A GIS-BASED INTEGRATED INFORMATION MODEL TO IMPROVE BUILDING CONSTRUCTION MANAGEMENT: DESIGN AND INITIAL EVALUATION

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ABSTRACT: Computer and information technologies offer significant potential to improve management practices in the construction industry. However, even though all parties involved in construction rely on computers to perform their tasks, the exchange of information among the different participants during the phases of a facility is still primarily paper-based. This paper presents a GIS-based integrated visual database model that allows for effective use of computer and information technologies for communication, project documentation, and knowledge sharing among the different participants throughout the life-cycle of a facility. The model allows for (1) accessing and retrieving construction information related to a certain construction element; (2) reporting and providing feedback from the field on the work progress, quality assurance, and inspection; and (3) evaluating the performance of the construction crews and generating cost and historical data for future reference. The proposed model is built using GIS as the base platform, and uses the 2D visual representation of the construction element (i.e. the 2D CAD drawing) as the least common denominator between the different participants throughout the life-cycle of the facility. Information related to the different construction elements, such as physical and functional characteristics and project life cycle information, is linked to the 2D CAD drawing and organized in tables and forms stored in an integrated database. The paper also reports the results of an initial evaluation of the model in the settings of a construction project.

KEYWORDS: GIS, building construction management, information models, visual databases

1. Introduction

Building construction depends heavily on a complex documentation process where the design intent is communicated via (a) a graphical representation of the building (which includes 2D floor-plans, elevations and cross-sections, and possibly 3D CAD models); (b) a set of specifications that dictate the quality of the components and finishes of the building; and (c) a legal document that highlights the project expectations. These three components constitute what is referred to as construction documents (CDs). Based on the provided CDs, the construction management team is able to gather information about the building (such as design information, geometric properties, etc.), add information related to constructability, re-
sources, sequence of work, schedule, and responsibilities (this is a dynamic model, as the construction team itself is fragmented and information is generated from multiple users' inputs), and document the construction process in fulfillment of the requirements of the legal contract. As a result, throughout the stages of the project, many different types and formats of information are gathered, documented, and shared. With current practices, in part due to the variations of the level of technological sophistication of the different participants, and in part due to the legal constraints of the process, communication is carried out primarily through paper-based documents. As a result, the information and the project documentation remain highly fragmented and the information gathered or generated in one phase of the project or within one team do not transfer seamlessly to other phases of the process or to other teams.

The construction industry suffers from what has been described as the “islands of information syndrome” (Dib 2007) due to the lack of connectivity between its various participants and functions, which hampers its ability to take advantage of advances in information and computer technologies. In an attempt to link these “islands of information” among the various parties involved in the construction processes, a substantial effort has been vested in developing Industry Foundation Classes -IFC which are standard data structures that allow computer applications to exchange project information about construction projects. Approaches such as Object Oriented Computer Aided Architectural Design (OOCAD), and Life Cycle Management (LCM) also aim to improve building information modeling and communication, in the Architecture, Engineering and Construction (AEC) industry. Despite these efforts, one of the major challenges that still needs to be overcome is inadequate interoperability among computer-aided design, engineering, and software systems--this is described in the August 2004 National Institute of Standards and Technology (NIST) report entitled "Cost Analysis of Inadequate Interoperability in the U.S. Capital Facilities Industry (Gallaher et al. 2004).

The objective of the work reported in the paper was to develop and validate an innovative integrated information model interface that allows seamless sharing (among all participants) of the graphical and non-graphical information generated throughout the entire construction process. The proposed approach does not utilize the parameterized 3D model of the building as the fundamental 'smart component' of the database, rather it uses the 2D CAD drawing.

The paper is organized as follows. In section 2 we review examples of application of computer technologies to the construction industry during the past two decades, and we discuss applications of GIS to building construction management. In section 3 we describe the design and technical implementation of the proposed model; in section 4 we report an application of the model to a real construction project and we discuss initial findings. Discussion, future work and conclusive remarks are included in section 5.

2. Background

2.1 Computer Technologies for Building Construction Management: a Brief Review of the Past 2 Decades

The last twenty years have witnessed a growing interest in introducing computer technologies and tools in the construction industry. In the 1980s the focus was on gathering project data and building historical databases and models; tools such as TIME (Gray 1986), ORPLAN (Darwicke et al. 1988) and Construction Planex (Zozaya and Hendrickson 1988) were developed at this time. In the 1990s a growing interest was devoted to integrating CAD within the construction project schedule in order to exchange information and communication among the design and construction teams. Databases related to CAD applications and Object Oriented approaches were developed, such as OPIS by Froese and Paulson (1994) and COMBINE, an at-
tempt to integrate design system to analyze the performance of a planned building (Augenbroe 1995). Around the turn of this century, 4D CAD approaches were applied to project planning. Life cycle approaches started with OSCON and OSCON-CAD by Aouad et al. (1998) and used an object oriented database linked to CAD in order to share information among various computer applications. These models focused primarily on the engineering aspect of the construction industry and did not target the construction management teams.

The last decade has seen the introduction of Building Information Modeling (BIM) technology. Although relatively new, initial experiences indicate that the creation of a parametric 3D model with associated information reduces errors of design, improves design quality, shortens construction time, and significantly reduces construction costs (Eastman et al. 2003). Due to these initial findings the popularity of BIM has grown tremendously in the past decade.

“BIM represents the process of development and use of a computer generated model to simulate the planning, design, construction and operation of a facility. The resulting model, a Building Information Model, is a data-rich, object-oriented, intelligent and parametric digital representation of the facility, from which views and data appropriate to various users’ needs can be extracted and analyzed to generate information that can be used to make decisions and to improve the process of delivering the facility” (AGC 2005).

The principal difference between 3D BIM and 2D CAD is that the latter describes a building by independent 2D views such as floor-plans, sections and elevations; editing one of these views requires that all other views must be checked and updated. In contrast, BIM represents a design as a series of parametric objects that composed together form the building model. These “smart objects” carry all the information related to the building, including its physical and functional characteristics and project life cycle information. For example, an air conditioning unit within a BIM would also contain data about its supplier, operation and maintenance procedures, flow rates and clearance requirements (CRC Construction Innovation, 2007).

In reality, no single, perfectly efficient Building Information Model exists. Although the benefits of BIM to the AEC industry are widely acknowledged and increasingly well understood and the technology to implement BIM is available and rapidly maturing, BIM adoption as a construction management tool is much slower than anticipated (Fischer and Kunz, 2004). Some of the major challenges that still need to be overcome in order for BIM to become widely used include:

1. The absence of a single, widely accepted BIM system– software vendors have produced different competing (and non-compatible) BIM implementations.

2. Inadequate interoperability among computer-aided design, engineering, and software systems (this is described in the August 2004 National Institute of Standards and Technology (NIST) report entitled “Cost Analysis of Inadequate Interoperability in the U.S. Capital Facilities Industry”).

3. The size and complexity of the files that BIM systems create – For complex projects, the scalability and manageability of a BIM project database represents a major challenge.

4. Sharing BIM information as drawing files – Users are used to exchanging drawings created as views of a building model rather than sharing “smart objects” from the 3D model.

The integrated information model described in the paper overcomes several of these limitations. The proposed model uses the 2D CAD drawing as the building block of the database. CAD drawings are saved in standard formats such as DWG, thus the problem of dealing with a variety of non-compatible software systems and files is eliminated (1). Although the use of an integrated database as a tool to store various types of information does not solve the issue of data interoperability completely, it facilitates user’s access to heterogeneous sources of information significantly (2). 2D CAD files are not as large as 3D BIM files
2.2 Geographic Information System (GIS) technology in the construction industry

GIS is among the most widely embraced software technologies of the past decade. For many people, GIS is “mapping software”. More specifically, GIS is a computer system capable of assembling, storing, manipulating, and displaying geographically referenced information, i.e., data are identified according to their locations. One of the main benefits of GIS is improved management of information resources. GIS can use information from many different sources, in many different formats and can link data sets together by common locational data, such as addresses. GIS makes it possible to link information that is difficult to associate through any other means. Thus, a GIS can use combinations of data sets to build and analyze integrated information. GIS can also convert existing digital information into a form that meets the user’s analysis need. Visualization of information analysis results is an important benefit of GIS as it presents facts in a compelling way. The information can be presented concisely in the form of a map and accompanying report, allowing understanding information clearly. Since better understanding of information leads to better decisions, GIS is not just an automated decision making system but a tool to query, analyze, and map data in support of the decision making process (ESRI 2000).

GIS applications are becoming common in diverse areas such as facilities location and planning, site selection and preparation, land management, road planning, management and design, environmental monitoring and analysis, residential and commercial site surveying, public works surveys and engineering, municipal land utility surveys, infrastructure evaluation, soils modeling, and more. However, not many applications of GIS in the construction industry can be found. Willenbacher et al. (2006) studied the potential of GIS as an approach for integrating spatial analysis in building model management in order to identify changes. The objective of this work was to minimize mistakes and inconsistencies during the building life cycle. Shanmugam et al. (2005) studied the potential of GIS for meeting the increasing demands of delivering projects on a fast-track basis, where the construction begins when the design is between 35% and 65% complete. One of the key challenges was ensuring that the flow of information and deliverables between the engineering, procurement, and construction is synchronized. They conducted a study to investigate the use of GIS as a solution to increase the information flow. Results showed that GIS has the capability to effectively capture the relationships between different deliverables, record the status of deliverables, and process queries from any of the teams regarding status and impact of disruptions. Thus, it supports the decision making required for rapid development of pragmatic plans.

Aouad et al. (2005) investigated the use of GIS technology for management and maintenance of bridges and road networks. Their study showed that the use of a hybrid business and information modeling approach to develop a model to support the development of a GIS-based bridge management system facilitates business decision making and business process change. Cheng and Chen (2002) developed an automated schedule monitoring system for precast building construction and erection of prefabricated structural components. The system, ArcSched, was developed to assist engineers in controlling and monitoring the erection process in real time. ArcSched is composed of a Geographic Information System GIS integrated with a database management system. Through systematic monitoring of the construction process and representation of the erection progress in graphics and colors, the scheduled components for erection are repetitively tracked and well controlled to implement the lifting schedule as planned. Heng et al. (2005) applied an integrated Global Position System (GPS) and GIS technology to reduce construction waste. During the study, the authors developed a prototype system to automatically capture and manage on site data.
for construction material and equipment (M&E) using barcodes integrated GPS and GIS technology based on the Wide Area Network (WAN) as a delivery method.

Cheng and Yang (2005) developed an automated site layout system for construction materials. The system, MaterialPlan, included a GIS-based cost estimating system integrated with material layout planning and aimed to assist managers in identifying suitable areas to locate construction materials. MaterialPlan demonstrated that GIS is a promising tool for solving construction layout problems and provides a new approach for managing spatial information in construction planning and design.

In summary, although some applications of GIS to improve the Building Construction Management process can be found, the integration of GIS and conventional construction project modeling methods has not evolved to the point where information analysis is widely conducted using spatially oriented decision-support systems.

3. The Proposed Model

The proposed GIS-based model uses the 2D CAD representation of the construction element as the basic building block of the database. The information pertinent to the various construction elements is organized in inter-related tables and every construction element is assigned a unique ID that is used as a “Key” relating the different tables. The different users access and operate different levels of the database using a user-friendly interface based on a visual Structured Query Language (SQL). The standardization of the information in the database eliminates the need for translators in order to share the information generated by the different users. The model allows for accessing the textual information from the drawing (by point and click), as well as viewing the graphical representation related to textual information in the database, thus creating a two-way connection between graphical and textual data. Figure 1 shows a screenshot of the proposed model.

![Fig. 1: A screenshot of the model illustrating the ability of the user to retrieve tabular information by pointing and clicking on the graphical representation of the construction element.](image)

Specifically, the model links information to the graphical representation of the construction elements in order to achieve the following:
**Information integration.** Each construction element has a unique identification number that links its graphical representation in the CAD drawing to a series of integrated, compatible tables.

**Information access.** A variety of information related to any construction element can be retrieved by point and click from the CAD drawing. By pointing on the CAD representation of the construction element the user can access multiple tables on the design, safety requirements, or other tasks related to the user’s job assignment.

**Knowledge sharing.** The user can report the work progress on-site by point and click from the drawing. The user can access the tables for work progress information and update the work in progress for that particular day.

**Improved documentation.** By reporting on a daily basis, and updating the work progress in the database, the user in the field can provide accurate documentation of the construction activities in the field and link the labor and manpower to the specific construction element.

**Increased control.** The information available from reporting the work progress and tracking labor provides the management team with reliable data that can be used to effectively manage the cost accounts and schedule progress, and monitor team performance.

**Effective management of change.** The tracking and the documentation of the work in progress allows the management team to measure the effect of change on the construction activities, schedule, labor and contract.

**Replacement of paper-based communication.** The users exchange construction information by updating the database. The tabular data provides the users with the flexibility to analyze, sort and organize the data, no paper based documents are required.

**Work progress monitoring.** The progress data allow the users to compare actual progress to the schedule, as described above.

**Productivity analysis.** The data provided by the users in the field, once organized and analyzed by the management team shows realistic representation of the teams’ productivity.

**Reference generation for future projects.** The database can be used to generate reliable historical data for teams’ productivity and costs of construction that can be used for future reference.

### 3.1 Technical Implementation

The proposed model has been developed using the Geographical Information System (GIS) as the base platform because of its capability of linking a database to a CAD drawing. The following steps were followed in order to achieve the integration of the database with the CAD drawing using GIS.

1. Obtain the CAD drawing from the architect.
2. Modify the CAD drawing such that all construction elements are organized in different, meaningful layers.
3. Create a Geo-Workspace in GIS. The Geo-Workspace is the area where the work will be performed. The Geo-Workspace was created as a Read-Write, and saved in the assigned name.
4. Define a coordinate system for the Geo-Workspace. In order to better represent construction data in GIS, a projection coordinates system is used. The coordinates of the points are based on the North and East coordinate system used in Surveying.
5. Create an access Warehouse. The access warehouse is the database that includes all the information related to the project.

6. Import the CAD layers into the GIS workspace and digitize them. Digitizing the information allows for defining the different elements so that all the data is vector data and has a coordinate system.

7. Connect the vector information to the data warehouse, (i.e. the database). For example, the layer “Doors” is connected to the database table titled “Doors”, and so forth for all the layers corresponding to the construction elements. The information in the database table “Doors” consists of the attributes of the features in the layer “Doors”.

Additional tables that are created separately in an access database format can be merged and/or linked with the tables in the database warehouse created in GIS. This allows the user to access the information in the additional databases through the queries displayed visually in GIS.

Further during the construction process, when changes occur, features can be added or modified using the editing functions within GIS using procedures similar to the ones described above. For example, additional doors can be added in the layer “Doors” and the information related to these doors is automatically added in the database table named “Doors”, allowing the user to access the information in the table from the drawing, or the visual information from the tables.

The construction elements of the building are organized in a DATA FRAME that can be called, for instance, “Project X”. The executive manager in construction company “Y” in charge of multiple projects has access to multiple “Data Frames”. To access information related to a specific project (i.e. “Project X”), he/she will have to access the data frame titled “Project X” to be able to see information pertinent to this project. The DATA FRAME titled “Project X” consists of layers organized in groups, which are representations of the different phases of the project or the different buildings. Each group includes a list of layers corresponding to different building construction elements; each layer acts as a reference to the data contained in data sources: vector datasets-- feature layers such as CAD files, coverages, shapefiles, geodatabase, and databases; and raster datasets-- raster layers such as grids and images.

GIS as the base platform for the model allows working graphically using the CAD construction element as the unit of analysis. It also enables the user to quickly develop custom tools, interfaces, and complete applications thus making the model easy to work with in any organization.

4. Example of Application and Initial Findings

To better illustrate the functionality of the proposed information model and validate its effectiveness, one of the authors used the model in a real construction project and applied it to a particular set of construction elements: the “Walls”.

The information provided in the contract documents related to the walls included the following:

- The CAD drawings showing the walls as well as other construction elements on the same drawing sheet. Figure 2 shows a portion from the contract document drawing sheet. The sheet includes the representation of a typical layout of the various construction elements as well as annotations that indicate to the user various details related to the construction elements. On this drawing the types of walls are represented in small diamond shapes with numbers; the numbers refer to the wall types and define the characteristics and the guidelines that need to be followed to provide the required items.
The guidelines and the specifications that the Construction Management team will have to provide such as: Preconstruction Testing Service; Concrete Masonry Unit Test for each concrete masonry unit indicated, per ASTM C 140; Prism Test for or each type of wall construction indicated, per ASTM C 13 14; Mortar Test for mortar properties per ASTM C 270, for each 5000 sq. ft. of wall area; Grout Test for compressive strength per ASTM C 1019, for each 5000 sq. ft. of wall area.

The Architect Supplemental Information (ASI) or Change Order (CO), which are changes that affect the construction processes.

In order to use the proposed model, the walls were digitized into GIS. The layer “Walls” was then connected to a table in the database warehouse that was filled with the attributes related to the different walls in this layer. The database in GIS was then connected to other database tables outside GIS. Instead of having one large and complex database table, the database consisted of independent linked tables, each one serving a specific purpose. The tables are shown in figure 3 and included:
A “General Company Information” table dedicated to the information about the Subcontractor; a “General Team Info” table used by the field superintendent to access the name and responsibilities of the different individuals in charge of the coordination tasks; a “Work Progress” table that allowed the Field Manager to track the work progress (this table contained fields such as: Wall ID, Number of Workers, Date, 8-courses, Inspection, Reinforced/Grouted, Date, 16-courses, Inspection, Reinforced/Grouted, Date, Top Up, Inspection, Reinforced/Grouted, Date, Finishing, Date, and Caulking); and a “Responsibilities” table that allocated the different responsibilities based on the wall types, Wall ID, Wall Type, and Responsibility. The “Responsibility” and “Work Progress” tables were linked by the key field Wall ID.

Using these four interconnected tables, the field manager could record the work progress by updating the work progress on site, and the project manager in the office had access to the up-to-date jobsite information and was able to generate the costs and the reports that were needed for billing, as well as compare the actual versus planned work progress.

The information presented in Figure 3 is tabulated as shown in Table 1. Initial information such as design requirements, type of walls and who is supposed to perform what task and when was determined from Table 1. The field manager could access the “General Information Access” table which included information organized in fields such as Wall ID, Wall Type, Width, Height, Scheduled Early Start, Duration, Actual Early Start, Actual Duration, RCO #, ASI #, and RFI #. This table provided the information needed for the construction of the wall and could be accessed from the drawing. The field Wall Type in this table was linked to the field Wall Type in the table “Wall Types” providing detailed information about the specific wall based on its annotation. The “General Information Access” table was also linked to the table of work progress by the field “Wall ID”. Hence all the work progress was shown in this table, as both were linked together.

For tracking of changes, a table dedicated to Change Orders titled “RCO” (Request for Change Order) was created. Once the CO was accepted by the construction management team, the change was updated in the table “General Information Access” under the field RCO #, as both tables were linked through the field “Wall ID”. The same applied to the RFI # (Request for Information), i.e., information generated to clarify the scope of work, and the ASI # (for any additional information and changes requested by the Architect or Owner to be processed immediately).

Table 1: Wall types in tabular format

<table>
<thead>
<tr>
<th>Wall Type</th>
<th>Wall Thickness</th>
<th>Security</th>
<th>Reinforcement</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>CMU 6 inch</td>
<td>Minimum/ Non Secure</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A1</td>
<td>CMU 6 inch</td>
<td>Medium Security</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A2</td>
<td>CMU 6 inch</td>
<td>Maximum Security</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A3</td>
<td>CMU 6 inch</td>
<td>T.O. CMU = 3’-4” AFF</td>
<td># 5 @ 16” 0.C. Vert</td>
<td>Provide Bullnose cap units at top of partial height walls per detail WT-002</td>
</tr>
<tr>
<td>A4</td>
<td>CMU 6 inch</td>
<td>T.O. CMU = 4’-0” AFF</td>
<td># 5 @ 16” 0.C. Vert</td>
<td>Provide Bullnose cap units at top of partial height walls per detail WT-002</td>
</tr>
</tbody>
</table>
Figure 4 shows an example of user query for activities by “Early Start” criterion. The user could query the data according to location, content, proximity, and intersection. For example, data could be added to maps to find the geographic factors that drive trends and distributions or locations at which particular characteristics coincide. By means of Structured Query Language (SQL), the user could aggregate data geographically by categorizing it based on areas such as the different phases of the project, or based on common characteristics such all “Features = Windows” and “Attributes = “Aluminum”. The user could narrow the search by adding to the selection AND “Attributes = Early Start = Today's date”. Furthermore, the output from one analysis could be used as the input to the next analysis which enabled the user to create advanced geoprocessing applications.

Applying the proposed information model to a real construction project revealed the following benefits and limitations.

**Benefits.**

Using the model allowed the construction team to:

- Reduce/eliminate loss of information (all information was shared in a network-accessible database)
- Detect miscommunication at early stages, thus reducing the need for later changes
- Reduce cost overrun caused by miscommunication and changes
- Reduce time loss (less effort spent on communicating and tracking changes)
• Reduce chances of litigations (less changes, less time delays, less cost overrun)

In addition to alleviating/solving these common problems, the model offered the following additional advantages to the construction company in the construction phase:

• Flexibility to manage human resource duties
• Ability to evaluate the team members’ performances
• Ability to create reliable historical data for future reference projects
• Ability to compare company performance to national averages
• Ability to compare and rate team performances vs. other teams within the same company
• Ability to collaborate and share knowledge and lessons learned among different teams within the same company

Limitations.

Using the system onsite revealed three types of limitations: legal, user-related, and cost/computer-related.

• The proposed model relies on databases and electronic filing of information therefore does not satisfy the legal requirements for documentation, as the legal system relies on paper-based documentation as the standard documentation method.
• The construction team might be reluctant to use such system since all information is shared (for instance, mistakes are documented and accessible by supervisors).
• The use of the proposed system requires computer hardware and computer literacy. Additional computer hardware means additional expenses for the construction company; computer literacy is something the current onsite construction workforce lacks. Furthermore, the system requires computers to be carried around on the construction site, which is typically not a computer friendly environment.

5. Discussion and Future Work

In this paper we have described the design, development and initial validation of a GIS-based integrated information model to improve the Building Construction Management process. The proposed model uses the digitized 2D CAD drawing as the least common denominator between the different participants throughout the life-cycle of the facility. Information related to the different construction elements, such as physical and functional characteristics and project life cycle information, is linked to the CAD drawing and organized in tables and forms stored in an integrated database. The proposed model aims to overcome many of the challenges faced by the construction team, such as understanding the scope of work, managing the construction work effectively, keeping track of the changes and the work progress accurately, and assuring compliance with the contract documents and the building codes.

Currently, the construction team relies extensively on communication through means such as faxes, photocopies, correspondence letters, phone calls, and emails. The construction information is available to the construction team in different formats such as architectural drawings, detailed drawings, general specifications, and building code. In the current situation, at any time the Project Engineer (PE) needs to look for a specific piece of information, he has to search through bits and pieces of data scattered in different formats. With the proposed model:
GIS provides the “one place to go” for a PE to retrieve the information needed to understand the scope of work. This process gives the PE fast access to up to date, reliable information.

- The database format of the information allows flexibility to maneuver the information in terms of quantity take off, costs, and dates to order materials.
- By updating the GIS model once, all the different team members can have access to the latest up to date information. Furthermore, the GIS model updated by one party eliminates the need to have the Project Manager Post, the Superintendent Post, and the Field Post.
- The GIS model allows for tracking the work progress effectively. The superintendent points to the work progress on the GIS model and adds relevant information such as, time of completion, percentage complete, inspection, errors, and responsibilities. Once in the GIS model, this information becomes part of the GIS database and is instantly accessible to the management team.

As mentioned in section 4, the application of the proposed system to a real construction project revealed some limitations which we believe can be solved in the near future. We plan to extend the system interface to mobile devices such that handheld devices can be used on site to replace cumbersome computers. We are in the process of designing and developing a more user-friendly interface to facilitate user’s interaction with the system and alleviate the construction team’s reluctance to use the tool. To satisfy the legal requirements of paper-based documentation, the system could be easily programmed to generate time-stamped daily print outs of the database contents.

6. References


