Integrating Construction Process Documentation into Building Information Modeling

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Abstract: The research described in this paper extends the use of building information modeling (BIM) throughout the construction phase of the project life cycle. The owner is a military base that uses three-dimensional (3D) modeling for underground services and the footprints of the buildings. They were interested in determining the feasibility of capturing the construction process and related documents into a similar format. The research was conducted in parallel with traditional methods. The objectives of this project were to create a 3D as-built model, a four-dimensional as-built model, and attach the construction process information to the model for the owner to use after construction. A literature review indicates that BIM application stops at the preconstruction phase with a limited amount of research regarding data collection of the construction process. Significant contributions include practical 3D data collection methods and extending the BIM software products to accommodate construction process documentation. Results indicate that BIM software is not specifically prepared to accomplish these objectives and some modification to procedures as well as software were necessary for the BIM to capture the construction process documentation.

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Introduction

The primary purpose of this research project is to extend building information modeling (BIM) into the construction process and to create a single repository of facility data for the owner. Also, construction document management is an essential component for the successful management of the facility in the postconstruction phase. BIM has been implemented by some architecture, engineering, and construction (AEC) firms because the productivity gains and long term benefits over existing practices are evident. For example, the General Services Administration (GSA) requires all AEC firms dealing with them to include a BIM as part of the work proposal beginning with fiscal year 2006 (Silver 2005).

Typical construction documentation includes an owner’s set of files transferred from the contractor at the end of the project in a number of file drawers or boxes. The information is marginally useful for an owner and staff since it is organized by a constructor in a format consistent with the constructor’s interest. The BIM is an excellent tool for data management capable of information retrieval and display in a format consistent with either the constructor or owner. The owner may organize the data by rooms or systems for more efficient availability. BIM can retrieve this information by any parameter established by the user.

The National Building Information Model Standard (NBIMS) defines BIM as “a digital representation of physical and functional characteristics of a facility and it serves as a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life cycle from inception onward” (Smith and Edgar 2006). BIM represents real world elements such as walls, doors, and windows as three-dimensional (3D) objects. In addition to geometry details, other information can be attached to these objects including manufacturers, fire rating, schedule, and cost estimates. Another BIM advantage is the ease to insert, extract, update, or modify digital data by owners, clients, engineers, architects, contractors, suppliers, and building officials.

Currently, 3D object-oriented computer-aided design (CAD) software models serve as communication between planning and design phases. These 3D models also have been used during pre-construction to resolve constructability problems, conduct interference analysis, and to perform scheduling and hazard analysis. However, little has been done to implement BIM beyond the use of these models albeit a substantial amount of information is still collected and transferred to the owner in boxes or file cabinets. This information, including requests for information (RFI), schedules, submittals, change orders, or as-builts, rarely serves as a reliable database for future decision making and would be more effective if incorporated into the BIM.

This project presents a practical approach to data collection that is incorporated into a BIM model. The objectives were to capture 3D as-built data into the BIM model; document the actual construction schedule; and use BIM to capture and store construction documents including specifications, submittals, shop drawings, change orders, and RFI. As-built information was collected

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and updated into 3D models. The daily construction sequence was documented as a four-dimensional (4D) model. Construction documents were collected and stored as pdf and dwg files in the local database and integrated with the model components for future retrieval. BIM software does not directly incorporate the construction process data but is adaptable with some programming.

Background

The traditional media of communication among various phases of life cycle is two-dimensional (2D) drawings. The introduction of CAD software facilitates the use of 3D graphical models between planning and design phases. Koo and Fischer (2000) showed the usefulness of 4D models for interference analysis and space conflict identification. This modeling refers to a 3D model linked to a schedule. Chau et al. (2004) demonstrated the use of a 4D model for effective site utilization. The five-dimensional (5D) model integrates a 3D drawing with time and cost estimates. The 5D model facilitates the impact of changes on the project and assists decision making for owners, project engineers, or managers (Tanyer and Aouad 2005).

Though the advantages of the 3D product modeling are well documented, the usage diminishes rapidly after the preconstruction stage. These benefits are seldom realized postconstruction due to the breakdown in continuity of data collection. The losses due to inadequate interoperability in the United States capital facility industry were estimated to be $15.8 billion (Gallaher et al. 2004). Technological advancements facilitate digital information exchanges among various project participants and replace the traditional paper based information exchange (Bjork 2003; Hjelt and Bjork 2006). Hajjar and Abourizk (2000), Hjelt and Bjork (2006), and Bjork (2003), reported positive results when using electronic document management systems (EDMS), also referred to as project extranets and project webs, for construction document management.

One limitation of the EDMS is that they do not directly facilitate any association to the product modeling (Caldas et al. 2005). The same component can be referred to by different names throughout the life cycle due to lack of standard terminology among various project participants. Manual mapping is required to search for the relevant information since this naming convention differs from information management systems terminology (Caldas and Soibelman 2002). Traditional manual information retrieval methods are in use throughout the project life cycle due to the high investment costs and the complexity of resolving the terminology issue.

The Facility Information Council (FIC) of National Institute of Building Sciences (NIBS) and North American Chapter of International Alliance for Interoperability (IAI) have initiated efforts called “buildingSMART” (NIBS 2006). The objective of this effort is “the dynamic and seamless exchange of accurate, useful information on the built environment among all members of the building community throughout the life cycle of a facility. It is simply a smarter process for managing the project life cycle” (IAI 2007).

FIC of NIBS formed a committee to create NBIMS. “The new NBIMS will complement IAI efforts by standardizing the way United States owners, managers, and their supporting professionals describe the information handled by open interoperable software and networks, at the same time coordinating its efforts with all major open and proprietary BIM systems” (Kennett 2006).

Objectives

The project in this study is a 390.192 m² addition to an existing child development center. The owner is a large government entity managing a number of facilities on a military base. The child development center is a service provided for its employees. The owner previously tracked underground services and the building shell in a 3D format throughout the base because of the highly disruptive potential resulting from damage to services from new construction. They were interested in extending the 3D as-builts and linking information to the building model. The research project ran parallel to the traditional methods used by the contractor and owner as neither was prepared to rely on the unproven methodologies.

Objective 1: Capture 3D As-Built Data into BIM Model

The traditional industry practice is to develop 2D as-built drawings for the owner. The process is often time consuming, inaccurate, and not very useful. The efficient management of the facility, postconstruction, depends on the availability of accurate as-built drawings or models. Geometrical variations of the components from the plans are inevitable during the process of construction. Capturing the x, y, and z coordinates for the 3D as-builts information is still time consuming. The accuracy achieved through this process is well within the tolerances needed for subsequent repairs, maintenance, and/or renovation on this project.

Photogrammetry and scanning technologies capture x, y, z coordinates and facilitate the development of 3D as-built models. The modeling process by photogrammetry becomes inefficient depending on the number of objects and level of details (Shih and Huang 2006). The 3D laser scanning technology provides 3D as-built models to an accuracy of 1 mm, but is expensive (Stone and Cheok 2001; Gray 2006). The use of a 3D laser scanner to develop a 3D as-built model is limited because of the excessive cost to capture and manipulate the data.

This project operationalized a less accurate but more cost effective alternative to develop the 3D as-built model. Two methods were used to collect the coordinates as needed. The collected coordinates were either the center line or end line of the installed component using the methods described below. The components were retrieved from a library and placed according to the guiding lines. Components, not available in the library, were created as needed for the 3D as-builts.

Objective 1: Methodology

The first method to collect coordinates used a custom built robotic laser rangefinder system. Tseng et al. (2002) developed a profile measuring system using this method for automatically quantifying the cross-sectional details of internal structures like window and floor profiles, floor patterns, and ceiling contours. The robotic laser rangefinder system includes a Directed Perception 230 tele-operated Pan and Tilt Unit (PTU) and Leica Disto Plus Laser rangefinder as shown in Fig. 1. The PTU records the pan and tilt angle. Pan is the rotation in the horizontal plane and tilt is the rotation in the vertical plane. The laser rangefinder is used to measure the distance to the target.

Communication between the PTU and notebook is achieved through an RS232 port. The unit is mounted on a tripod and rotation and tilt are controlled by using a track ball controller. Pan, tilt, and distance of the target point are then acquired. The mounted tripod height, pan, tilt, and distance are used as inputs to
solve three degree of freedom forward (3 DOF) kinematics problem to determine the \( x, y, z \) coordinates of point targets (Cho 2000).

The Leica Disto Plus laser rangefinder software is a Windows based control program written in C++. Directed Perception 230 tele-operated PTU software is a DOS based program written in C. It was necessary to integrate the acquired data from different software programs, solve a 3 DOF forward kinematics problem, and develop a user friendly Windows based operator interface. A program in C++ was written to solve the 3 DOF forward matrix using the acquired data. The user friendly operator interface was developed using visual basic (VB). The interface screen is shown in Fig. 2.

The \( x, y, z \) coordinates of the target points were collected for an element or component and stored in Microsoft Excel. There is no interface available between Microsoft Excel and Revit, however Revit has a feature to import dwg file format. A VB application was developed to provide an interface between Microsoft Excel and Autodesk’s AutoCAD. AutoCAD was used to generate the 3D as-built guiding line layout in dwg file format by using the collected coordinates as shown in Fig. 3. The collected \( x, y, z \) coordinates of the components establish a guiding line layout used to locate the component within the Revit model.

The second method used to collect coordinates was a robotic total station that includes a Leica TPS 1200 total station. This system is more expensive when compared to a customized robotic laser rangefinder system but no development is necessary. Commercially available software can be used to transfer the \( x, y, z \) coordinates from the total station to AutoCAD to develop 3D as-built guiding line layouts. The dwg file format was chosen because it is supported by most BIM products. The dwg file layout was imported into Revit using the import feature. A 3D as-built model was developed by tracing over this layout using respective components or objects from Revit as shown in Fig. 4. For example, the wall component provides three placement options relative to the data points that place the wall. They are center, left, and right. Center option places the wall centered on the data point creation line. Left and right options place the wall to the left or right of the data point creation line, respectively. The 3D guiding line layout was used as the creation line and based on the orientation, the walls were relatively placed using center, left, or right placement options. When the components were not available in the library, they were created.

Autodesk Revit building 9.0 was used to develop the 3D as-built building model and Revit Systems was used to represent mechanical/electrical/plumbing (MEP). The information integration with the Revit model was achieved using Autodesk Revit application programming interface (API) 9.0 and Microsoft Visual Basic.Net (VB.Net) programming language. The 4D as-built was developed by integrating the 3D as-built model with the actual construction schedule using Bentley Navigator. A static 4D as-built model was developed in Revit by programming in VB.Net and using Revit API 9.0.

**Objective 2: Document Actual Construction Schedule**

The 4D modeling has gained wide acceptance as a tool for planning the construction process. This section describes a process whereby the actual construction progress is captured and attached to the 3D model. This can be extremely valuable for training, evaluation of processes, and claims documentation. Daily jobsite photos were also made retrievable within the BIM.

Typical BIM components like walls, slab, windows, and doors are useful to represent the finished component but cannot serve to depict the actual construction progress. For example, an exterior wall of brick on metal stud construction is readily available in the component library and can be used to represent a final finished wall. The actual construction of this wall, however, consists of several individual components installed in stages including metal studs, insulation, exterior brick, and gypsum wall board. The as-built 4D model must be capable of depicting these operations in stages.

**Objective 2: Methodology**

Bentley products were used to develop the 4D as-built model since the features necessary to integrate the 3D model with the schedule were readily available. The as-built guiding layout developed in dwg file format described in an earlier section was used to create the 3D as-built model by tracing over the 3D as-built layout using the components from Bentley Architecture and
Bentley Structural. The actual construction schedule depicting progress as recorded on the daily site progress reports were created in Microsoft Project. The 3D as-built model and actual construction schedule were linked to generate the 4D as-built model using Bentley Navigator as described below.

Bentley Navigator facilitates the 4D simulation using JScape object model (JSM) files. JScape is an object-oriented technology by Bentley Systems. The objects within a JSM file are used to store data from graphical and non-graphical sources. The graphical source includes 3D CAD files while non-graphical sources include schedule files of Microsoft Project or Primavera Engineering & Construction. The 3D as-built model and the actual construction schedule were converted into JSM files using features available in the Bentley products. The relationship between the graphic model objects and schedule activity object was established manually by using the manage schedule relationships windows as shown in Fig. 5. This 4D model is a dynamic model that shows the progress of the 3D model relative to the schedule change. In order to use the Revit BIM as a 4D model it was necessary to program some additional features into the software. The additional features needed to display a static graphical model showing the components installed during a specified time period. The static 4D model used VB.Net to create the conditional query.

Executing conditional query is not readily available in Revit but it is feasible through Revit API. The writers customized this feature by developing an interface between Revit, and MS Access through Revit APIs using VB. This query facilitates the retrieval of elements or components completed during a particular period of time. Fig. 6 shows the interface screen for executing a date conditional query. The range of dates required is specified in the...
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in each parameter is of the following type: text, integer, number, length, area, volume, angle, URL, material, and yes/no.

Revit facilitates the addition of a new parameter as project parameter or share parameter as shown in Fig. 8. Only the shared parameters are exported to databases. These are shared by other families and projects, whereas project parameters are not exported to the databases. The newly created parameters on this project focused on information important to the owner in the postconstruction phase of the life cycle.

Objective 3: Methodology

The traditional practice requires the facility manager to search 2D as-built drawings for dimensional details and multiple construction documents to obtain information regarding a building component. The new shared parameters include specifications, RFI, change orders, submittals, and shop drawings. They were created as instance parameters and assigned to all categories like walls, windows, doors, and columns. The URL data format was used for each parameter. This format is useful to establish the link between the respective files and component. The link between the documents through the path stored in the parameter allows easy access to the required information. The ease of integration depends upon the availability of information in digital format. This project used traditional practices so most of the information was in paper format. Paper based information was scanned and converted into digital format. The information was then attached to the BIM model by creating shared, instance parameters as described previously. These parameters are made to appear under the group “Other” in the instance parameters list as shown in Fig. 9.

The specifications, submittals, shop drawings, and RFIs were integrated by linking the file path location to the respective parameter as shown in Fig. 9. The project data are stored locally as a URL type in order to maintain the integrity of the data beyond the life of a remote website. BIM facilitates any time access to query and retrieve information by the stakeholders throughout the life cycle. The information like specifications, submittal, shop drawings, and RFIs can be retrieved by accessing the respective instance parameters of a particular element also shown in Fig. 9.

Benefits and Limitations

The greatest limitation of this study is the inability to measure results in a quantifiable metric. The benefits of extending BIM beyond the preconstruction planning phases are difficult to measure. Even the benefits of preplanning with interference analysis and 4D modelling are obvious yet difficult to quantify. The American Institute of Architecture’s (AIA) Large Firm Roundtable (LFRT) recently commissioned a study to arrive at appropriate metrics to measure the benefits of BIM in the architecture and engineering stages. BIM in this phase is much more mature than in construction and yet quantifiable measures are still elusive.

This research project ran in parallel with the traditional method and did not directly influence the project outcome. The primary benefit is that the owner now has access to a BIM model with the full range of project information. The quantitative as well as qualitative benefits may result from the availability of such information throughout the life cycle of the project. With continued research and development of software and protocol the cost associated with capturing the construction process information could be reduced substantially.

The 3D as-built information was captured using two processes that were less accurate but also less expensive than photogram-

“From” and “To” text boxes. The query results in a graphical representation of highlighted elements completed within the specified time period. The results can also be displayed in the form of a table.

Site progress photos were integrated with the 3D as-built model by developing an interface between Revit and VB.Net through Revit API. The option to view the site progress photo is displayed in the “External Tools” fly out menu under the “Tools” menu. The user interface screen is shown in Fig. 7. This screen facilitates selection of the day from the calendar. A list of photographs available on that particular day is displayed and the user can select the photograph to view and compare with the 3D as-built model as shown in Fig. 7.

**Objective 3: Use BIM to Capture and Store Construction Documents**

The existing parameters in BIM software do not facilitate integra-
tion of the construction process documents and need to be cre-
ated. Each element or component is associated with predefined
parameters and these are categorized into type parameters and instance parameters in Rivet. The type parameters control all el-
ments of that type whereas the instance parameters control se-
lected or created instances. The type and instance parameters are further categorized into different groups. The data format stored

![Fig. 5. Manage schedule relationships screen](image)

![Fig. 6. Interface screen for date conditional query](image)
metry and scanning. Data collection and manipulation, however, is still more costly to collect in 3D than 2D and may need to be selective depending on the importance of the information. For example, a child development center may not need to know where each electrical conduit is located within a wall but valve and damper locations within a ceiling may be very useful. Accuracy available with photogrammetry or scanning is not an issue for most components on this project but could be extremely important in an industrial or power project. Standards will be necessary to establish reasonable protocols for accurate modeling information.

The 4D as-built modeling was equally successful using existing software with some modifications to the programs. There are a number of BIM software limitations regarding 4D modeling. First, the model needed to be replicated with the components broken down to the smallest element. BIM programs can produce
the desired level of detail but at an additional cost of recreating
the model. This cost could be reduced with a feature to expand
the composite behavior of the components as needed by down-
stream users. Second, most BIM software are not prepared to
handle 4D modeling. Additional programming was necessary to
create a query capable of a 4D display. An additional benefit of
BIM was the ability to attach daily job site photographs.
The interoperability issue was most apparent with document
collections. Documents created digitally were distributed to the
job site in the traditional manner and then scanned to create a
digital image of the document. This information was stored with
defined fields available for manual input of appropriate attributes
for future queries. Most queries require only small parts of the
information provided. For example, a query looking for length of
warranty would result in a complete warranty document. Efforts
are underway to standardize the format of manufacturer’s infor-
mation in order to improve the distribution of information.
The ongoing research on standardization of storage location is
in progress under aegis of NBIMS. Information integration en-
hances the efficiency of the information management and reliabil-
ity of the model. The existing 2D as-builts and paper based
information storage were replaced with data rich 3D as-built mod-
els. These information integrated models facilitate seamless flow
of information from the initial phase to the final phase of the life
cycle.

**Conclusion**

The objectives of this research were to extend BIM into the con-
struction process by documenting 3D as-builts, produce a 4D as-
constructed model, and capture and store construction documents
for the owner during subsequent stages of the life cycle. Existing
practices facilitate the implementation of BIM up to the precon-
struction phase only. The availability of the 3D as-built model and
integration of the construction process documents extends the
implementation of BIM throughout the project life cycle. The
methodology discussed in the paper serves as an initial step to
extend BIM through the construction phase of the life cycle.

The 3D as-built model developed in this project was more
time consuming than traditional 2D as-built. Because of the single
entity behavior of components the model developed in the design
stage is not useful to depict the actual construction progress. Fu-
ture developments should include software modifications to ex-
and components.

The 4D as-constructed model has a number of advantages in-
cluding training, work study analysis, and process documentation.
In addition, to software modifications described in the previous
paragraph, query features that include time dependant variables
should be included. Interoperable software that link a daily
progress report to the model would reduce redundancy. A man-
ger could simply click on each component and update the status
as installed. Other features could include the same information
provided in a standard daily report.

The integration of construction process documents is done by
selecting each component and linking the documents by specify-
ing the documents storage path. The files could be placed in a
preassigned path with automated links if the storage location was
standardized. Much has been done through the NBIMS effort but
even more is necessary. The standards will help the manufacturers
as well as BIM and other software developers reduce the burden
of interoperability.

BIM has the potential to substantially change the way con-
struction is performed and documented. The transition requires a
complete paradigm shift through all phases of the life cycle. BIM
could eventually become the sole source of information including
facilities management and planning. There are a number of ad-
vantages including productivity improvements associated with
BIM. Future research will be necessary, as is currently being
funded through the AIA LFRT, to develop metrics to measure the
value of BIM in construction.

![Fig. 9. Integration of RFI, specifications with as-built 3D model](image-url)
References


