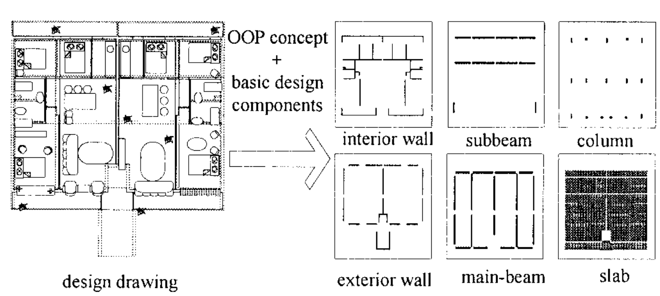

FIG. 2. Architectural Design Components

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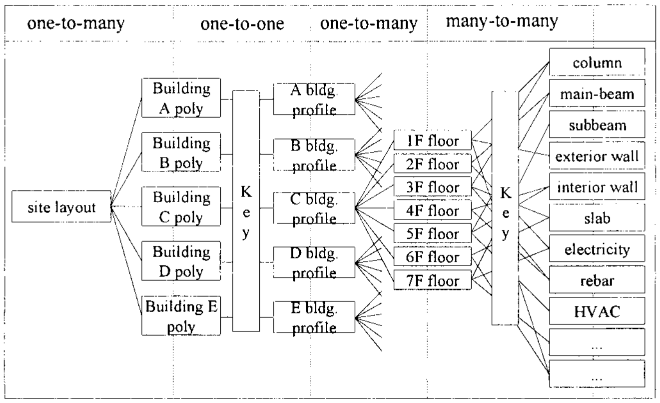

FIG. 3. Graphic-to-Graphic Linking Relationship

tabases. For GIS-based cost estimates, the basic parameters required for quantity takeoffs are area and perimeter. Thus, the topologic data structure of the basic design layers is created as polygons. The attributes needed for each layer in the database for cost estimates consist of two types of information: locational and thematic. Locational information including spatial features such as coordinate, area, perimeter, and spatial relationship are derived from the creation of the coverage, whereas thematic information involving the identification (ID) code, district, floor number, etc., describe what these spatial features represent.

Step 3: Data integration—Data integration concerns integrating locational information with thematic information, thus generating the spatial relationship between coverage and the feature attribute table. GIS is a one-to-one linkage between a coverage feature and a data record. However, because of the complexity of cost estimates, the one-to-one relationsip is insufficient for quantity takeoffs. Thus, through key (or ID code) linkage, as shown in Fig. 3, the spatial relationship can be extended not only to one-to-many and many-to-many relationships but also to graphic-to-graphic and graphic-to-quantity queries, which are also shown in this study.

Step 4: Spatial operations—Spatial operations involve two types of processes, namely, retrieval of spatial data and topological overlay. The quantity takeoffs for different working activities require different spatial attributes such as coordinate, area, perimeter, length, and width. The process of spatial data retrieval is to acquire the attributes required for quantity takeoffs from a GIS-related database. Topological overlay functions such as coverage intersection, union, and extraction are used to identify the precise dimensions of the graphical features by extracting repetitious calculations of area or length.

Spatial Analysis of Graphical Features for Cost Estimate

As mentioned above, spatial operations involve a series of database queries and topological overlays. This section uses examples to describe the analysis procedures in more detail.

Retrieval of Spatial Data

The six basic data layers constituting an architectural design are the basis for GIS-based cost estimates. Different working activities require different spatial attributes for quantity takeoffs. The attributes needed for GIS-based quantity takeoffs in the study include area, perimeter, length, and width. The default spatial attributes, area and perimeter, are automatically generated when the polygon coverage is created. Based on the area, perimeter, and vertex coordinates of the graphical feature, the polygons are further broken down into lines; thus, the lengths of lines are identified. Fig. 4 shows an example to

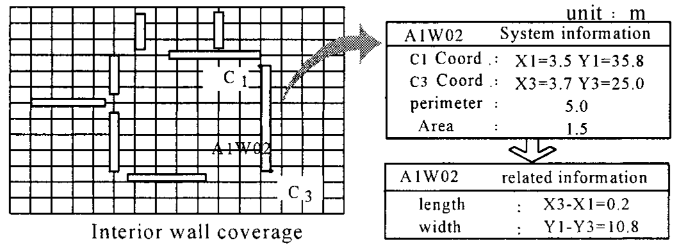

FIG. 4. GIS Geometric Dimensions Retrieval

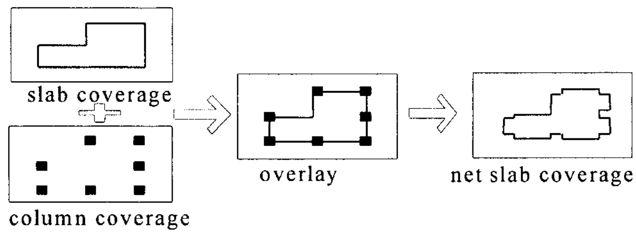

FIG. 5. Topological Overlay of Column and Slab Coverages

TABLE 1. GIS Spatial Operations List

spatial operations	commands	graphical illustration
1.area retrieval	Area	
2.perimeter retrieval	Perimeter	
3.length/width retrieval	ObjectNodeX ObjectNodeY	
4.net perimeter	Erase+Perimeter	− =
5.net area	Erase+Area	− =

retrieve the geometric dimensions of the brick wall, ID A1W02, from an interior wall design layer. The graphical features representing interior wall components are created as objects. The geometric dimensions of the polygons, such as area, perimeter, and coordinates, can be identified using the Map/Info commands Area, Perimeter, ObjectNodeX, and ObjectNodeY. Based on the coordinates of diagonal vertices, the length and width of the polygon are calculated. The quantity of the brick wall can be obtained by multiplying the length with the height of the wall.

Topological Overlay

The geometric dimensions of the polygons in a single layer are insufficient for calculating the quantities of the working activities. Map/Info overlay functions including intersection, union, and erase are used to identify the net dimensions of the graphical features by extracting repetitious calculation of area or length. Fig. 5, for example, shows the overlay of slab coverage with the column coverage to obtain the net slab area. The slab coverage is defined as editing coverage, whereas the column coverage is used as extraction coverage. By eliminating the areas occupied by the columns from the editing coverage, the net slab area is obtained. The commands Area and Perimeter are used to retrieve the area and perimeter of the slab. Table 1 shows the analytical process and commands used for acquiring the various geometric dimensions of the graphical features.

GIS-Based Quantity Takeoff Procedure

After identifying the dimensions of the graphical features, examples are demonstrated to describe the calculation process

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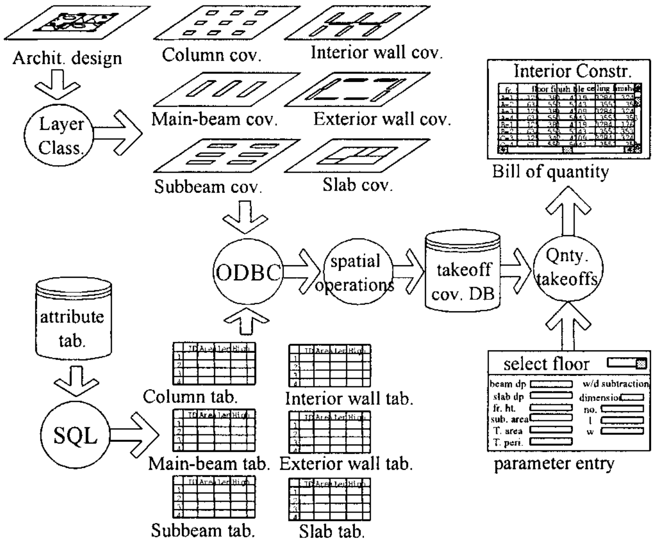

FIG. 6. GIS-Based Quantity Takeoffs Algorithm

for GIS-based cost estimates. Fig. 6 shows an overview of the calculation algorithm. Through data layer classification and coverage modeling, the six basic design layers and related attribute tables are created for analysis. The Structured Query Language (SQL) is used to retrieve the data required for quantity takeoffs from the related attribute tables. Data integration is achieved by applying the Open Database Connectivity (ODBC) technique provided by Microsoft Corp. Performing spatial operations involves coverage overlay to identify the required geometric dimensions of the graphical features. To complete the quantity calculation, the related parameters such as the depth of beam and slab, floor height, and area of door and window, are input by the user. Thus, an aggregated tabulation of quantities for different working activities is obtained.

GIS-BASED COST ESTIMATES INTEGRATING WITH MATERIALS LAYOUT

Although the bill of quantities is calculated using GIS, the linkages between the graphical features of detailed design and the related estimating quantities are also established. Integrating the construction schedule of working activities with the calculated quantities, a DMRP is developed. Based on the information regarding quantities, scheduling, and locations of the materials required for the project, this study identifies the area and suitable site to store the materials. Thus, the information obtained from GIS-based quantity takeoffs can be used not only to develop an MRP but also to plan materials storage layout. Fig. 7 describes how the takeoff quantity information is passed to the construction phase for material layout planning. The procedure involves four steps.

Step 1: Identification of materials storage space and location needs—The layout and size of lay-down areas and warehouse space will be completed prior to the construction of these facilities, as included in the construction schecule (Tommelein 1994). The DMRP integrating the BOM with scheduling work activities is developed to identify the space required for materials storage (Zouein and Tommelein 1999). Considering the average stock duration of the materials and the estimated quantity required per day, the periodic materials requirements plan (PMRP) is retrieved and aggregated from the DMRP. Through ODBC integration of PMRP with the site geometric features, the location requirements and materials quantities are determined.

Step 2: Spatial operations to identify the potential sizes—Using the concept of searching by elimination, the system develops an algorithm for generating the potential sites for placing the materials. Considering the constraints and selection criteria, MaterialPlan identifies the spatial relationship between the data layers that represent the site geographies (Valeo et al. 1998). The heuristic approach initiates a search of the available space to place materials and then eliminates the areas occupied by permanent facilities (PFs), working areas adjacent to the PFs, and areas closed for safety considerations. A number of alternatives that satisfy the search criteria are generated. In addition, MaterialPlan also provides users with the flexibility of changing the search criteria.

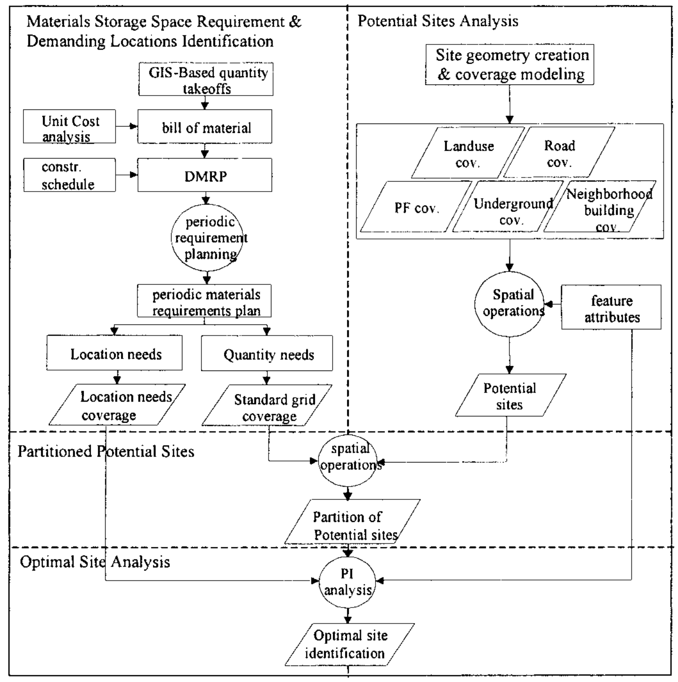

FIG. 7. System Design and Development Algorithm

Step 3: Partition of the potential site—Usually, the area of the potential site identified in Step 2 is much greater than the required area for materials storage. Further spatial operations to partition the potential sites are conducted using a grid coverage. The functions included for partition of the potential site entail (1) generation of the grid coverage; and (2) spatial operation to partition the potential site.

Step 4: Proximity index (PI) analysis to identify the optimal site—Initially, the dominant constraints have to be determined to identify the optimal site. Based on the constraints and the supply-demand of materials transport distance and frequency, an objective function for calculating a facility PI was developed to rank the partitioned potential sites. This objective function is used to identify the optimal site. In addition, MaterialPlan allows users to select their preferences of the partitioned potential sites.

Material Storage Space Requirements and Identification of Location Needs

Dynamic Materials Requirements Planning

Hierarchy Analysis of Construction Scheduling. When the quantity takeoffs using GIS are completed, the next step in the planning process is to define the various work tasks that must be accomplished. These work tasks represent the necessary framework to permit scheduling of construction activities, along with the estimated material quantity required by the individual work tasks. The terms work ''packages,'' ''tasks,'' and ''activities'' are used in this study to refer to specifically defined items of work. The scheduling problem concerns deter-

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mining an appropriate set of activity start times, materials allocations, and completion times that will result in completion of the project in a timely and efficient manner. The number and detail of activities in a construction plan can depend on a matter of either judgement or requirement. Construction plans can easily range from <100 to thousands of defined tasks, depending on the planner's decisions and scope of the project. If the subdivided activities are too refined, it is not beneficial when reasonably accurate estimates of activity durations and required resources cannot be made at the detailed work breakdown level. On the other hand, if the specific activities are too coarse, it is impossible to develop realistic schedules and details for resource requirements during the project.

The work breakdown structure is designed to describe the work elements of a project in a logical hierarchy that can be applied at various levels to structure schedule planning. For material planning purposes, the hierarchy of the work breakdown structure is developed in three levels, namely, main schedule, subschedule, and detailed schedule (as shown in Fig. 8). The work packages involved in the main schedule include foundation, structure, and interior constructions. This division is based on the major types of design elements to be constructed. The subschedule work tasks are derived from dividing the work packages based on the building code. In dividing the structural work packages, for example, a further subdivision is into rebar, formwork, and concrete of each building. Within the rebar subdivision, detailed scheduling activities for rebar according to the number of floors are identified.

Integration of Bill of Quantities with Scheduling Work Tasks. Integrating the bill of quantities with the scheduling work tasks involves two processes: (1) unit cost analysis for the bill of quantities; and (2) integration of BOM with scheduling work activities.

Unit Cost Analysis for Bill of Quantities. The individual items within the bill of quantities are deemed to include the following elements of cost: labor, material, and equipment. For any measured item of work within the bill, the unit cost must contain one, two, or all three of these resources. Each element is normally priced separately in accordance with the stated unit of measurement for each item, and the individual costs are then added together to represent the total anticipated net cost to the contractor of carrying out each unit of the work described.

Materials takeoff is specially addressed in this study for material planning purposes. The quantities of materials required for works as itemized in the bill are broken down and identified. These takeoffs, when multiplied by the quantity measured, produce the total materials requirement quantities of

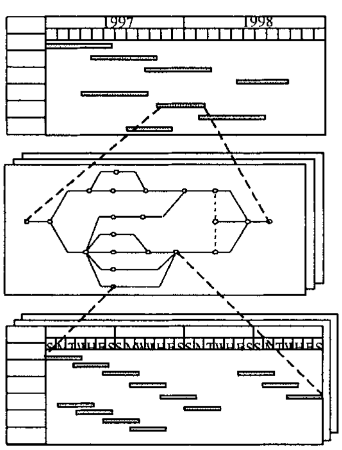

FIG. 8. Hierarchy of Work Breakdown Structure

Bill of Quantity

floor	item	item code	Qnty
A_1	wall finish	rep01001	250
A_1	floor finish	rep01002	120
A_1	ceiling finish	rep01003	150
A_2	wall finish	rep01001	250
A_2	floor finish	rep01002	120
B_1	wall finish	rep01001	275
B_1	floor finish	rep01002	145
B_2	wall finish	rep01001	275
B_2	floor finish	rep01002	155
C_1	wall finish	rep01001	200

Unit cost

mat'l code	item code	mat'l	unit	Qnty
mat01001	rep01001	cement	bags	0.195
mat01002	rep01001	sand	m^3	0.015
mat01003	rep01001	waterproof	gals	0.4
mat01004	rep01001	rapid set	each	1
mat02001	rep01002	cement	bags	0.3
mat02002	rep01002	sand	m^3	0.03
mat02003	rep01002	waterproof	gals	0.04
mat02004	rep01002	rapid set	each	1

Bill of Material

floor	mat'l code	item code	mat'l	Qnty
A_1	mat01001	rep01001	cement	48.8
A_1	mat01002	rep01001	sand	3.75
A_1	mat01003	rep01001	waterproof	100
A_1	mat02004	rep01001	rapid set	250
B_1	mat01001	rep01002	cement	43.5
B_1	mat01005	rep01002	sand	4.35
B_1	mat02001	rep01002	waterproof	5.8
B_1	mat02004	rep01002	rapid set	145

FIG. 9. Development of BOM

Schedule

NO	floor	item code	start date	finish date
1	A_1	rep01001	85/3/5	85/3/17
2	A_1	rep01002	85/2/26	85/3/5
3	A_1	rep01003	85/1/12	85/1/25
4	B_1	rep01001	85/3/12	85/3/24
5	B_1	rep01002	85/3/5	85/3/12
6	B_2	rep01001	85/4/21	85/5/16

Bill of material

floor	Mat'l code	item code	mat'l	Qnty
A_1	mat01001	rep01001	cement	48.8
A_1	mat01002	rep01001	sand	3.75
A_1	mat01003	rep01001	W.P.	100
A_1	mat01004	rep01001	rapid set	250
B_1	mat02001	rep01002	cement	43.5
B_1	mat02002	rep01002	sand	4.35
B_1	mat02003	rep01002	W.P.	5.8
B_1	mat02004	rep01002	rapid set	145

DMRP

floor	Mat'l code	Qnty	use date
A_1	mat01001	48.8	85/3/5
A_1	mat01002	3.75	85/3/5
A_1	mat01003	100	85/3/5
A_1	mat01004	250	85/3/5
B_1	mat02001	43.5	85/3/12
B_1	mat02002	4.35	85/3/12
B_1	mat02003	5.8	85/3/12
B_1	mat02004	145	85/3/12

FIG. 10. Integration of BOM with Scheduling Work Activities

that work activity. Fig. 9 shows the example of materials takeoff and the establishment of the BOM.

Integration of BOM with Scheduling Work Activities. The DMRP, as shown in Fig. 10, is achieved by integrating the BOM with scheduling work activities. This consolidation becomes the quantity of materials needed to support the construction schedule for the work activity. With this type of information, the status of the required materials can be assessed and procurement activities adjusted to meet the field need dates. In Fig. 10, the start and finish dates of the work activities for each floor of the building can be derived from the scheduling tabulation and through key linkage of the tables, and the corresponding quantities of materials required can be retrieved from the BOM.

The consolidation of information, including material types, quantities, location demands, and need dates, makes DMRP an invaluable reference for conducting the material management process. The advantages of applying DMRP are described as follows:

1. For dynamic linking of scheduling tabulation with BOM, the DMRP can be changed in accordance with adjustments in the scheduling plan. Thus the data integrity, contingency, and accuracy are ensured.
2. Owing to GIS's ability to integrate graphical features and materials takeoff information, the design changes associated with adjustments of materials requirement quantities can be correspondingly reflected into DMRP. The

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goal of integrating GIS-based estimating data and material management information is thus achieved.

3. Based on the schedule, quantity, and locations of the needed materials that are identified, the project managers can plan and dispatch materials more efficiently and accurately.

Rules of Thumb and Experience for Sizing Materials Storage Area

Because of its complexity, determining the materials storage area varies from one company to another and sometimes even between projects within the same company. Most of the practices are based on an individual's experience, common sense, and adaption of past layouts to present projects. Adopting experts' experience, this study uses the general equation developed by Popescu (1981) to determine the materials storage area for any type of construction. Table 2 shows the parameters that constitute this equation. Using the equation, the total required storage area A_N, is computed as follows:

$$A_N = (Q_{\max}/I_m)/q_n \tag{1}$$

where $Q_{\max} = q_{\text{daily}} \cdot t \cdot k$; $q_{\text{daily}} = Q_{\text{total}}/T$; $Q_{\max}$ = maximum estimated quantity in storage space; I_m = utilization index for materials; q_n = quantity of materials that can be stored (m^2); Q_{total} = total quantity of materials required for the project; q_{daily} = estimated quantity required per day; T = construction period (not total project duration); t = average stock (days); and k = fluctuation factor 1–1.3.

According to the average stock duration, the periodic materials requirements quantity is retrieved and aggregated from the dynamic materials requirements table. The data referencing the parameters used in the equation are shown in Table 3.

The rebar storage yard, for example, is used to describe the calculation process for determining the required area for storage. Based on the average duration of the rebar stocked on site, the total quantity of rebar use for each period is calculated in the dynamic material requirement table. In Table 4 an excerpt from DMRP according to the district number classified in the project shows an example for estimating the quantity for rebar storage. The total duration of the rebar usage is the extraction of finish and start dates (as shown in Table 5).

Material item: rebar
Unit: ton
Average duration stocked on site: 75 days
Total quantity required: $Q_{\text{total}} = \sum$ (quantity received/time)
Daily quantity required: $Q_{\text{daily}} = Q_{\text{total}}/T$

In addition to these parameters, engineers determine the values of the rest parameters within the identified ranges. Table 6 shows the calculation results of the example.

TABLE 3. Parameter and Periodic Materials Requirement Referencing Table

Popescu equation parameters	Periodic materials requirement table
Q_{total}	Sum of quantity received per period
T	Finish date–start date

TABLE 4. Periodic Materials Requirement for Each Working District

Date	First district	Second district	Third district
February 10 to April 24, 1996	430	420	356
April 25 to July 9, 1996	1,018	966	921
July 10 to September 14, 1996	677	678	644
Sum, Q_{total}	2,125	2,064	1,921

TABLE 5. Rebar Construction Duration for Each District

Parameter	First district	Second district	Third district
Start date	February 10, 1996	February 17, 1996	February 21, 1996
Finish date	September 14, 1996	September 20, 1996	September 20, 1996
Duration T	217	216	212

TABLE 6. Required Rebar Storage Area in Each District

Parameter	First district	Second district	Third district
I_m	0.8	0.8	0.8
q_n	1.45	1.5	1.5
t	75	75	75
k	1.1	1.1	1.15
q_{daily} (t)	9.8	9.6	9.1
Q_{total} (t)	2,125	2,064	1,921
$Q_{\max}$ (t)	808	788	781
A_N (m^2)	696	657	648

Analysis of Materials Location Requirements

In practice, material storage yards and warehouses are located as close as possible to the work areas to reduce excess on-site transportation. This section deals with identifying materials location requirements based on the DMRP. According to the average stock duration, the PMRP is retrieved and aggregated from the DMRP. Through SQL query of the PMRP, as shown in Fig. 11, the quantity of the material required for each floor of the building is identified. The total quantity for each building is obtained by summing the number in the quantity column according to the building code. Then, ODBC is used to integrate the aggregated attribute table with the site's topographic features; thus, the materials location demands are recognized. Fig. 11 describes an example of identifying the monthly requirement for cement for each building and its spatial relationship. The proximity analysis is used to determine suitable sites for placing the materials.

TABLE 2. Parameters for Sizing Storage Area

Description	Delivery and storage method	Unit	Average stock t (days)	q_n (quantity/m^2)	I_m utilization factor	Waste (%)
Cement	Bags	ton	30	1.5–1.8	0.5–0.6	1.5
	Bulk	ton	30	—	—	0.5
Aggregate for concrete	Bulk	cubic meters	60	1.5–2.0	0.6–0.7	2.0
Bricks	Units	units	30	700–1,000	0.7–0.8	2–3
Concrete blocks	Pieces	units	30	75–100	0.7–0.8	3–3.5
Lumber	Pieces	cubic meters	45	1.7–2.6	0.6–0.7	2–3
Reinforcing bars	Bars	ton	75	1.3–1.5	0.75–0.8	1–1.2
Concrete pipes	Pieces	ton	30	0.8–1.1	0.6–0.7	1.0
Iron pipes	Pieces	ton	75	0.6–1.5	0.6–0.7	0.5
Fuel	Barrels	ton	30	0.5–0.7	0.7–0.8	1.0

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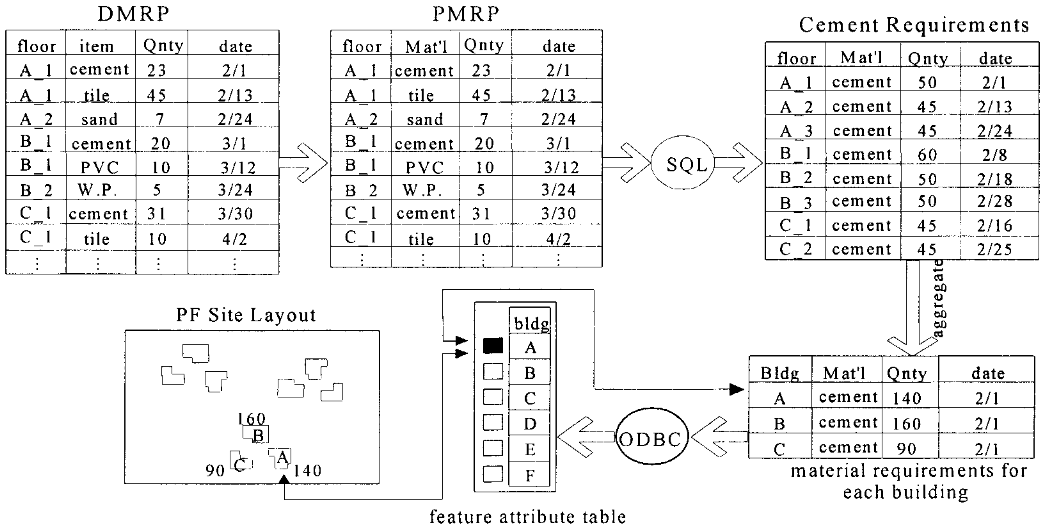


FIG. 11. Materials Location Needs Analysis

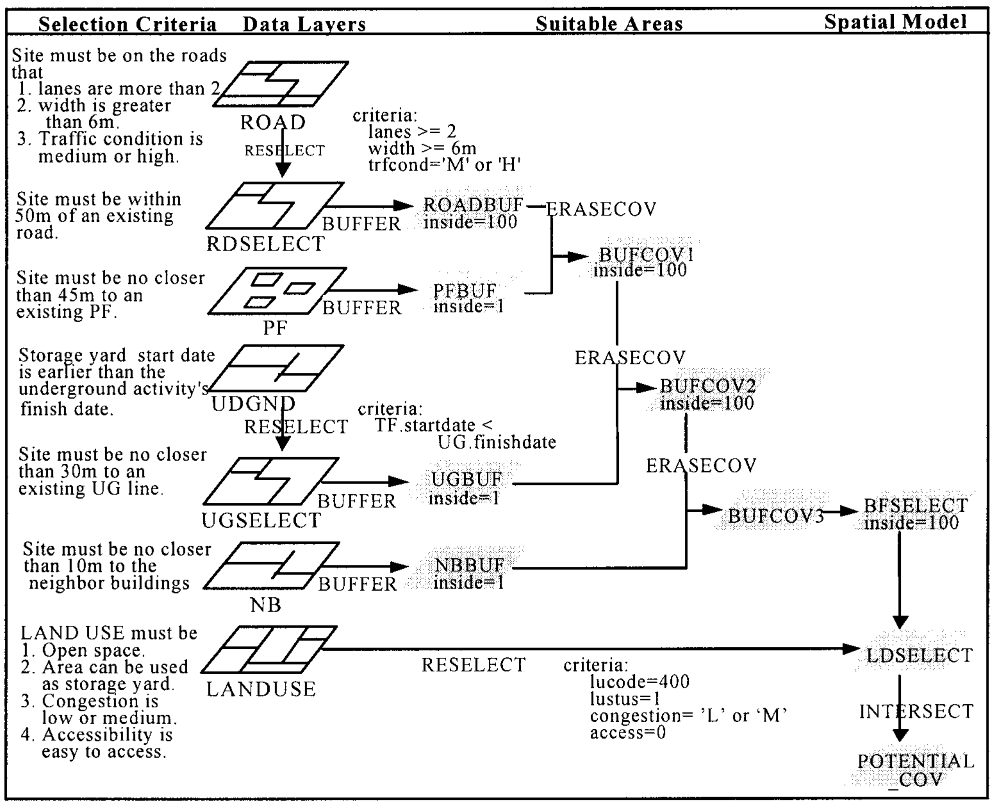


FIG. 12. Spatial Operations to Identify Potential Sites for Materials Storage Yard

Spatial Operations to Identify Potential Sites

MaterialPlan generates potential sites using the concept of searching by elimination. The available space for placing the construction materials is generated by buffering the access roads whose conditions satisfy the search criteria. By eliminating the areas occupied by the PF, the working areas adjacent to the PF, and the safety restriction areas of the buffer zone bordering the access roads, potential sites are obtained. A default algorithm was developed in MaterialPlan to generate these potential sites. However, the distances of working area, safety restrictions, and database query can be changed by the user. MaterialPlan provides the user with the alternative to locate the materials either within the PF or in the other open areas. Fig. 12 shows an example of generating the potential sites for locating materials in an open area. Referring to Fig. 12, the queries of the database and searching criteria are described in the "Selection Criteria" column. In the "Data Layers" column, the name of the basic operation coverage is listed under the rhomboid and the Map/Info operation command is listed between or under the arrow. There are five basic coverages, namely access roads (ROAD), PF, underground activity (UDGND), neighborhood buildings (NB), and land use (LANDUSE). Suitable areas represent the generated coverages containing enough space to satisfy the search criteria. The shaded rhomboid represents the coverage dynamically generated during the spatial operations.

Partition of Potential Sites

Usually, the areas of the potential sites identified are much greater than the required area needed for materials storage.

Further spatial operations to partition the potential sites are conducted using a grid coverge (Preas and Lorenzetti 1988). The two processes of generating the grid coverage and partitioning the potential site coverage to locate the materials within the site are discussed in detail.

Generation of Grid Coverage

After determining the material storage area, the width and height of the grid is calculated according to a ratio of 5 to 2. The software package AutoCAD is used to create the grid coverage. The coverage is saved as a DXF file and transferred to Map/Info for spatial partitions.

Partition of Potential Site Coverage

Spatial partitions involve topological overlay of two coverages, namely, grid and potential site. Fig. 13 shows the process of spatial operations. In the figure, the grids outside the potential sites are eliminated. The irregular shape polygons within the potential sites are also eliminated using the database query function. However, considering the error tolerance, the system allows the user to determine the search criteria of the polygon area. The partitioned potential sites are the areas in which to place the materials.

PI Analysis to Identify Optimal Sites

PI analysis is an objective function used in MaterialPlan to rank the potential sites and determine which is best. PI is calculated by summing the product of the distance and travel frequency between facilities. Travel frequency is defined as the trips or frequency that materials are transported between two facilities. Through GIS-based cost estimates and DMRP, the quantity needs, locations, and schedule of materials are identified. The supply-demand spatial relationship of the materials is obtained by overlaying the materials needs locations data layer with the partitioned potential site coverage. Then, the materials quantity needs are divided by the transport capacity between two facilities per trip to calculate the travel frequency. For each potential site, the PI can be described and calculated as follows:

$$\mathrm{PI\_}P_j = \sum_{i=1}^{m} D_{ij} \cdot Ri/Q_{\mathrm{mat}} \tag{2}$$

where n = number of potential partitioned sites; m = number

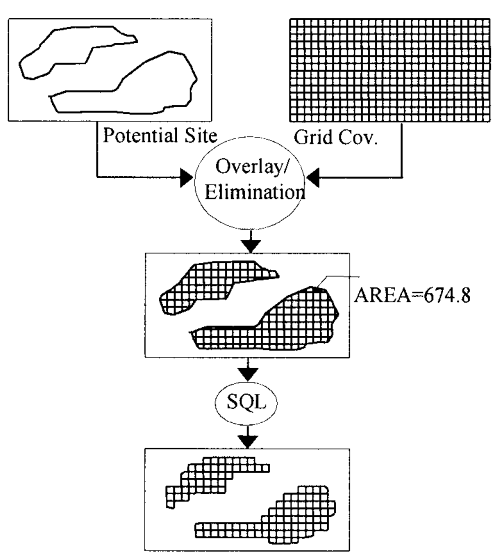
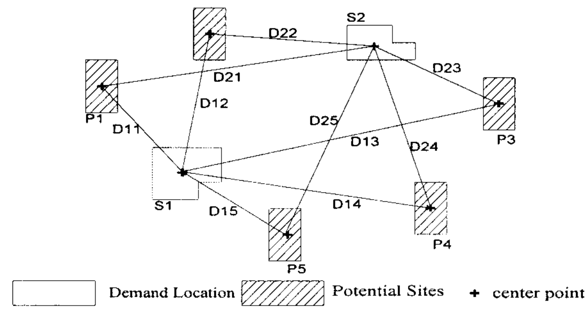


FIG. 13. Topological Overlay of Grid and Potential Site Coverage



$$\mathrm{PI\_P1} = \mathrm{D11} \times \left(\frac{\mathrm{R1}}{\mathrm{Qmat}}\right) + \mathrm{D21} \times \left(\frac{\mathrm{R2}}{\mathrm{Qmat}}\right)$$

$$\mathrm{PI\_P2} = \mathrm{D12} \times \left(\frac{\mathrm{R1}}{\mathrm{Qmat}}\right) + \mathrm{D22} \times \left(\frac{\mathrm{R2}}{\mathrm{Qmat}}\right)$$

$$\mathrm{PI\_P3} = \mathrm{D13} \times \left(\frac{\mathrm{R1}}{\mathrm{Qmat}}\right) + \mathrm{D23} \times \left(\frac{\mathrm{R2}}{\mathrm{Qmat}}\right)$$

$$\mathrm{PI\_P4} = \mathrm{D14} \times \left(\frac{\mathrm{R1}}{\mathrm{Qmat}}\right) + \mathrm{D24} \times \left(\frac{\mathrm{R2}}{\mathrm{Qmat}}\right)$$

$$\mathrm{PI\_P5} = \mathrm{D15} \times \left(\frac{\mathrm{R1}}{\mathrm{Qmat}}\right) + \mathrm{D25} \times \left(\frac{\mathrm{R2}}{\mathrm{Qmat}}\right)$$

Objective Function:

Min（ PI_P1, PI_P2, PI_P3, PI_P4, PI_P5 ）

FIG. 14. Example of PI Analysis

of locations meeting materials needs; P_j = potential sites j: $1-n$; S_i = demand locations i: $1-m$; R_i = S_i material demand quantity i: $1-m$; Q_{mat} = transport capacity per trip; and D_{ij} = transport distance between S_i and P_j.

Objective function:

$$\mathrm{PI} = \min(\mathrm{PI\_}P_j) \tag{3}$$

Each partitioned potential site is ranked based on the PI_P_j [(2)]. As shown in (3), the potential size with the minimal PI is the optimal site. An example illulstrating the mathematics used for the PI analysis is presented in Fig. 14.

SYSTEM DEVELOPMENT

System Development Algorithm

MaterialPlan uses the constructive placement procedure in generating a materials storage layout (Cheng and O'Connor 1996). Based on the construction schedule, materials are selected and placed one at a time until the final layout is achieved. During the iterative process, the system generates the potential sites for each material using the concept of searching by elimination. Through qualitative PI analysis, MaterialPlan determines the optimal site of each material. Considering the system flexibility, MaterialPlan provides the user with options to select his preference site. In addition, the materials layout solution is sensitive to the materials design sequence. Different materials design priorities can result in various layout solutions. Therefore, by changing the materials design sequence, the user can conduct a ''what-if'' analysis to solve both real and hypothetical on-site design layout problems.

System Architecture

The system's architecture involves identification of the tools used to develop the system functional modules and the means by which each will interface with one another and the user. Fig. 15 shows the system's architecture. The user and program interface for MaterialPlan is established at three levels: application user interface, command user interface, and program data interface.

The prime components of the system including Map/Info, Access, and MS-Project are developed under a Windows en-

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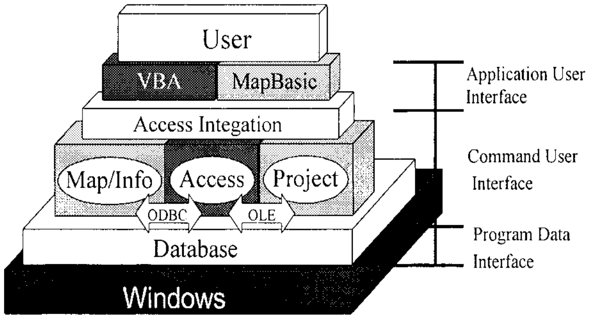

FIG. 15. System Working Environment

vironment. The user communicates with the components of the system through a custom interface developed using VBA and MapBasic. A set of the application user interface objects, including pull-down menus, pop-up menus, and forms, were developed for the system. In addition to automating the system design and directing the program flow of control, the command user interface is used to integrate the tools applied for the development of functional modules. Applying ODBC, the program data interface writes/reads the information to/from the associated databases. Using this method, the data files, which are stored in a standard *.mdb file format, act as the communication media.

CONCLUSIONS

This paper demonstrates that GIS is an effective tool for quantity takeoffs, presenting a new process for the development of computer-aided cost estimates. Adopting the continuous data acquisition and life-cycle support concept, MaterialPlan successfully integrates GIS-based cost estimates with construction scheduling to develop a dynamic materials requirements plan, continuously passing the retained information into construction phases for materials planning. The information required for the development of this system was thus represented and integrated within a computer environment. In addition, an automated site layout system was also developed and included in the program to identify options and solutions for problems regarding materials layout.

MaterialPlan was developed to replace manual methods, and it assists planners in quantity takeoffs and assessing materials layout design. The technical feasibility was substantiated by the development of the system. The system incorporates rules of thumb and experience for sizing materials storage areas and uses state-of-the-art industry practices for placement of materials. Also, a heuristic approach regarding the facility layout problem was developed to eliminate the manifestation of site choice of the materials into an ill-structred problem. MaterialPlan proves that GIS is a promising tool for solving quantity takeoffs and materials layout problems and thus opens up a new way of thinking in the management of spatial information for construction planning and design.

A prime issue in quantity takeoffs and construction planning concerns the integration of locational and thematic information in the design process. In construction, the information required for planning and design are stored in different forms, such as drawings, specifications, and bar charts. In the planning process, the planner has to repetitively reorganize and interpret information collected from the various resources. This process is thus tedious and prone to mistakes. GIS improves construction planning and design efficiency by integrating locational and thematic information in a single environment. This not only speeds by the modeling process by avoiding data extraction from various resources but also, more importantly, ensures data integrity and accuracy. GIS forms an effective foundation for planning construction activities.

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