

# A Visual Approach to Construction Cost Estimating

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A VISUAL APPROACH TO CONSTRUCTION COST ESTIMATING

by

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ABSTRACT  
A VISUAL APPROACH TO CONSTRUCTION COST ESTIMATING

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Marquette University, 2010

Construction cost estimating is considered one of the most important and critical phases of a construction project. Preparing reliable and accurate estimates to help decision makers is the most challenging assignment that estimators face. An estimate is not only necessary for proposal preparation but also for several project management functions. Despite the importance of estimating, it has remained a very time consuming process. The most inefficient part of construction cost estimating is determination of the amount of resources needed for the construction of a project. This is also known as quantity takeoff. Quantity takeoff is a very long and error-prone process that is performed manually by estimators. Missing or duplicating work items are among the errors that can occur during the quantity takeoff process.

New Parametric CAD software has recently attained widespread attention in the Architectural, Engineering, and Construction (AEC) industry. It represents the development and use of computer-generated models to simulate the planning, design, construction and operation of a facility. It helps architects, engineers, and contractors visualize what is to be built in a simulated environment and to identify potential design, construction or operational problems. The model created from parametric CAD software will significantly increase construction cost estimator productivity by substantially reducing the manual work necessary for performing quantity takeoffs.

This study presents a methodology that uses parametric CAD software and visualization technologies to streamline the estimating process. Although this methodology won't totally automate the estimating process, it will help in the following areas: (1) providing a navigable 3D model of the project, (2) simplifying the quantity takeoff process, and (3) eliminating manual calculations and search for data. This study uses visualization technologies to navigate through a 3D CAD model. This would provide the estimator with a tool to improve the understanding of the location and relationships between elements in a model. The quantity takeoff process may be simplified by using properties and geometry information extracted from the 3D CAD model. This study also uses a database technology to store labor, equipment, and material cost data. This helps eliminate manual calculations and enables an estimator to search for data stored in the database. A case study is presented to illustrate the process and capabilities of the developed system.

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## **CHAPTER 1**

### **INTRODUCTION**

Construction cost estimating is a cumbersome process. It takes a long time for an estimator to complete an accurate estimate and construction contractors must prepare cost estimates quite often in order to prepare bids for new projects. This presents a challenge to an estimator who has to prepare several estimates in a short period of time. In recent years, computers and estimating software have reduced the amount of manual work necessary for preparing an estimate by organizing and providing fast access to latest labor, material and equipment costs, quickly performing calculations and generating reports. There is room to improve the estimating process even more. This can be accomplished by using the latest CAD and visualization technologies. Improvements can be made in how information is transferred from design files to estimating applications and in visually matching CAD elements with estimating database assemblies.

This chapter provides a brief description of the current technology used in the construction cost estimating process. It also discusses research goals, approach, and scope. Finally, the organization of the thesis will be described.

#### **1.1 REVIEW OF TECHNOLOGIES USED IN CONSTRUCTION COST ESTIMATING**

Today, estimating technologies used by contractors vary tremendously from contractor to contractor. Some might still be using simple tools such as paper and pencil, while others are more technologically advanced and use computers for activities such as quantity take off, calculations, and estimating report generation and use digitizing tablets

to transfer the dimensions of building elements from paper onto computer. Spreadsheet templates are also widely used in estimating by contractors.

Most building design drawings currently used by contractors are produced using 2D CAD systems. Since 2D CAD systems do not contain building element properties, it would be difficult to develop estimating systems that can directly import building information from the CAD files. With the advent of new 3D CAD software, new generations of estimating systems are being designed that can directly import all information necessary for creating an estimate from CAD models.

Database technology has also advanced greatly in recent years and has made it possible to organize and rapidly retrieve a large amount of up-to-date data from remote sources. Application of the latest relational databases has also become easier with the latest data access languages and scripting technology.

Another technology that has advanced tremendously in recent years and can be employed in improving the estimating process is 3D graphics and visualization technology. With the advances in visualization technology, it is now possible to visualize the building and allow the estimator to interact with it. This allows the estimator to select elements that should be included in an estimate as he/she walks inside the building.

## **1.2 RESEARCH GOAL**

The goal of this research is to make the process of construction cost estimating simpler and more intuitive by incorporating visualization technology. It is difficult and time consuming to prepare an estimate by looking at a long list of building elements.

With the visual approach to cost estimating, the estimator can see exactly the location and relationship between building elements while inside the virtual building. Information from a 3D CAD model can be extracted and transferred to estimating software. This helps reduce the time for manual data entry.

### **1.3 RESEARCH OBJECTIVE AND APPROACH**

To achieve the research goal, the following objective and approach have been completed:

1. A visualization module has been developed to assist the visual estimating process using the Microsoft DirectX graphic library. A virtual environment for a 3D model is provided by both geometry and material information extracted from a 3D CAD model.
2. Components have been developed to navigate and interact with the 3D model. First and third person cameras enable users to walk around or inside the virtual building for visualization of the project and visually estimate the project by selecting elements. This approach is based on the findings of cognitive theories which emphasize visualization, in the form of images or walkthrough, to help reduce the user's memory load.
3. Database technology has been used to store cost information that is necessary for construction cost estimating.
4. To minimize the tedious process, a connection between 3D CAD model the process of construction cost estimating must be formed. An estimating application has been developed to provide an interface that uses the latest

findings in cognitive science, virtual reality, and interactive visualization to simplify the cost estimating process, making it more intuitive.

#### **1.4 RESEARCH SCOPE**

This research focuses on a visual approach to construction cost estimating. Estimating the cost of a building project consists of determining the cost of a large number of building elements made of different materials. For example, a building might consist of concrete, steel, masonry, mechanical, electrical, and plumbing elements.

The Revit Architecture BIM software package has been used to create 3D CAD models. Visualizing the 3D CAD model is limited to a computer workstation using keyboard and mouse navigation.

#### **1.5 THESIS ORGANIZATION**

This thesis consists of eight chapters. Chapter 1 provides an introduction to the research problem, approach, and scope for the thesis. Chapter 2 provides an overview of current construction cost estimating practices, focusing on detailed estimates, information needed for a detailed estimate and an example illustrating how the information is used to make an estimate. Chapter 3 discusses the impact of building information modeling (BIM) on the construction industry and how BIM is used to change the way construction is done. Chapter 4 discusses cognitive psychology, how it explains the way humans think and solve problems and how construction industry implements virtual reality and interactive visualization to visualize construction projects.

Chapter 5 discusses the architecture of a visual estimating computer application developed in this study and its objectives. It also explains the interaction of the Visual Estimating Application with Autodesk Revit, 3D CAD models, and cost estimating databases. Chapter 6 discusses database models, especially the relational model, and how a database was designed for the Visual Estimating Application. Chapter 7 demonstrates the Visual Estimating Application developed in this study. This is divided into two parts; database management and visual estimating process. It shows Visual Estimating Application can be used to estimate a building project. Chapter 8 provides a brief description of research summary, contributions, limitations, and recommendations for future research in the area of visual construction cost estimating.

## **CHAPTER 2**

### **CONSTRUCTION COST ESTIMATING**

#### **2.1 INTRODUCTION**

Cost estimating is an essential task for budgeting and bid preparation for any construction project. A good estimate depends on many factors including time given to the estimator, estimator's experience, and a wide range of assumptions regarding the project (Jrade and Alkass, 2007). Construction cost estimating involves collecting, analyzing, and summarizing all available data for a project (Holm et al., 2005). This chapter will focus on detailed estimates, the information needed for a detailed estimate and an example illustrating how the information is used to make an estimate. Today's detailed estimating technologies and the difficulties associated with detailed estimates are also reviewed.

#### **2.2 WHAT IS CONSTRUCTION COST ESTIMATING?**

A construction cost estimate is a prediction of the total cost of a construction project. It's the estimator's responsibility to assist the owner of the project to plan and budget for the construction of the project (Choi, 2004). There are three different types of estimates used at different stages of construction: conceptual, semi-detailed, and detailed cost estimates (Holm et al., 2005). The difference between these three estimating methods is explained in table 2-1.

As Table 2-1 shows, the accuracy varies among estimating methods. The completeness of construction documents and the methodologies of different contractors

are two aspects that could affect the accuracy. This thesis will focus on detailed cost estimating.

<b>Type of Estimate</b>	<b>Construction Development</b>	<b>Expected Percent Error</b>
<b>Conceptual</b>	Programming and schematic design	± 10-20%
<b>Semi-Detailed</b>	Design development	± 5-10%
<b>Detailed</b>	Plans and specification	± 2-4%

TABLE 2-1: Three types of construction cost estimating methods. (Holm et al., 2005)

### **2.3 DETAILED COST ESTIMATES AND THE ESTIMATING PROCESS**

Detailed cost estimating is a time-consuming process. It is prepared when all documents of the construction project have been completed. Creativity and knowledge are essential for preparing a construction cost estimate. Different contractors use different processes, methods, and technologies during construction. Therefore, estimators need knowledge, creativity, and experience to execute the estimating task successfully.

Detailed cost estimating consists of two important steps: quantity estimate, also known as quantity takeoff, and pricing.

In a detailed cost estimate, the estimator divides the project into individual work items and estimates the quantities of materials for each work item. This is also known as quantity takeoff. Labor, equipment, and material needed for executing a work item are then determined based on the specification and the construction method.

After the element has been selected for cost estimating, the estimator must select work items necessary for the element. Construction of a building element may consist of a number of work items. For example, a concrete slab element may consist of several

work items such as forming, reinforcing, concrete pouring, finishing, and curing. A sample of work items for a concrete slab-on-grade is tabulated in Table 2-2 (RSMeans Building Construction Cost Data, 2009).

<b>Work Item</b>	<b>Crew</b>	<b>Productivity</b>
Place Welded Wire Fabric (WWF)	1 ironworker	450 SF/Hr
Place Concrete (Use Pump)	1 non-working foreman, 5 laborers, 1 concrete finisher, 1 pump operator, 2 gas vibrators, 1 concrete pump	130 CY/Day
Screed and Bull-Float	2 concrete finishers	750 SF/Day
Machine Trowel	1 concrete finisher, 1 ride-on trowel machine	550 SF/Day
Curing	1 laborer	4500 SF/Day

TABLE 2-2: Working Items for Concrete Slab-On-Grade

As Table 2-2 shows, different work items require different sets of labor and equipment. The combination of labor and equipment for performing a work item is called a crew. Productivity is defined as the amount of work a crew can perform in a unit of time. Determining productivity is necessary to accurately calculate the price of each work item.

Costs of labor, equipment, and material must be decided after the work items have been determined for the elements. Labor cost depends on different factors such as hourly rate, fringe benefits, applicable taxes, and insurance costs. Table 2-3 shows a sample of different labor trade rates in the Milwaukee area, their base hourly rate, and fringe

benefits (State of Wisconsin Department of Workforce Development Website, Milwaukee County, 2009; ACEA Website, 2008).

<b>Labor Trade</b>	<b>Base Hourly Rate</b>	<b>Fringe Benefits</b>	<b>Total</b>
Concrete Finisher	\$27.82	\$12.97	\$40.79
General Laborer	\$24.32	\$13.93	\$38.25
Non-Working Foreman*	\$26.75*	\$10.78*	\$37.53
Concrete Pump Operator	\$26.94	\$16.75	\$43.69
Ironworker	\$28.96	\$18.18	\$47.14

TABLE 2-3: A sample of labor trades (State of Wisconsin Department of Workforce Development Website, Milwaukee County, 2009; \*ACEA Website, 2008).

Equipment could be owned or rented. If owned, the cost is based on two components: ownership cost and operation cost. However, if rented, the cost is based on the rental cost of the equipment and whether rented hourly, daily, weekly, monthly, or annually. Table 2-4 is a sample of equipment costs based on daily rental (RSMeans Building Construction Cost Data, 2009).

<b>Equipment</b>	<b>\$/Day</b>
Concrete Pump	\$737.80
Gas Vibrator	\$52.00
Ride-On Trowel Machine	\$145.00

TABLE 2-4: A sample of equipments (RSMeans Building Construction Cost Data, 2009)

Cost of material is the easiest one to determine. It is based on the market unit price of the material. Table 2-5 shows a sample of different material unit costs (RSMMeans Building Construction Cost Data, 2009).

<b>Material</b>	<b>Unit Cost</b>
Welded Wire Fabric	\$0.66/SF
4000 psi Concrete	\$106/CY
Curing Compound	\$0.53/SF

TABLE 2-5: A sample of materials (RSMMeans Building Construction Cost Data, 2009)

Quantity takeoff and pricing can be calculated after all of the necessary information has been gathered. Quantity takeoff must be calculated based on the blueprints and the specification. The quantity estimated and the cost of labor, equipment, and material are used to calculate the total cost for each work item.

After each work item has been estimated, all work item costs are summed to get the total cost. Afterward, taxes, overhead cost, and profit are added to complete the estimate. The estimate worksheet can then be printed for bidding documents or future reference. Review and analysis by the estimator is also required to determine if the price of the assembly seems reasonable for the amount of work that has to be performed.

Each building assembly represents a building construction activity that can be fully defined as an element in the project. Each assembly is made up of different work items that are created for construction cost estimating. After the cost of the assembly has been determined, assembly unit cost must be determined. Assembly unit cost is

determined based on the unit of measurement. For the slab-on-grade example, the assembly unit is a square foot.

### 2.3.1 A Detailed Estimate Example

An example of a detailed cost estimate is shown below. The project consists of two different element types: wall and concrete slab-on-grade, as shown in Figure 2-1. Figure 2-2 shows the detail between wall and concrete slab in a sectional view. Thickness of the slab can also be found in Figure 2-2. In this example, the estimator must determine the cost of concrete slab-on-grade element using the information from Table 2-2, 2-3, 2-4, and 2-5. 15% of overhead cost and 5% profit are assumed values for this example.

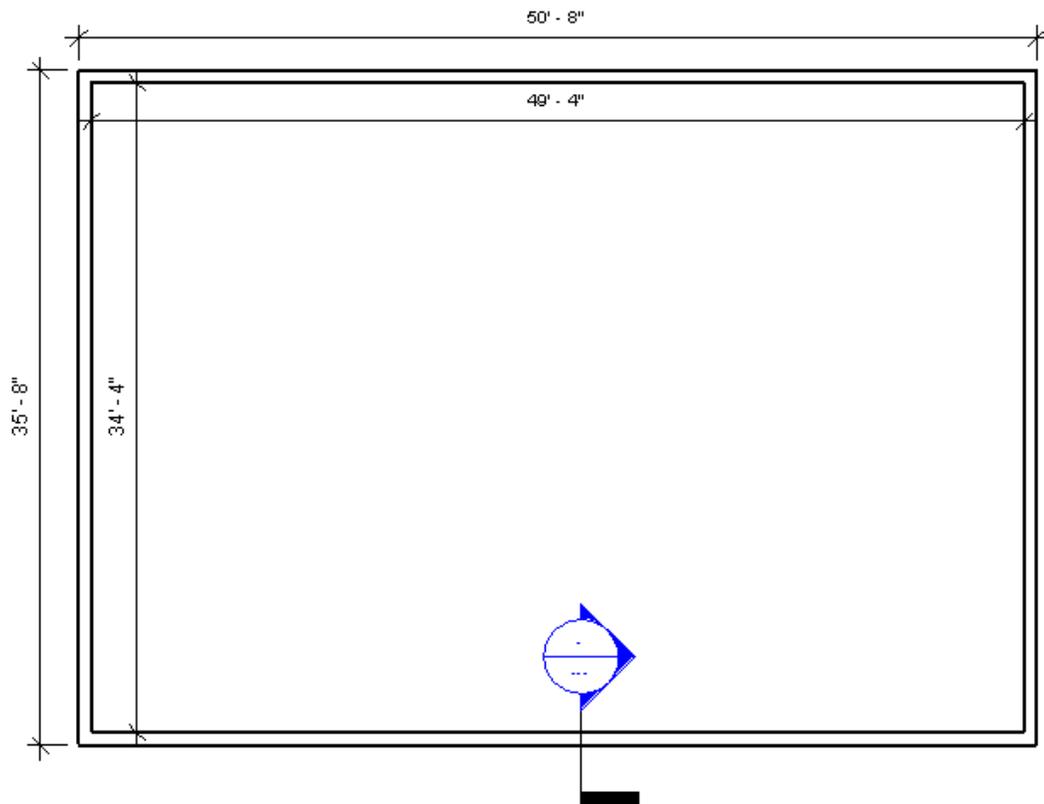


FIGURE 2-1: A building plan consisting of four walls, and a slab-on-grade.

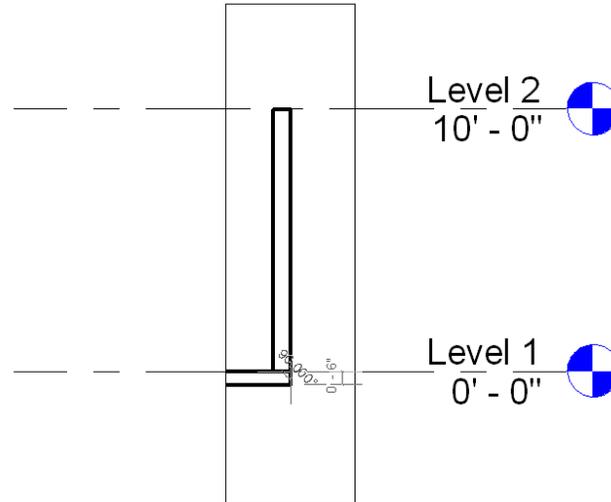


FIGURE 2-2: A section view of wall and slab-on-grade. Slab-on-grade is six inches thick.

Since the information has been already been determined, the quantity takeoff can be calculated based on the blueprints provided in Figure 2-1 and 2-2. Table 2-6 shows the quantities for each work items that has been calculated.

Work Item	Quantity	Unit
Place Welded Wire Fabric (WWF)	1807.40	SF
Place Concrete (Use Pump)	33.47	CY
Screed and Bull-Float	1807.40	SF
Machine Trowel	1807.40	SF
Curing	1807.40	SF

TABLE 2-6: Quantity of work items for the slab-on-grade assembly

Pricing can then be determined based on the calculated quantity in Table 2-6 and the productivity of each work items in Table 2-2. Table 2-7 shows the detailed costs of different work item.

As one can see from Table 2-7, the amount of work that needs to be performed for each work item is based on how much labor or equipment is needed and how long it takes to finish the particular work item based on the productivity given in Table 2-5. For example, productivity in Table 2-5 provided 130 cubic yards of concrete can be poured in a working day. 33.47 cubic yards of concrete must be poured for this concrete slab-on-grade example. Therefore, it takes only 2.06 hours to pour concrete. Five laborers are needed to pour concrete for the slab; therefore, 10.3 hours of laborer are needed to estimate the work item.

Sum of all the costs are then calculated for different cost categories. For this example, 5.6% sales tax is added to the total material cost. This is based on the 2009 Milwaukee County sales tax. The assumed value for overhead cost and profit are 15% and 5% respectively. The over head cost is added to the total cost of labor, equipment, and material. The profit is then added to the total cost.

Work Item	Quantity	Unit	Labor		Equipment		Material	
			Unit Cost	Total	Unit Cost	Total	Unit Cost	Total
<b>Place Welded Wire Fabric (WWF)</b>	<b>1807.4</b>	<b>SF</b>						
Ironworker	4.02	Hours	\$47.14	\$189.50				
Welded Wire Fabric	1807.4	SF					\$0.13	\$234.96
<b>Place Slab Concrete (Use Pump)</b>	<b>33.47</b>	<b>CY</b>						
Non-working Foreman	2.06	Hours	\$37.53	\$77.31				
Laborer	10.3	Hours	\$38.25	\$393.98				
Cement Finisher	2.06	Hours	\$40.79	\$84.03				
Pump Operator	2.06	Hours	\$43.69	\$90.00				
Concrete	33.47	CY					\$106.00	\$3,547.82
Concrete Pump	1	Day			\$700.00	\$700.00		
Gas Vibrator	2	Day			\$35.00	\$70.00		
<b>Screed and Bull-Float</b>	<b>1807.4</b>	<b>SF</b>						
Cement Finisher	38.56	Hours	\$40.79	\$1,572.86				
<b>Machine Trowel</b>	<b>1807.4</b>	<b>SF</b>						
Cement Finisher	26.29	Hours	\$40.79	\$1,072.37				
Ride-on Trowel Machine	4	Day			\$95.00	\$380.00		
<b>Curing</b>	<b>1807.4</b>	<b>SF</b>						
Laborer	3.22	Hours	\$38.25	\$123.17				
Curing Compound	1807.4	SF					\$0.05	\$90.37
<b>Sub-total (Slab On Grade)</b>				<b>\$3,603.21</b>		<b>\$1,150.00</b>		<b>\$3,873.15</b>

TABLE 2-7: Detailed estimating of work items for the slab on grade assembly

Work Item	Quantity	Unit	Labor		Equipment		Material	
			Unit Cost	Total	Unit Cost	Total	Unit Cost	Total
<b>Sub-total (Slab On Grade)</b>				<b>\$3,603.21</b>		<b>\$1,150.00</b>		<b>\$3,873.15</b>
Sales Tax (5.6%)								\$216.90
Labor Burden Cost (50%)				\$1,801.61				
Overhead (15%)				\$540.48		\$172.50		\$580.97
<b>Sub-total</b>				<b>\$5,945.30</b>		<b>\$1,322.50</b>		<b>\$4,671.02</b>
<b>Total</b>	\$11,938.83							
<b>Profit (5%)</b>	\$596.94							
<b>Grand-Total</b>	<b>\$12,535.77</b>							

TABLE 2-7 (continued): Detailed estimating of work items for the slab on grade assembly

## **2.4 TODAY'S TECHNOLOGIES FOR DETAILED COST ESTIMATE**

As one can see, detailed cost estimating is a cumbersome process that involves a lot of data and calculations. Any technology that could assist the process of construction cost estimating would help reduce estimator's work load. Computers are considered to be effective tools for assisting estimators during the construction cost estimating process. Computers provide many benefits including reducing estimation errors and the time needed to produce an estimate. Today's estimating technologies include, but are not limited to, spreadsheets, cost estimating software, digitizing tablets, on-screen digitizing systems, and the yet to be matured 3-D CAD parametric estimating software.

### **2.4.1 Spreadsheet Estimating**

A spreadsheet is a computer application that simulates a paper worksheet. It provides the user with cells that are compiled into rows and columns. Each cell can contain either text, numerical values, or formula can be defined in cells to obtain calculated value from the related cells. Complicated mathematical calculations can be automated with a change of a single cell with the use of formula in the spreadsheet. Contractors use worksheets to accelerate the estimating process. The estimator can set up a template with saved formula in the spreadsheet. Estimator can also perform quantity takeoff calculations within a spreadsheet. Although a spreadsheet requires a lot of input from the estimator, it eliminates the cumbersome and error prone manual calculations during the quantity takeoff and pricing.

### **2.4.2 Construction Cost Estimating Software Packages**

Various software packages are available to assist the estimator during the detailed cost estimating process. The capabilities of software packages vary greatly. Some include labor, equipment, and material cost databases, which facilitates the estimating process after the database is set up. In order to perform a quantity takeoff, estimating software packages include technologies such as digitizing tablets, on-screen digitizing systems, and 3D CAD models.

### **2.4.3 Digitizing Tablets**

A digitizing tablet is a computer input device that uses a stylus and a tracking surface to capture the drawing on to the computer system. The drawing traced on the tracking surface transfers point coordinates to a computer, thus it can be used for many different purposes including construction cost estimating. Digitizing tablets' purpose in construction cost estimating is to digitize the paper-based blueprints provided by the owner of the project or the designer. For example, the estimator can get the length, perimeter, or area out of the drawing by the scale provided in the blueprints. These parameters are available when using the digitizing tablet via software package. The software package may also include estimating software. After the paper blueprints have been digitized and the quantities for all work items have been determined, the estimator can use those quantities to estimate the prices of items.

### **2.4.4 On-Screen Digitizing System**

On-screen digitizing systems work the same way as a digitizing tablets. The main difference is that an on-screen digitizing system works with computer graphic files or

scaled CAD documents instead of paper blueprints. This saves money by eliminating the need for printing large paper blueprints and delivering them, since digital files or documents can be sent by e-mail using electronic files.

#### **2.4.5 3-D CAD**

3-D computer aided drawing (CAD) models help estimators visualize what is going to be built in the 3-D environment. The ability to digitally extract and transfer data can speed up cost estimating process. A building model can be seen in many different views, where details of elements, including their dimensions can be extracted and transferred to the estimating software. A software company named Innovaya (Innovaya Website, 2009) has already attempted construction cost estimating using 3-D CAD; however, it is still a work in progress. Innovaya uses the estimating engine from Timberline (Timberline Website, 2009) or MC<sup>2</sup> ICE (MC<sup>2</sup> ICE Website, 2009).

### **2.5 INEFFICIENCIES ASSOCIATED WITH TODAY'S DETAILED ESTIMATING METHODS**

As discussed in section 2.4, even though computers have become a part of the construction cost estimating process, there are still inefficiencies in the estimating process. Quantity takeoff using the digitizing tablets or on-screen digitizing systems may provide errors from unstable hand during tracing the drawing. Digitizing a large number of blueprints is also a very time-consuming process.

Most building design drawings currently used by contractors are produced in 2-D CAD systems. Since 2-D CAD systems do not contain building element properties, it would be almost impossible to develop estimating systems that can directly import

building information from the CAD files. Although Innovaya has attempted using the data provided by 3-D CAD, it is a work in progress and has yet to be proven. The test run of Innovaya and MC<sup>2</sup> ICE estimating software showed that the parametric data such as length, width, or height from CAD models do-not transfer to the cost estimating software automatically. It requires manual input by the estimator. Although it saves time, the system could be improved by developing an application to directly import necessary information from CAD files.

## **2.6 SUMMARY**

Today, detailed cost estimating is done using computer-assisted technologies, which includes spreadsheets and estimating software. However, error prone and time consuming processes are a few difficulties that could arise during the estimating process. Although, the process of estimating has been improved, a solution to these difficulties could ease the estimator's task of construction project cost estimating.

3-D CAD and visualization can provide the estimator with a tool necessary to cope with the ever increasing complications in design. Chapter 3 will focus on 3-D CAD and the building information modeling technology, also known as BIM, and how this technology is changing the way contractors work.

## **CHAPTER 3**

### **BUILDING INFORMATION MODELING**

#### **3.1 INTRODUCTION TO CAD AND BIM**

A cost estimate for a construction project can be prepared at any phase of the construction project. However, detailed cost estimates require a complete set of plans and specifications. Although most plans and specifications today are in 2D CAD format, advanced technologies have changed the way drawings are prepared, and 3D CAD drawings are playing a bigger role in documenting design intent. Building information modeling (BIM) is another technology that is making an impact and becoming popular throughout the architecture, engineering, and construction (AEC) industries. The use of BIM enables architect to improve design efficiency. Structural designs can be optimized by the engineer and contractors can improve the planning for the construction of the project. This chapter will discuss in more detail CAD, BIM, the differences between the two technologies, BIM's applications, and the future of the construction industry with BIM technology.

#### **3.2 COMPUTER-AIDED DRAWINGS**

Computer-aided drawings (CAD) have been a significant tool helping architects and engineers in the engineering and design process (Jrade and Alkass, 2007). The basic function of CAD software is to allow the user to prepare drawings by manipulating lines, circles, rectangles, and text interactively on the computer screen. Some types of architectural specific software offer graphical libraries of commonly used building elements such as doors and windows. Creating a drawing is not the main advantage of

using CAD because it could be done on a paper-based medium; however, the main advantage of CAD is its ability to easily edit a design (Sun and Howard, 2004). CAD allows users to delete, move, copy, rotate, scale, and mirror design elements with ease. CAD also has the functions to create repetitive design components, create elements at equal distance on a line, a circle, or on a grid, extending lines, trimming lines, and fillet any corners of an edge. These tasks are not easily carried out on the paper based drafting. CAD allows designers to concentrate on the creative aspects of the design instead of being distracted from unproductive activities (Bazjanac, 1975). CAD can be divided into two major categories: two dimensional (2D CAD) and three dimensional (3D CAD).

2D CAD is considered to be fast and easy to use. It is the most popular method of drafting in today's construction industry (Sun and Howard, 2004). A 2D CAD drawing, as shown in Figure 3-1, is a vector-based display of a project.

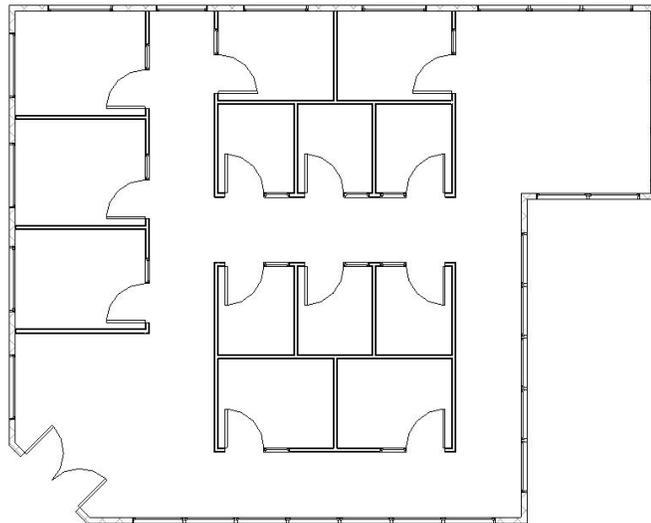


FIGURE 3-1: A 2D CAD Drawing

Although it is fast and easy to use, 2D CAD uses lines to draw components instead of the actual elements. Viewing of 2D drawings does not provide designer with different angles of the design. 3D CAD is an alternative to 2D CAD, allowing views from different angles and potential virtual environment capabilities of walking through or flying through the structure.

3D CAD can be created from 2D CAD by adding depth and elevation to the design. 3D CAD models are three dimensional drawings which represent objects in the X, Y, and Z axis (Reffat, 2002). The benefit of 3D CAD is the ability to visualize the building; designers can determine spaces available, thus improving the design. 3D CAD can also be turned into animation and visualization system where clients can experience the design at various settings of the project from different angles and views (Dzambazova, Demchak, and Krygiel, 2008; Vince, 2004; Sun and Howard, 2004).

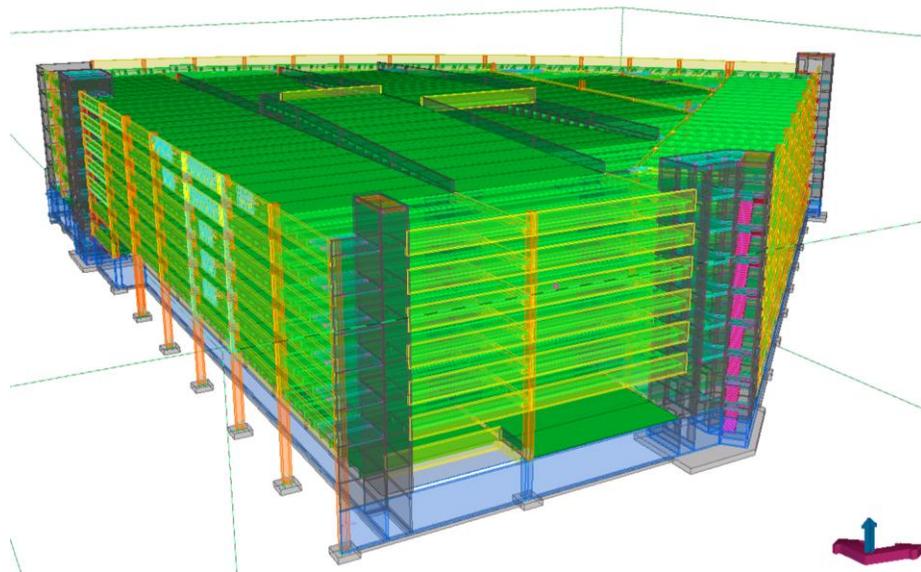


FIGURE 3-2: 3D CAD Wire Frame Model

Different types of views, such as a wire 3D or a solid provided by the 3D CAD model, can be used extensively for different purposes. For example, wire 3D model, as shown in Figure 3-2, can be used to evaluate the structural integrity of the design. Solid model, as shown in Figure 3-3, can be used to see if the design will fit in the surrounding environment.



FIGURE 3-3: Rendered 3D CAD Model

### **3.3 BUILDING INFORMATION MODELING**

Although 3D CAD helps visualize the proposed structure during the design process, building information modeling or BIM can provide a better alternative. The process of BIM could help improve many aspects of the construction project.

Building Information Modeling (BIM) is one of the most promising developments in the Architecture, Engineering, and Construction (AEC) industries (Azhar et al., 2008).

According to Khemlani, BIM is a revolutionary technology that goes well beyond the design phase to impact construction and lifecycle management of the project (AECbytes Website, 2009). BIM 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). Information provided by BIM includes, but is not limited to, dimensions, coordinates, properties, and other element details for the building. BIM technology would provide the potential for improving communication between participants involved in the construction project, improving the quality of information, the quality of services delivered, and reducing cost at every stage in the life cycle of a building (Smith and Tardif, 2009).

As today's technology grows more complex, building design has become more complicated. The involvement of the computer technology at the earliest phase of the design process is becoming more common. Difficulties of the design associated with the complexity of the building could provide many problems to not only the designer but also the engineers and the contractors who build it. BIM provides the ability for the designer to design the building with the modeling tool that creates object elements instead of different types of lines connected to make up a model. The 3D parametric model that BIM provides does not only provide the visualization of the model in three dimensions, but it also stores information about the elements that make up the building. This information includes its physical characteristics such as dimensions, locations, and texture of the objects. Functional characteristics could also be found in the parametric

model, including the information about manufacturers and operating and maintenance procedures (Azhar et al., 2008).

Structural analysis could also be done concurrently with the design process. Since BIM contains all the geometric information of the building, engineers could extract the necessary information to perform structural analyses.

Contractors can also benefit from BIM. It provides many features that help contractors avoid costly errors during construction of the project. Element clashes can be detected before the construction has started, saving contractors' time and money. Complexity of the construction or the design of the building could also provide many difficulties during the preparation of plans and specifications. With an integrated parametric 3D model, it's possible to detect spatial clashes between the multitudes of systems in the building (Dzambazova, Demchak, and Krygiel, 2008). Computer analytical systems could support design decision making by enabling designers to test and evaluate design alternatives rapidly in the search for an optimum solution (Bazjanac, 1975). Ambiguities in the design can also be highlighted by any team member and resolved before the design has been finalized. Constructability issues can be raised and debated among the parties involved (Levy, 2006). Time that is normally spent manually checking all the drawings by the design consultants and by the contractor and their subcontractors will be reduced considerably. This allows all parties to be more productive on other tasks such as project management or quality control.

Facility management could also benefit via the completeness of documents at the end of the construction. BIM provides the model where every detail of the constructed

building is included. The information provided by BIM is very detailed and can be used not only for design and construction purposes, but also for the post construction documentation where the details of every element of the building are archived. This provides convenience for the owner because the BIM file can be used for many purposes. Since the file is updated throughout the construction, it contains all the elements that have been used in the actual project rather than the originally designed elements that might be modified during construction.

BIM provides reliable features to architects, owners, engineers, contractors, and all participants involved in the project (Alkas and Jade, 2007). It uses a single outlet to store all information about the building (Cyon Research Website, 2003). It is a system that creates a single building model as a repository for all elements of a building (Levy, 2006). The development of a digital database enables collaboration among participants in the construction project (Smith and Tardif, 2009), thus documents can be kept consistent with one another (Cyon Research Website, 2003). Review and changes can be recommended from every party involve in the project.

### **3.4 BIM vs. CAD**

BIM provides many advantages over CAD. The key difference between BIM and CAD is that a traditional CAD system uses many separate 2D documents to explain a building. These documents are created separately and have no intelligent connection between them. The possibility of uncoordinated data is very high. The change management created by CAD is a tedious and error-prone process. BIM takes a different

approach: it assembles all information into one location and cross-links that data among associated objects.

By and large, CAD is strictly a 2D technology with a specific need to output a collection of lines and text on a page. These lines have no meanings, whether inside the computer or on the printed sheet. CAD drafting has its efficiencies and advantages over pen and paper, but is really just a simulation of the act of drafting. Historically, the designer drew a set of plans and then used those plans to manually derive sections, elevations, and details. During the development of a project, if any of those items changed, the designer had to modify each of the other drawings that were affected to take the change into account. This is where BIM makes a significant departure from legacy CAD platforms.

The beauty of BIM is that it manages change without having to change all drawings. Unlike CAD, the intent of BIM is to let the computer take responsibility for redundant interactions and calculations, providing the designer with more time to design and evaluate decisions. A core feature of BIM allows users to create and modify everything in one design context. The system will propagate changes to all relevant views in the project. As the designer models in plan, the elevations, sections, and details are also being generated. It doesn't matter where the change is made, the system will propagate this change as necessary. For example, if a change is made to the size of a window opening in elevation, this change is made throughout the entire model.

An additional advantage of a BIM methodology is that the design cannot be cheated. The elements have properties based on actual character; it is difficult to fake

elements within the design. In CAD system, this can be easy to overlook, because the door has to be manually transcribed from plan to section and elevation. Because BIM is based on actual assemblies it's very difficult to misrepresent dimensions or objects within the model.

A CAD system uses many separate files to document a building, whereas a BIM project typically has only one file. CAD files are created individually and have no intelligent connection between them. Each drawing represents a separate piece of work to be managed and updated throughout the design process. The possibility of uncoordinated data between drawings is therefore very high. BIM takes a different approach by combining all the information and relating it to a single file, thus guaranteeing a consistent model (Dzambazova, Demchak, and Krygiel, 2007; Dzambazova, Demchak, and Krygiel, 2008). Interference checking in BIM also permits the user to immediately see conflicts among architectural, structural, and mechanical elements in 3D.

BIM is based on an architectural classification system, not "layers". Because a building model is an assembly of meaningful, to-be-built objects, the user controls visibility and graphics of objects using a rational list of well understood categories. This is different from CAD, where every line belongs to a layer, and it is up to the user to manage all layers.

BIM's digital file can be used to instruct machines to produce components. Traditional CAD files need to be annotated before they are sent to the fabricator. Models from BIM can be sent directly to fabrication machines without the need of traditional shop drawings (Dzambazova, Demchak, and Krygiel, 2008).

### 3.5 INTEROPERABILITY

No single computer application can support all of the tasks associated with building design and production (Eastman et al., 2008). Data exchange between various parties involved in the project is also critical (Day, 1997). Interoperability depicts the need to pass data between applications, allowing multiple types of experts and applications to contribute to the work at hand. Interoperability is defined as the ability to exchange and use information. It is also the capability of different software to communicate and work together seamlessly. In the instance of BIM, it is the sharing of information between software (Reffat, 2002; Levy, 2006). The standard and compatibility between different applications have to be realized.

Another definition of interoperability is an open standard for building data exchanges, in effect, interoperability means that your system can “talk” to mine, and we can all “talk” to the designers, contractors, subcontractors, vendors, and owner’s representatives in the same language. Transmitting 3D imagining to all parties of the design and construction process, if it is to be fully utilized, requires a single, seamless integration of the entire project’s database-from design and construction to commissioning and continuing on through the building’s lifecycle, and that’s where interoperability plays a major role.

The design and construction of a building is a team activity, and increasingly each activity and each type of specialty is supported and augmented by its own computer applications. Beside the capability to support geometry and material layout, there are structural and energy analyses, cost estimation and scheduling the construction, and

fabrication issues for each subsystem. Interoperability identifies the need to pass data between applications, and for multiple applications to jointly contribute to the work at hand. Interoperability eliminates the need to replicate data input that has already been generated, and facilitates smooth workflows and automation.

Data exchanges between two applications are typically carried out in one of the four main ways listed below:

1. Direct, proprietary links between specific BIM tools
2. Proprietary file exchange formats, primarily dealing with geometry
3. Public product data model exchange formats
4. XML-based exchange format

Direct links provide an integrated connection between two applications, usually called from one or both application user interfaces. Direct links rely on middleware software interfacing capabilities such as ODBC (Open DataBase Connectivity) or proprietary interfaces such as Revit's API (Revit's Application Programming Interface). These are all programming level interfaces, relying on C, C++, or C# languages. The interfaces make portions of the application's building model accessible for creation, export, or modification.

A proprietary exchange file format is one developed by a commercial organization for interfacing with that company's application. While a direct linking of application is a runtime and binary interface, and exchange format is implemented as a file of human readable text format. A well known proprietary exchange format in the AEC area is DXF (Data eXchange Format) by Autodesk.

The public level exchange formats involve the use of an open-standard building model. In 1994, an industry consortium was initiated to develop a class library for representing construction project information and facilitating project data exchange among software serving the AEC industry. The consortium was initially called Industry Alliance for Interoperability. In 1997, the Alliance was renamed to International Alliance for Interoperability (IAI) and became a global standards-setting organization representing diverse constituencies including architects and engineers, software manufacturers, government agencies, contractors, building owners and product manufacturers (IAI Website, 2009). The IAI's goal of developing standards for interoperability throughout the AEC industry is primarily achieved through its Industry Foundation Classes (IFC). IFC is a comprehensive data representation of the building model. The IFC object descriptions deal with not only full 3D geometry but also relationships, process, material properties, cost, and other behavior data (Hamilton et al., 2007). Integrating a CAD model with IFC enables the accurate geometric representation to be integrated with structural and behavior elements and facilitates linking with external applications. According to Khemlani (AECbytes Website, 2009), the IFC data model is likely to become the international standard for data exchange and integration within the building construction industries.

XML or eXtensible Markup Language is an extension to HTML, the base language for the Web. XML allows definition of the structure and meaning of some data of interest; that structure is called a schema. The different XML schemas support exchange of many types of data between applications. XML is especially good in

exchanging small amounts of business data between two applications set up for such exchanges.

Interoperability provides the opportunities in the AEC industry to discover applications that could be used with BIM. This creates more possibilities for BIM to be used by different participants during a construction project. Applications associated with BIM are discussed in section 3.6.

### **3.6 APPLICATIONS OF BIM**

BIM provides many benefits throughout the lifetime of a construction project. It is useful during the design phase, during actual construction and after the construction has been completed. BIM uses interoperability to enable the exchanging of information between different applications. Interoperability, as discussed in section 3.5, is used to facilitate collaboration between different project participants. Therefore, BIM could be used as a tool to help improve not only the construction process but it also helps to manage the facility after the construction is completed.

#### *Concept and Feasibility Study*

Before the owner approaches an architect, it is necessary to determine the size of the building, its functionalities and features that can be built within the budget and time constraints. The goals and expectations could be achieved if the concept and feasibility study of the project are within the acceptable limitations. A rough sketch of building model built and linked to a cost database can be a tremendous assistance to an owner. BIM could be used as an application to help owner during the concept and feasibility study.

### *Accuracy and Consistency of 2D Drawing*

2D drawings can be extracted and generated directly from a BIM model. This reduces the amount of time and number of errors, while generating project drawings. Also, when changes are made to a model, the drawings are updated and may be regenerated as soon as the modifications are made.

### *Early Collaboration of Multiple Design Disciplines*

BIM enables virtual coordination of a building's infrastructure across all disciplines. The coordination of mechanical, electrical and plumbing (MEP), architectural, and structural systems can be achieved through the fully integrated 3D models that BIM provide. Design time could be shortened and design errors and omissions can be reduced. Rework due to the design flaws could be avoided with this coordination of work. It also gives an earlier insight into the design problems and provides an opportunity for a design to be improved continuously.

### *Check of Design Intent*

BIM provides an early visualization of the 3D model. It allows the designer to see if the design intent of the project has been achieved. The intent of the design is the arrangement of features and dimensions that has been specified at the conceptual design of the project. Purposes of spaces and rooms can be visualized at an earlier stage of construction where changes can be made with little to no addition cost.

### *Cost Estimating*

Construction cost estimating can be achieved at a better level. Estimates that use conceptual BIM consisting of components can provide owners with quick feedback on various design scenarios. Accurate estimates can be very valuable early in the project life cycle, especially for assessing a project's predicted cash flow.

BIM provides quantity takeoff tools to create faster, better detailed, and more accurate estimates. During the construction of a project, owners and estimators struggle with the ability to respond to design and requirement changes and to understand the impact of those changes on the overall project budget. By linking the design model to an estimating application, the project team can speed up the quantity takeoff and overall estimating process to get faster feedback on proposed design changes.

### *Improve Energy Efficiency and Sustainability*

The green building trend is leading many owners to consider the energy efficiency of their facilities and the overall environmental impact of their projects. Sustainable building is good business practice and can lead to greater marketability of a facility. Building models provide several advantages over traditional 2D models due to the richness of object information needed to perform energy or other environmental analyses. Daylight analysis, glare, and solar heat gain are a few scenarios that help reduce the cost of operation for the facility.

### *Construction Planning*

Pre-fabrication provided by BIM-based design can greatly reduce the project duration, from project approval to facility completion. The parametric nature of the BIM model makes design changes easier and it automatically updates the necessary documentations.

Owners also pay the cost for construction delays or lengthy project durations, either in interest payments on loan, delayed rental income, or other income from sales of goods or products. The application of BIM to support coordination and prefabrication can result in-improved field productivity, reduced field effort, and reductions in the overall construction schedule, which results in on-time delivery for the owner.

BIM models can also be used to create a 4D model by adding the time dimension. Owners and their service providers often encounter unforeseen conditions that even the best digital models cannot foresee. Teams using digital models are often in a better position to respond to unforeseen conditions.

### *Local Code Compliance*

Owners and their design teams must work with a variety of jurisdictions to ensure their facilities meet design, performance, and work place safety codes. Regulatory personnel also face challenges for ensuring compliance and conformance during design and construction. A potential benefit of a building information model is the ability to automatically analyze and check the model for code compliance.

### *Clash Detection*

Design errors could be a result of inconsistencies in the 2D drawings. These errors are eliminated with the adaptation of virtual 3D model. Clashes can be identified before the construction in the field begins.

### *Design Model as Basis for Fabricated Components*

BIM provides a better involvement with the manufacturer of the component. BIM shows exactly how the component will fit into the project. Necessary information for the component is provided within the model. Fabrication of components on site would be faster through better coordination, better connections, better assembly planning and training.

### *Lean Construction*

Lean construction is a way to design production systems to minimize waste of materials, time, and effort in order to generate the maximum possible amount of value (Koskela et al. 2002). BIM maximizes the efficiencies by providing accurate model information and the material resources needed for the different stages of construction. It provides the basis for better planning and scheduling. This helps ensure that labor, equipment, and material are ready at the job site when they are needed.

### *Facility Operation and Management Systems*

BIM helps produce higher quality and maintainable infrastructure through interactive review of coordinated models. Some owners need more than typical MEP

systems to be accessible and maintainable. Interactive review of the model allows owners to virtually access and simulates maintenance procedures.

BIM could be used to quickly populate a facility management database. Since BIM is updated throughout the construction of the project, it can also be used as the as-built plans that are used to manage the facility. Maintenance work and impact to retrofits could be evaluated by using the visual and intelligent models to help facility managers.

A model, which has been updated throughout the construction, is a tool with great accuracy for operating and managing the completed building. BIM can be used as an advanced facilities management tool. It could be used for an evacuation plan, fire protection simulation, thermal calculation and air-conditioning analysis (Eastman et al., 2008).

### **3.7 FUTURE OF CONSTRUCTION INDUSTRY WITH BIM**

BIM is a promising technology that will change how things are done in the AEC industry. The transition from early adoption of technology to the mainstream practice is expected in the near future. The future impact of BIM can be separated into different parties and participants.

#### **3.7.1 Designers**

Designers will notice the productivity gains and deliver higher quality services to project owners. Architects and engineers will be able to explore different designs while keeping the cost and schedule of the project in check. BIM will also provide the architects with more information, not only regarding the detail of elements in the

building, but also the visualization aspect. Virtual reality will enable exploration of different environmental impact scenarios such as sun studies, wind analysis, and energy efficiency. Engineers will also be able to do the structural analysis aspect of the model.

### **3.7.2 Owners**

Owners will be able to better explore different designs and have a better plan and schedule for the project. Owners will be able to see 3D visualization of the project at an earlier stage.

### **3.7.3 Contractors**

Contractors will be able to collaborate with other parties involved in the project and have less to worry. Change orders and material changes will be instantaneously updated throughout the model. BIM will allow faster and easier calculation of the construction cost. The collaboration of both designers and the contractors can help minimize delays during construction.

## **3.8 SUMMARY**

There are many advantages that BIM provides. Estimators are able to use the properties provided in the model to estimate the cost of construction. Labor intensive tasks during estimating process can be simplified. BIM facilitates collaboration between project participants. Interoperability also enables different applications to be developed. BIM delivers many significant benefits and tools for all participants during various phases of the project. Reducing errors and more efficient and reliable delivery process

that reduces time and cost are a few benefits to all participants. This thesis will utilize BIM as a technology to develop a visual approach to construction cost estimating.

## CHAPTER 4

### COGNITIVE THEORY AND VIRUTAL REALITY

#### 4.1 INTRODUCTION

Construction cost estimating is a time consuming and tedious process. Although there are technologies to assist with the cost estimating process, inefficiencies still abound. During the process of construction cost estimating, the estimator must learn about the design and conditions of the project. A lot of data are needed to prepare an estimate. Reviewing drawings, extracting information for quantity takeoff and looking up the latest cost information from the cost databases are tasks that estimators must accomplish. To improve the process and ease the estimator's tasks, it is important to understand how humans process information. The latest findings in cognitive psychology, a branch of science that relates to how humans process information, will be examined for this purpose.

In addition to cognitive psychology, visualization technology can also help improve how humans understand and process information. As it has been said "a picture is worth more than words can describe" (Gardiner and Christie, 1987; Retik, 1993), this means visualization can help humans absorb and understand information easier. Visual communication can also reduce humans' cognitive load when processing new information. Computer aided design (CAD) and building information modeling (BIM), which have been discussed in Chapter 3, are two examples of how visualization is currently used in the construction industry. Visualization is useful not only in the design process but also during the construction. Visualization can also benefit cost estimating; it

can make it easier for estimators to become familiar with the new project before starting to prepare the estimate and make the estimating process more intuitive. This chapter will discuss cognitive theory along with virtual reality.

## **4.2 COGNITIVE THEORY**

Cognitive psychology is a science branch that investigates how humans understand and process information distributed across the internal mind and the external environment (Gardiner and Christie, 1987; Nishida, 1992; Boland et al., 2008). According to visual computing theorists and dual processing theory, a basic way to effectively facilitate the connection between internal mind and external environment is to improve the visibility of the information embedded in the data. A good external representation will be one that links naturally to the internal representations that people are capable of forming, thereby supporting their overall cognitive process. The ability to visualize objects and situations in one's mind and to manipulate those images is a cognitive skill vital to many career fields, especially those which require work with graphical representations such as visual arts and engineering (Holliday-Darr, Blasko, and Dwyer, 1999). Using lines and symbols to represent the thoughts and ideas of engineers and designers often provides a more effective means of communicating these concepts than verbal descriptions (Scribner and Anderson, 2005). According to Bertoline et al. (1992), 92% of the design process is graphically based while the other 8% divided between mathematics and written or verbal communications.

Human information processing model consists of both processors and memories that interact in order to process information (Te'eni, Carey, and Zhang, 2007). Figure 4-1

shows the simplified human information processing model that includes both processors and memories. There are three types of processors: perceptual, cognitive, and motor processors, and there are two types of memories: working memory and long-term memory. Attention is needed to facilitate and control this cognitive system.

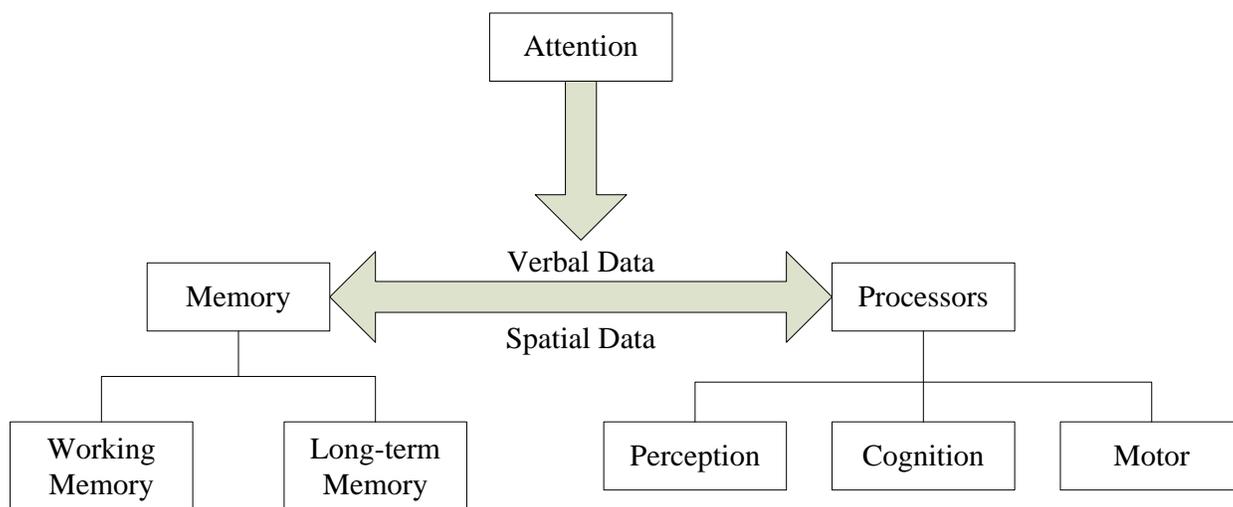


FIGURE 4-1: Simplified model of human information processing (Te'eni, Carey, and Zhang, 2007).

Each processor has specific functions. The perceptual processor senses, detects, and accepts inputs from the external world and stores parts of the input in the working memory. The cognitive processor interprets, manipulates and makes decisions about the inputs. The motor processor is responsible for interpreting cognitive decisions into physical actions. As stated earlier, the processors work with memory in order to process information.

Capacity to store data is differed in two types of memory. Working memory, comparable to the computer RAM, can store five to seven chunks of data that can be

retained for 10 to 20 seconds. A chunk of data is a unit of information such as name. The capacity and retention of long-term memory is practically unlimited, however, retrieval of information can be difficult.

It is very important to understand how the processors and memories work together. Research in the field of cognitive science and human-computer interaction has shown limitations of human brain during the information-processing task. Three limitations are described by Te'eni, Carey, and Zhang (2007). First, the user will not notice screen changes that fall within an interval of 100 milliseconds. Second, the user cannot be expected to work with more than seven chunks of information simultaneously; displaying more chunks means the user will concentrate on some parts of the screen, ignoring other parts. Third, retrieval of information that is not expected to be in working memory will probably degrade both speed and accuracy during information processing. This is very important for software developers to keep in mind during design of software such as an estimating program.

According to Gardiner and Christie (1987), realizing that designing for human-machine cognitive compatibility can help make a machine more acceptable and more useful to its intended user. The benefits of realizing the use of cognitive science in developing software are many. Less training is needed to use the software, errors in using it are less likely, more complex operations can be carried out by more people, work can be done faster, and more interesting work can be done with little or no undesirable stress on the user (Gardiner and Christie, 1987). The knowledge that users bring to the interaction and the way in which they develop their understanding will influence the ease of use of the software (Hammond et al., 1987).

Since there are a lot of data involve in the construction cost estimating process, cognitive psychology principles and visualization technology can help improve the process. A visual interface for estimating applications can provide a virtual model of the project for the estimator in which he/she can see what is going to be built and will allow the estimator to easily access project information thus reducing the need to repeatedly referring to drawings or retrieving information from long-term memory.

### **4.3 VIRTUAL REALITY**

During the design phase of a construction project, it is helpful to see the designed building in 3D. Whether it is to see if the designed building would fit in the surrounding environment or owner requirements have been fulfilled. One way to view a project during the design is by using virtual reality.

Virtual reality systems can be described as a computer technology that enables a user to look through a special display and instead of seeing the real world, he/she sees a computer generated world. Virtual reality is about creating acceptable substitutes for real objects or environments for training, entertainment, or design purposes (Vince, 2004; Gutierrez, Vexo, and Thalmann, 2008). According to dictionary, “virtual” is something in effect but not in actual form. For example, a virtual keyboard is a keyboard that can be typed on, but it’s not present in the physical form. Virtual reality is about using computers to create images of 3D environments within which one can participate in real time and experience a sensation of being there (Vince, 2004; McMenemy and Ferguson, 2007; Gutierrez, Vexo, and Thalmann, 2008). The presence could be found in the form of navigation and interaction. Navigation implies the ability to move around and explore the

features of a 3D scene such as walking in a building, while interaction implies the ability to select and move objects in a scene.

The use of virtual reality is to immerse the user in the display (Richards, 1995). Virtual reality requires real time graphics and a stereoscopic display that is used for producing the depth for 3D images. Commonly used technologies include but are not limited to head-mounted displays (HMD), personal computers (PC), workstations, cave automation virtual environments (CAVE), large screen systems, and virtual tablets. Interaction can be achieved using a tracking device, which may be integrated in the HMD itself, for tracking head and body movement. Data gloves can be used to track hand movements. Computer mice can be used to navigate and interact on the personal computer level. These devices let the user point to and manipulate objects in the virtual scene (Vince, 2004; Gutierrez, Vexo, and Thalmann, 2008).

According to Richards (1995) and Vince (2004), Virtual reality can be a model for other types of visualization systems and a test system for display and interactive techniques. The benefits of seeing a product as a true 3D object is immense, and the ability to explore different perspectives of the project before anything is built are immeasurable. Designers will be able to explore different design alternatives to maximize value.

One advantage of using virtual reality in construction industry is its capability to represent complex building components as a three dimensional graphical object. This helps user to visualize a project better than with 2D drawings. Virtual reality is also superior to miniature models in showing design details because of its ability to provide

the user virtual walkthroughs inside or outside the virtual building (Hadikusumo and Rowlinson, 1999).

Since virtual reality could be used to explore designs before they are built, engineers and designers can use the technology to visualize structures before actually building them (McMenemy and Ferguson, 2007). In addition to visualizing buildings and structures, designers and engineers are also able to interact with them. Engineers can use virtual reality in many applications, such as structural analysis and construction cost estimating.

In this study, a virtual model of a project is created by extracting the geometry and material properties from each element in a CAD model. Microsoft DirectX Library is used to create a virtual environment using the extracted information. Construction cost estimating can then be done by walking in the building and selecting elements in the virtual model for estimating. Next section will discuss interactive visualization in more detail.

#### **4.4 SUMMARY**

By applying the findings of cognitive psychology and visualization technology, software can be designed that simplifies the process of construction cost estimating. Virtual reality and interactive visualization can be used to perform estimating while navigate in a virtual model of the building. Information could be extracted from the model during navigation. A cost estimating application is needed in order to use extracted information. The next chapter will discuss computer database technology and how a cost estimating database can be developed for an estimating application.

## **CHAPTER 5**

### **COST ESTIMATING DATABASES**

#### **5.1 INTRODUCTION**

Construction cost estimating requires a lot of data on building elements, material, equipment, labor, and other related information. These data need to be organized in a way that they can be easily accessed. One way to solve the problem is to use a database for storage of the data. A database is a storage facility or a collection of related records or documents. Databases are designed, built, and populated with data for a specific purpose and has an intended group of users and some applications in which these users are interested (Retik and Langford, 2001). The estimating software designed for visual estimating adopts database technology to store all the information necessary for estimating. The cost estimating database will also be used to store new estimate information. This chapter will discuss why databases are used, database models especially the relational model, and how the estimating database used in this study was designed.

#### **5.2 WHY USE A DATABASE?**

A database is an organization or a collection of related data. It is designed specifically to manage large bodies of information, and store data in an organized and structured manner that makes it easy for users to manage and retrieve data when required (Agarwal et al., 2008). It is very much like a spreadsheet. However, a database is designed to perform some very specific tasks which a spreadsheet is not able to do effectively. These tasks include but are not limited to retrieving all records that match

particular criteria, update or modify a complete set of records at one time, and extract values from records distributed among multiple tables (Brandon et al., 1985; Agarwal et al., 2008).

These are some of the reasons why databases are used (Agarwal et al., 2008):

- *Compactness*: Databases help in maintaining large amounts of data, and thus completely replace voluminous paper files.
- *Speed*: Searches for a particular piece of data or information in a database are much faster than sorting through piles of paper.
- *Less drudgery*: It is a dull work to maintain files by hand; using a database completely eliminates such maintenance.
- *Currency*: Database systems can easily be updated and so provide accurate information all the time and on demand.

There are three “logical” database models – hierarchical, network, and relational. These models present three ways of logically perceiving the arrangement of data in the file structure (Bagui and Earp, 2003). Following is a brief description of each database model.

### **Hierarchical Database Model**

The hierarchical model represents data using hierarchical tree structures. Each hierarchy represents a number of related records, arranged in multi-level structures, consisting of one root record and any number of subordinate levels (Retik and Langford, 2001). This can be seen in Figure 5-1.

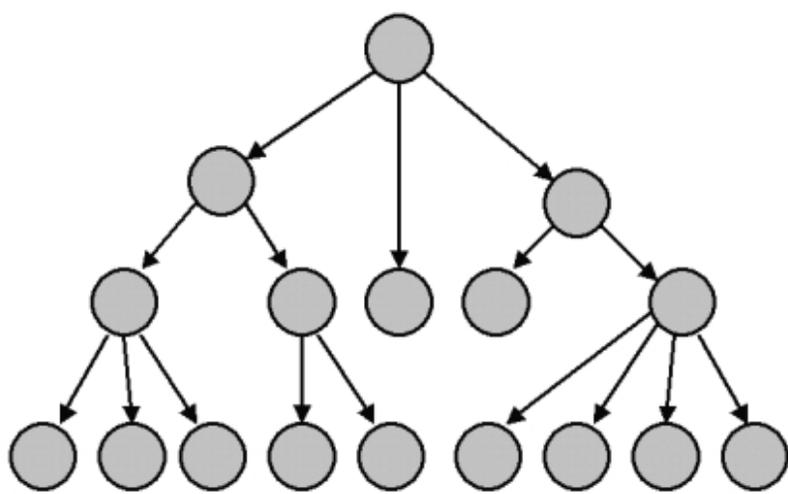


FIGURE 5-1: Hierarchical Database Model

**Network Database Model**

The network model was developed as a successor to the hierarchical model. The network model represents data as record types with more complex many-to-many relationships. This allows flexibility in describing different structures and relationships.

Figure 5-2 shows how network model is arranged.

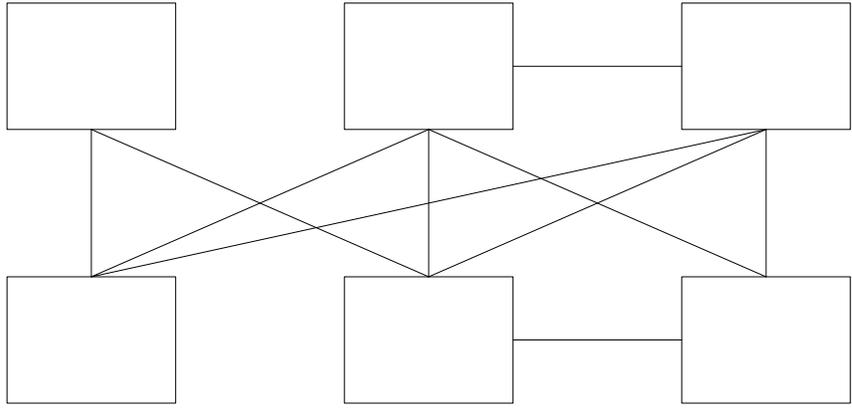


FIGURE 5-2: Network Database Model

### Relational Database Model

The essence of the relational approach is to represent data to the users as a set of tables in which data is stored. Tables consist of a number of rows, each row containing the same number of columns (Carter, 1995). A database based on the relational model was developed by E.F. Codd during the 1970s. A relational database allows the definition of data structures, storage, and retrieval operations and integrity constraints. Figure 5-3 shows how data is viewed in the relational model.

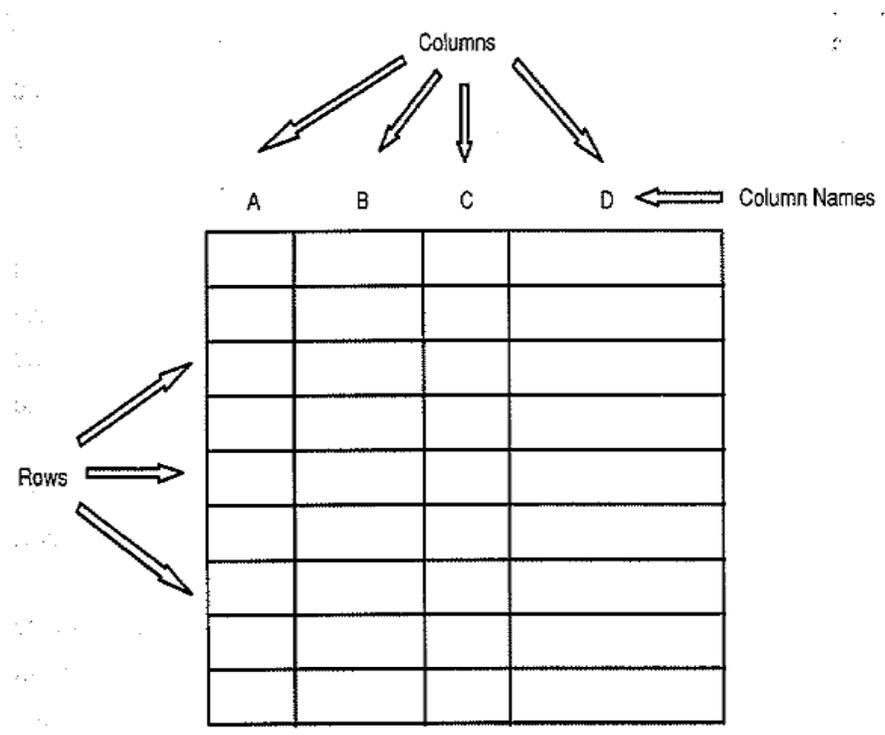


FIGURE 5-3: The Relational Database Model (Carter, 1995)

Relational databases normally contain the following features (Dewson, 2008):

- *Tables:* This is where data is kept within the database. A database must contain at least one table to be of use, although there are databases with no

user tables and only system tables. System tables are special tables that SQL Server uses to help it work with the database. These tables contain information within rows and columns.

- *Columns:* These provide a definition of each single item of information that builds up to a table definition. A column is made up of cells that all hold data. Each cell can hold a different type of data. Although they are restricted to what the data within it relates to, the type of data it will hold, and how much information can be stored in it. Each table must have at least one column.
- *Rows:* A row is made up of one cell from every column defined for the table. There can be any number of rows in a table; the limitation is set by the disk space, the amount of disk space that was defined as the maximum in database creation definition, or the amount of disk space in the server. A row will define a single unit of information, such as, a person name, address, phone number, etc. Rows are also called records.
- *SQL statements:* SQL or structured query language is database computer language designed for managing data in the relational database management systems.
- *Stored Procedures:* When it comes to requiring a program to manipulate or work with data, or perform the same data-intensive task repeatedly, it's often better to store this code in a stored procedure. Stored procedures contain one or more SQL statements, which are compiled and ready to be

executed when required. Stored procedures are permanently stored in the database, ready for use at any time.

- *Indexes:* These can be regarded as predefined lists of information that can inform the database how the data is physically sorted and stored, or they can be used to find rows of data quickly using information supplied by a SQL query and matching this information to data within columns. An index consists of one or more columns from the table it is defined for, but it is not possible for an index to cover more than one table. Index is very much like the index of a book, which is used to locate a piece of information faster than looking through the book page by page.
- *Views:* These can be thought of as virtual tables. Views can contain information combined from several tables and can present a more user-friendly interface to the data. Views can also add a great deal of security to an application, but they do give reduced functionality over the use of stored procedures or direct access to the tables. Views can also be indexed to speed processing of data within.

Since in this study a relational database is used for keeping data for cost estimating purposes, it would not be a relational database at all if database relationship is not discussed. The following section will provide the definition of relationship in the relational database model and how it works with data.

## *Relationships*

A relationship in a relational database is a logical link between two tables. It is impossible to have a physical link, although a physical line is drawn between two database tables when graphically illustrating the structure of a database.

The following sections present specific details about relationships, starting with a look at cardinalities.

## *Cardinalities*

Cardinality is a description of how many of one record type relate to the other, and vice versa. Mapping cardinalities, or cardinality ratios, express the number of entities to which another entity can be associated via a relationship set. Three main types of cardinality can exist in a database, these are; One-to-one, One-to-Many, and Many-to-Many.

- *One-to-one (1:1)*: For each row in Table A, there is at most only one related row in Table B, and vice versa. This relationship is typically used to separate data by frequency of use to optimally organize data physically. This relationship type isn't very common within a working database. Typically, there is no real reason for one record in one table to match just one record in another. For example, one department can have only one department head.
- *One-to-many (1:M)*: For each row in Table A, there can be zero, one, or more related rows in Table B; but for each row in Table B, there is at most one row in Table A. This is the most common relationship found in a

database. For example, a customer can have many orders, but an order can only belong to one customer.

- *Many-to-many (M:M)*: For each row in Table A, there are zero, one, or more related rows in Table B, and vice versa. Although it can happen relatively frequently, many-to-many relationship is not so easy to achieve. It also requires a special technique to implement. This relationship is actually implemented in a one-many-one format, so it requires a third table (often referred to as a junction table) to be introduced in between that serves as the path between the related tables. An example of a many-to-many relationship might be where an order can have many products and a product can belong to many orders.

Now that all the cardinalities have been explained, keys will be discussed next.

### *Keys*

Relationships are represented by data in tables. To establish a relationship between two tables, data in one table must be related to rows of data in another table. That's where keys come in. A key is one or more columns of a relation that is used to identify a row. In relational database management system, it mainly works with two types of keys: primary keys and foreign keys.

#### *Primary Keys*

A primary key is an attribute (column) or combination of attributes (columns) whose values uniquely identify records in an entity. Before choosing a primary key for an entity, an attribute must have the following properties:

- Each record of the entity must have a not- null value.
- The value must be unique for each record entered into the entity.
- The values must not changed or become null during the life of each entity instance.
- There can be only one primary key defined for an entity.

Besides helping in uniquely identifying a record, the primary key also helps in searching records as an index automatically gets generated when assigning a primary key to an attribute.

### *Foreign Keys*

A foreign key is an attribute that completes a relationship by identifying the parent entity. Foreign keys provide a method for maintaining integrity in the data (called referential integrity, this will be discussed in the following section) and for navigating between different instances of an entity. Every relationship in the model must be supported by a foreign key.

### **Data Integrity**

Data integrity means that data values in a database are correct and consistent.

There are two aspects to data integrity: entity integrity and referential integrity.

- *Entity Integrity:* As mentioned earlier in “Primary Keys” that no part of a primary key can be null. This is to guarantee that primary key values exist for all rows. The requirement that primary key values exist and that they are unique is known as entity integrity.

- *Referential Integrity*: Once a relationship is defined between tables with foreign keys, the key data must be managed to maintain the correct relationships to enforce referential integrity. Referential integrity requires that all foreign key values in a child table either match primary key values in a parent table or, if permitted, be null. This is also known as satisfying a foreign key constraint.

## **Normalization**

Normalization is a technique for avoiding potential update anomalies, basically by minimizing redundant data in a logical database design. Normalized designs are in a sense “better” design because they keep each data item in only one place. Normalized database designs usually reduce update processing costs but can make query processing more complicated. These trade-offs must be carefully evaluated in terms of the required performance profile of a database. Often, a database design needs to be denormalized to adequately meet operational needs.

Normalizing a logical database design involves a set of formal processes to separate the data into multiple, related tables. The result of each process is referred to as a normal form. Five normal forms have been identified in theory, but most of the time third normal form (3NF) is as far as needed in practice. This thesis will not get into detail about normal form. The cost estimating database will use 3NF.

Now that all the necessary components of relational database have been described, cost estimating database will be described in the following section.

### **5.3 THE COST ESTIMATING DATABASE**

Estimating requires the input of data from many sources. The ability to integrate this data into the estimating process would be beneficial during an estimate. A cost estimating database was developed to store all the data required for the estimating application developed in this study. The application is named Visual Estimating Application. This section will present what should be stored in the cost estimating database, how the database was designed using the relational database model, and how the estimating data are related to each other.

The cost of a building element is the sum of the costs of the work items necessary for the construction of the element. The data needed for estimating include labor, equipment, material costs and productivities. Figure 5-4 shows the schema of the database developed for storing the necessary data.

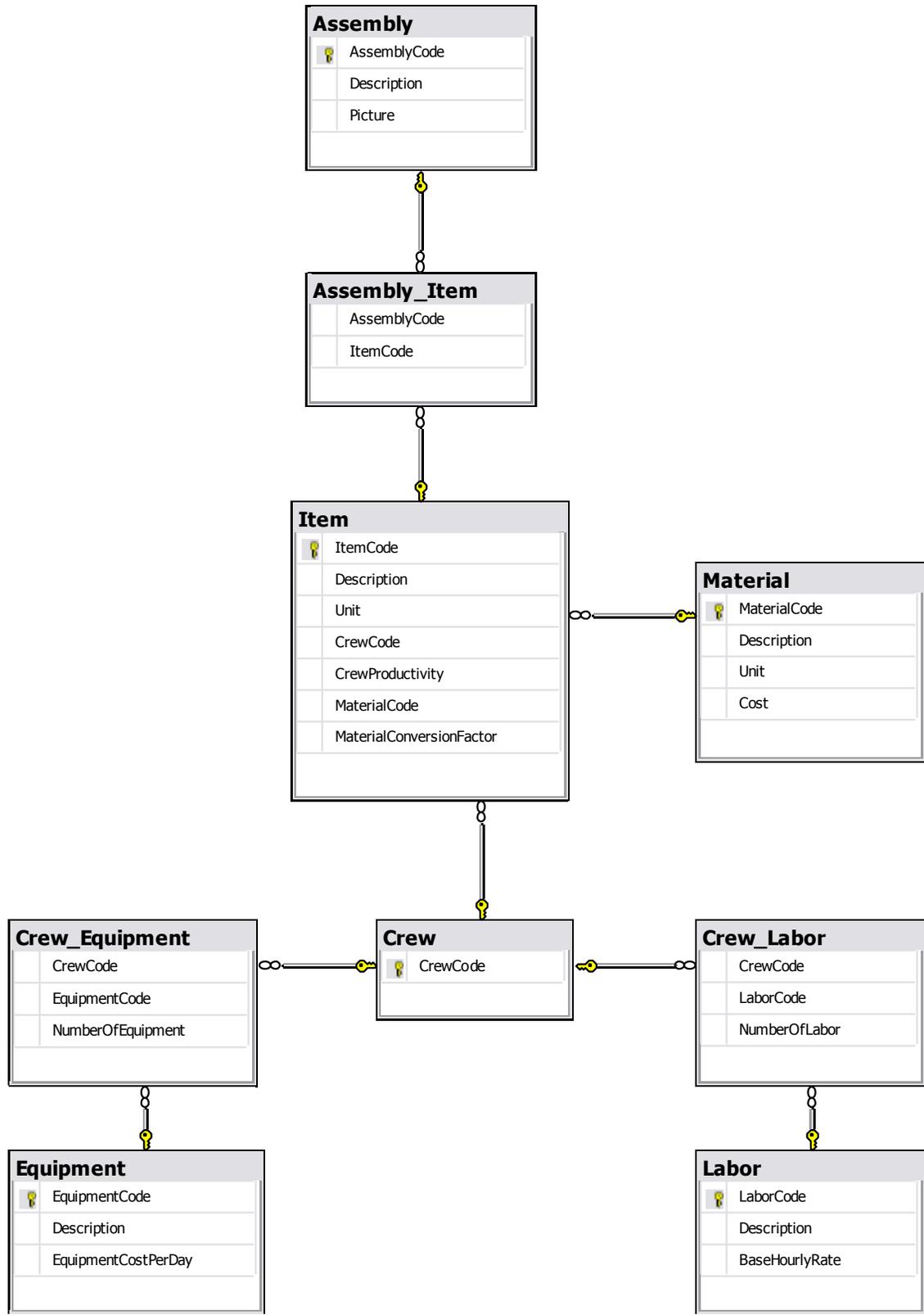


FIGURE 5-4: Cost Estimating Database Schema

As seen from the schema, nine tables are created to hold all the data necessary for the cost estimating application. The following will discuss each table in the cost estimating database.

**Labor Table:** The labor table is used to keep data for each labor trade. A code is assigned to each labor trade because it is easier to find a labor trade by code rather than searching by its description. Description attribute is used to store the name of the labor trade, and BaseHourlyRate attribute keeps the cost for each labor in the database. Figure 5-5 shows a sample list of labor trades stored in the Labor table.

LaborCode	Description	BaseHourlyRate
Asbe	Asbestos/Insulation Workers/Pi...	44.1000
Boil	Boilermakers	50.2000
Brhe	Bricklayer Helpers	32.1500
Bric	Bricklayers	40.5000
Carf	Carpenter Foreman	41.9500
Carp	Carpenters	39.9500
Cefi	Cement Finishers	38.3000
Clab	Common Building Laborers	31.6000
Claf	Labor Foreman	33.6000

FIGURE 5-5: Labor Table

**Equipment Table:** Equipment table is used to store equipment-related data. Equipment data that is required to be stored in the equipment table include equipment code, equipment description, and equipment cost per day. Similar to labor code, equipment code is uniquely assigned to each piece of equipment. This is to help make it easier to find equipment, rather than trying to find it by using equipment name. Equipment description provides the equipment's make, model, its sizes, and functions. Equipment cost per day reflects the rental cost per day for the equipment. Equipment can

also be rented by week or month. However, the database in this study only stores the rental cost on the daily basis. Figure 5-6 shows a list of equipment from the Equipment table in the cost estimating database.

EquipmentCode	Description	EquipmentCost...
01 54 33 10 0200	Bucket, concrete lightweight, 1/2 CY	17.2000
01 54 33 10 0300	Bucket, concrete lightweight, 1 CY	20.2000
01 54 33 10 0400	Bucket, concrete lightweight, 1-1/2 CY	27.0000
01 54 33 10 0500	Bucket, concrete lightweight, 2 CY	32.0000
01 54 33 10 0580	Bucket, concrete lightweight, 8 CY	201.0000
01 54 33 10 0600	Cart, concrete, self propelled, walking, 10 CF	55.2000
01 54 33 10 0700	Cart, concrete, operator riding, 18 CF	86.4000
01 54 33 10 0800	Conveyor, concrete, portable, gas, 16" W, ...	154.0000
01 54 33 10 0900	Conveyor, concrete, portable, gas, 16" W, ...	173.2000
01 54 33 10 1000	Conveyor, concrete, portable, gas, 16" W, ...	179.0000
01 54 33 10 1100	Core drill, electric, 2-1/2 HP, 1"-8" bit diameter	52.9500

FIGURE 5-6: Equipment Table

**Material Table:** Material table is needed to store material code, material's description, its measurement unit, and cost. Material code is used similarly as labor code and equipment code where each material is assigned a code for easy access. Material description is provided in the description attribute. A unit for each material is also needed because different material can have different units of measurement. Cost of material is also displayed as cost per unit. Figure 5-7 shows a list of materials in the Material table.

MaterialCode	Description	Unit	Cost
03 11 13.45 0020	Forming plywood	SFCA	7.4500
03 11 13.45 0500	Dowel supports	LF	0.6500
03 15 05.95 4000	Nail stakes, 3/4" diam. 18" long	EACH	5.2500
03 15 05.95 4050	Nail stakes, 3/4" diam. 24" long	EACH	6.2500
03 15 05.95 4200	Nail stakes, 3/4" diam. 30" long	EACH	7.8500
03 15 05.95 4250	Nail stakes, 3/4" diam. 36" long	EACH	8.8500
03 21 10.60 0500	Reinforcing in place, footing, #4 to #7	TON	1475.0000
03 21 10.60 0750	Reinforcing in place, footing, #8 to #18	TON	1400.0000
03 22 05.50 0700	4 x 4 - W4 x W4 (4 x 4) 85 lb per CSF	CSF	65.5000
03 31 05.35 0300	Normal weight concrete, ready mix, delivered, 4000 psi	CY	106.0000
03 39 23.23 0200	Curing blanket, burlap-poly, 2 ply	CSF	16.9500

FIGURE 5-7: Material Table

**Crew, Crew\_Labor, and Crew\_Equipment Tables:** Crew is related to both Labor and Equipment. To make up a crew, there must be at least one or more labor and zero or more equipment. The relationships between crew and labor tables and crew and equipment tables are many-to-many. This relationship is actually implemented in a one-many-one format, so it requires a third table, also known as a junction table, which serves as the path between the related tables. In the estimating database, Crew\_Labor and Crew\_Equipment tables are created to be used as junction tables for Crew-Labor and Crew-Equipment relationships respectively.

Crew table in Figure 5-8 was created to keep crew data. Although it was only developed with one attribute, CrewCode, it is necessary and plays an important role by identifying both labor and equipment makeup for each crew.

Since they are junction tables, Crew\_Labor (Figure 5-9a) and Crew\_Equipment (Figure 5-9b) tables store CrewCode, LaborCode or EquipmentCode and number of labor or equipment. In each row in Crew\_Labor table, there must be a crew code, a labor code,

and the number of labor in the crew. This is to show that there are a number of laborers for that particular crew code. This method is also applied to the Crew\_Equipment table. For example, “C-1” crew consisted of three carpenters, one common laborer, and no equipments. In the Crew\_Labor table, there are two rows that keep data for C-1 crew, the first row is C-1, Carp, 3, and the second row is C-1, Clab, 1. C-1, Carp, 3 row specifies that there are three carpenters in the C-1 crew and C-1, Clab, 1 row means there is one common laborer in the C-1 crew. Since there is no equipment for C-1 crew, no equipment row is entered.

CrewCode
1 Brhe
2 Carp
2 Clab
2 Rodm
4 Rodm
C-1
C-2
C-20

FIGURE 5-8: Crew Table

CrewCode	LaborCode	NumberOfLabor
C-1	Carp	3
C-1	Clab	1
C-2	Carf	1
C-2	Carp	4
C-2	Clab	1
C-3	Rodf	1
C-3	Rodm	4
C-3	Eqlt	1

CrewCode	EquipmentCode	NumberOfEquipment
C-6	01 54 33 10 3000	2
C-3	01 54 33 60 5500	3
C-4	01 54 33 60 5500	3
C-3	01 54 33 10 2180	0.5
D-4	01 54 33 40 5655	1
C-7	01 54 33 10 0300	1
C-7	01 54 33 10 3000	2
C-7	01 54 33 60 2600	1

FIGURE 5-9a: Crew\_Labor Table

FIGURE 5-9b: Crew\_Equipment Table

**Item Table:** Item table is used to store information for different work items. Item code and item description define the work item. A code is a unique number that is used to provide easy access to each item. Description is used to provide more information about the item. Each item has a unit which is used to define its quantity. Each item has a crew that builds the item. The crew code defines the item's crew. Crew productivity rate is the rate that represents a typical number of units that the crew can install in a normal eight-hour day. Material attribute specifies the material code that is installed by the crew. A material also has an attribute called MaterialConversionFactor, which is used for converting material's unit cost to the item's unit cost. Figure 5-10 shows examples of items in the Item table.

ItemCode	Description	Unit	CrewCode	CrewProductivity	MaterialCode	MaterialConver...
03 11 13.45 0010	Forms in place, footings	NULL	NULL	NULL	NULL	NULL
03 11 13.45 0020	Forms in place, footings, continu...	SFCA	C-1	0.085	03 11 13.45 0020	375
03 11 13.45 0100	Forms in place, footings, continu...	SFCA	C-1	0.068	03 11 13.45 0500	0
03 11 13.45 0150	Forms in place, footings, continu...	SFCA	C-1	0.066	NULL	NULL
03 11 13.45 0500	Dowel supports for footings or b...	LF	C-1	0.064	03 11 13.45 0500	500
03 15 05.95 0010	Wall and foundation form access...	NULL	NULL	NULL	NULL	NULL
03 15 05.95 4200	Nail stakes, 3/4" diameter, 30" l...	EACH	NULL	NULL	03 15 05.95 4200	NULL
03 21 10.60 0015	Reinforcing in place A615 Grade ...	NULL	NULL	NULL	NULL	NULL

FIGURE 5-10: Item Table

**Assembly Table:** AssemblyCode, Description, and Picture are stored in an Assembly table (Figure 5-11). Assembly code is used to uniquely identify an assembly. Assembly description provides the assembly with a definition. Image of the assembly is stored-in the Picture attribute.

AssemblyCode	Description	Picture
A1010110	Concrete footing	<Binary data>
B1010000	Floor	<Binary data>
B1020000	Roof	<Binary data>
B2010156	Exterior Wall - B...	<Binary data>
B2020100	Windows	<Binary data>

FIGURE 5-11: Assembly Table

**Assembly\_Item Table:** Assembly\_Item table (as shown in Figure 5-12) was created as a junction table. Since the relationship of assembly and item can be classified as many-to-many; one assembly can have many items, and one item can be included in many assemblies. For example, A1010110 – Concrete footing uses three items, so AssemblyCode and ItemCode are all indicated in the table.

AssemblyCode	ItemCode
A1010110	03 11 13.45 0010
A1010110	03 11 13.45 0020
A1010110	03 11 13.45 0500
B2010156	04 21 13.13 0010
B2010156	04 21 13.13 0050
B2010156	04 22 10.14 0010
B2010156	04 22 10.14 1150
B2010156	04 22 10.16 0010

FIGURE 5-12: Assembly\_Item Table

## 5.4 SUMMARY

A cost estimating database is used to store data for an estimating application. Although there are several database models, the relational database model was adopted in this study. This chapter described the database schema, the structure of the tables in the estimating database and their relationships.

The next chapter will discuss the architecture of the Visual Estimating Application. It discusses various components of the application, the function of each component and how they are related to each other.

## **CHAPTER 6**

### **VISUAL ESTIMATING APPLICATION ARCHITECTURE**

#### **6.1 INTRODUCTION**

Construction cost estimating requires a lot of manual work. Available methods, such as digitizing tablet and on-screen quantity takeoff, require manual inputs, albeit currently they are forefront technologies in construction cost estimating. In a project where there are thousands of elements to be estimated, this proves to be tedious and very time consuming. To minimize the tedious process and provide visualization at the early stages of building process, a Visual Estimating Application (VEA) is developed to provide the connection between building information modeling and the process of construction cost estimating. VEA not only does help in repeated calculations, summarizing and reporting, but it also helps extracting information from CAD models. The application of BIM and visualization technology in estimating makes it easier for estimators facing this task on a regular basis. This chapter discusses the objectives of VEA and an overview of its architecture. It also explains the interaction of the VEA with Autodesk Revit, 3D CAD models, and cost estimating databases.

#### **6.2 OBJECTIVES OF VISUAL ESTIMATING APPLICATION**

Building information modeling (BIM) is not limited to just the graphical representation of a project, it also contains non-graphical information that include functional, behavioral, and semantic properties. Since BIM contains information about the model, it has become increasingly important in both architectural and engineering practices. Applications could be developed based on BIM to help architects and engineers

do their work more efficiently (Reffat, 2002). For construction cost estimating, the geometry and properties of elements are necessary. This information can be extracted from BIM easily. To manipulate the data and visualize the 3D model, an application named Visual Estimating Application (VEA) is developed. In VEA, an estimator can see exactly the location and relationships among building elements while walking inside the building. Information from a 3D CAD model can be extracted and transferred to estimating software. This helps reduce the time for manual data entry. Looking up cost information for estimating is also available from a custom database. VEA and its architecture will be discussed in the following sections.

### **6.3 VISUAL ESTIMATING APPLICATION ARCHITECTURE**

VEA was developed to improve the process of construction cost estimating. The application and its components are shown in Figure 6-1. These components will be discussed individually in the following sections.

VEA is developed for projects that use Autodesk Revit as their BIM modeler. The element geometry and material information can be extracted from a Revit model via Revit API. Using the extracted information and Microsoft DirectX graphics library, a virtual prototype of the project is created in the visualization module (Van Verth and Bishop, 2004, Karshenas, 2009). Section 6.3.1 will discuss Revit API in more detail. The visualization module allows estimators to navigate and interact with the virtual environment. First and third person cameras are developed for navigation while input devices are used to interact with the model. This will be discussed in further detail in section 6.3.2.

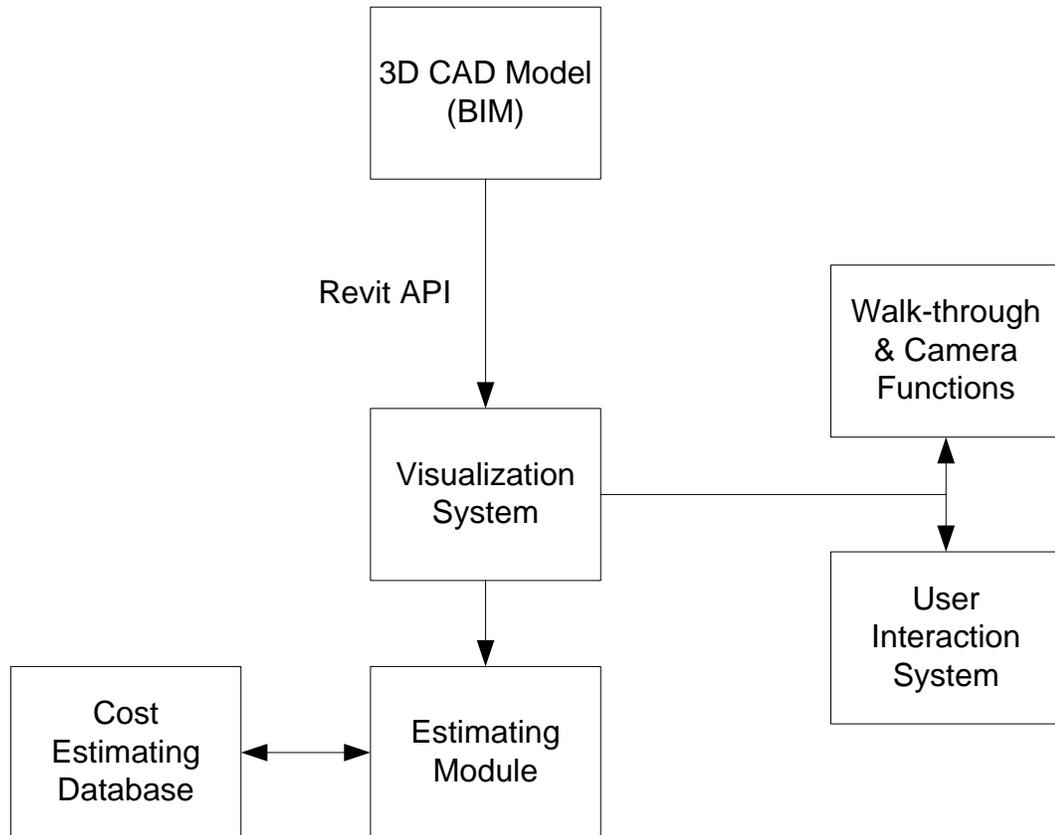


FIGURE 6-1: Visual Estimating Application Architecture

### 6.3.1 REVIT APPLICATION PROGRAMMING INTERFACE (API)

There are a variety of methods to interact with BIM data from Revit Architecture models. Many software applications use STEP, IFC, or CIS/2 (Hamilton et al., 2007). These interactions are open file formats for passing BIM's data back and forth between software programs. Other integrations use database connectivity such as ODBC to translate between software programs. Integration based on application programming interface or API offers a very close link between applications. Revit API allows independent software developers to create software programs that can access elements in the Revit model. Application developers can use the Revit API to query and change

element properties as well as to add and modify some elements. Even individual Revit users and companies are taking advantage of the API to create their own custom tools and add-on modules (Rundell, 2008). Integrations that use an API to link software applications are often termed dynamic because the API enables software applications to interact with each other directly (Revit API User's Manual, 2008).

The visualization system module interfaces with Revit Architecture using Revit API via C# programming language. The visualization system module extracts not only element geometry, but also element material properties.

### **6.3.2 VISUALIZATION SYSTEM MODULE**

After information has been extracted from the CAD model, a 3D representation of the project is created by the visualization system module. This module was designed with a custom graphics engine, full navigational control, and two-way communication with the CAD engine. It was developed using Microsoft DirectX graphics library. Capabilities of the visualization system include (Karshenas, 2009):

- Interface with Revit Architecture for extracting geometry and material information for a building model.
- Create a 3D visualization of a building using information extracted from its Revit design files.
- Interface with other applications such as Microsoft Project for 4D visualization.
- Provide multimedia information about building elements.

Input devices such as mouse and keyboard allow the user to navigate and interact with the 3D model. Navigation in a visualization system model includes orbiting or flying over a model using a third person camera, or walking around and inside the model with a first person camera. The camera's yaw, pitch and travel are controlled by user for complete real-time navigation of a model. Both camera function and input devices are discussed in more details below.

### **6.3.2.1 Camera Function**

In order to view objects in the virtual world, it is necessary to present the notion of the viewer. This could be the main character's viewpoint in a first person shooter, or an over the shoulder view in a third person adventure game, or it could be a zoomed out wide shot in a strategy game. These properties can be encapsulated into a single entity commonly called virtual viewer or camera which allows the user to control which objects lie in his or her current view (Pepke, 1995, Van Verth and Bishop, 2004). Virtual viewer or a camera is a combination of the position of the eye and direction in which the viewer is looking. This controls which object lies in the current view. As shown in Figure 6-2, the virtual camera in the 3D environment is defined by the following three vectors:

- View direction vector indicates the direction in which the viewer is looking.
- View up vector indicates the direction out of the top of the camera or the character's head.
- View side vector is pointed out towards the camera's right.

All three view vectors are represented in the world frame. Since they are orthogonal, by normalizing them, an orthonormal basis could be created. Using this basis together with the view position, a new frame relative to the world coordinate system could be specified. This is known as the view frame or view space. This is how the camera's position and orientation in the world is determined.

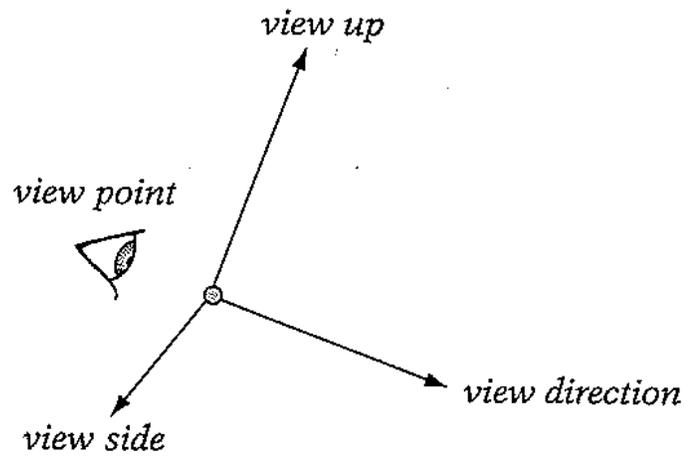


FIGURE 6-2: View Frame Relative to the World Frame.

### 6.3.2.2 Input Devices

Input devices facilitate navigation and interaction with the 3D model in the visualization system module. Visual Estimating Application uses mouse and keyboard to allow the user to navigate and interact with the 3D model. Other input devices such as 3D mouse and game controller can be used to provide easier navigation as they have been used by many video games or other visualization application. Data gloves can also be used to interact with the model as the user can use them to move or grab objects in the virtual environment.

### **6.3.3 COST ESTIMATING DATABASE**

After an element has been selected from the visualization system module, it must be matched to an assembly from the cost estimating database for pricing. Chapter 5 provided an in depth discussion of the cost estimating database and its architecture.

### **6.3.4 ESTIMATING MODULE**

The estimating module is a custom application designed to be an estimating toolkit. It accesses and uses both the cost estimating database and the visualization module. It also provides an interface for maintaining the estimating database. Estimating module was developed for user-friendliness and simplicity. In order to successfully develop and implement the module, several guidelines were established. The guidelines are as follows (Karshenas, 2005):

- To allow iteration over all building element instances included in a project.
- To allow an estimator to review geometry imported from Revit for a building element instance.
- To allow an estimator to review and adjust the work items necessary for the construction of a building element.
- To allow an estimator to add the cost of an element instance to the project cost estimate.

These guidelines will allow fast access to the information necessary for preparing an estimate and eliminate a lot of repetitive and tedious estimating tasks.

## 6.4 SUMMARY

Visual Estimating Application is developed to help ease the estimating process by utilizing 3D CAD models and information extracted from BIM. It includes an estimating module, a visualization module and a database.

The visualization module is used to help the estimator navigate and interact with the project model. The cost estimating database keeps all the cost data necessary for estimating. The visualization module interfaces with Revit Architecture using Revit API via C# programming language. The estimating module matches a building element with an assembly from the cost estimating database for estimating the element's cost. The next chapter will demonstrate the application applied to a simple cost estimating case.

## **CHAPTER 7**

### **CASE STUDY**

#### **7.1 INTRODUCTION**

This chapter will demonstrate how Visual Estimating Application (VEA) is used for cost estimating. Step-by-step procedure will be provided along with screen shots taken from the application. There will be two parts in this case study: database management, and visual estimating process. The database management part will discuss database access, adding to, editing, and deleting from the database. The visual estimating part will explain the procedure for extracting information from a Revit model, selecting an element for estimating, selecting an assembly from the cost database, reviewing the item quantities, summarizing and creating an estimate report.

#### **7.2 BASIC COMPONENTS OF THE GRAPHICAL USER INTERFACE**

The Visual Estimating Application allows an estimator to visually select elements from a 3D model and estimate their costs. The application was developed based on how human brain perceives and processes information; therefore, minimizing the load on the estimator's long-term memory while preparing an estimate.

Access and use of the application's Revit element extractor, 3D visualization system, database management module, and cost estimating module are discussed below.

##### **7.2.1 Revit Element Extractor**

Revit element extractor (as shown in Figure 7-1) interfaces with Autodesk Revit to extract all Revit elements from a 3D CAD model. The user must create a directory

and save the extracted project element information in a file. After extraction, the user does not need the parent software (Revit Architecture) and the Revit model file.

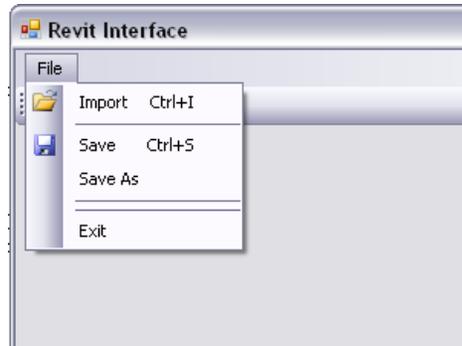


FIGURE 7-1: Revit Element Extractor

## 7.2.2 Visualization System

The visualization system interface allows users to visually interact with the 3D model and estimate a building element. The main functions of this interface are discussed below.

**Navigation:** Navigation inside a 3D model is done by using the mouse and the keyboard. To move forward, the right key is pressed. To look around the building, the left key is pressed and the mouse is moved around to the desired direction. To look up and down, both left and right keys must be pressed together.

**Element Selection:** A building element can be selected for estimating by changing the interface state from “Navigate” to “Select”. This enables users to select any element in a 3D model to be estimated. An element is highlighted after it has been selected.

### 7.2.3 Database Management

The system's database uses Microsoft SQL Server to keep cost estimating data in an organized manner. One can use the database interface to add data to, edit, and delete data from the database. This will be shown in more detail in section 7.3.

The application's database can be accessed from both the visualization system module and the visual estimating module. In the visualization system module, the database can be accessed through a button on the application's toolbar. Figure 7-2 shows where the button is located.

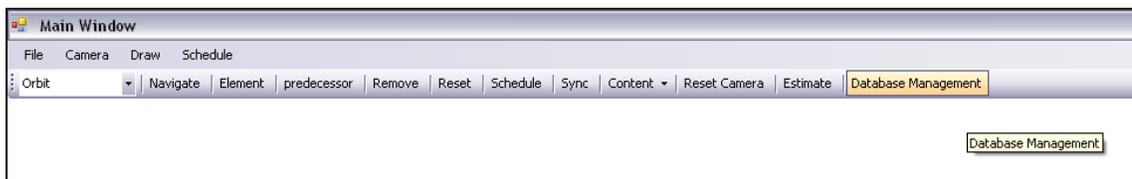


FIGURE 7-2: Database Management Button in the Visualization Walk-Through Application

After the user selects the database management button, a dialog box will appear with nine buttons representing nine different tables in the database. Figure 7-3 shows this dialog box along with the buttons that the estimator can select to organize each of the nine tables.



FIGURE 7-3: Database Management Dialog Box

The cost estimating database can also be accessed through the Visual Estimating Application via the management menu as shown in Figure 7-4. The estimator can bring up a table by selecting its menu item.

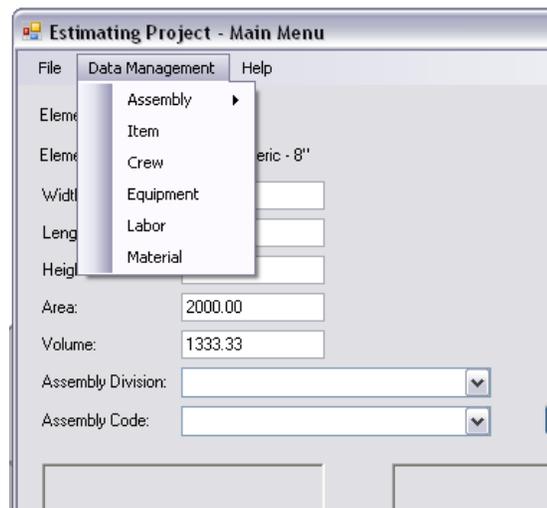


FIGURE 7-4: Database Management Menu in the Visual Estimating Application

### 7.2.4 Estimating Module

The cost estimating module interface is used to get the information from the extracted 3D model in the visualization system. An element can be matched to an assembly from the cost estimating database for pricing. The geometry data of an element

is used to calculate the necessary material quantities for the item. Step-by-step description of the cost estimating module will be discussed in section 7.4.

### **7.3 STEP-BY-STEP DESCRIPTION OF DATABASE MANAGEMENT SYSTEM**

This section provides a step-by-step description for managing the cost estimating database. Users can choose whether to add, edit, or delete data from different tables in the cost estimating database. Since each table has its own dialog box, one can select the table that he/she wants to view and adjust any data necessary for that table.

#### Adding Data

To add new data, the user can select “Add” radio button; as illustrated in Figure 7-5 for the Labor table dialog box. After the button is clicked, textboxes are enabled for the user to input data into the database as can be seen in Figure 7-6. After the necessary data have been entered, the estimator can click “OK” to add the data into the estimating database, or the estimator can click “Cancel” to abort data entry. Figure 7-7 shows databases’ data grid view after an update with the latest data entry.

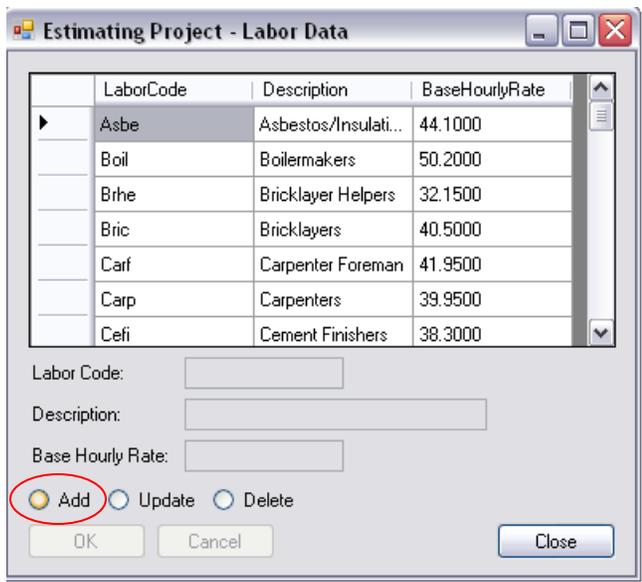


FIGURE 7-5: “Add” Radio Button in the Labor Table Dialog Box

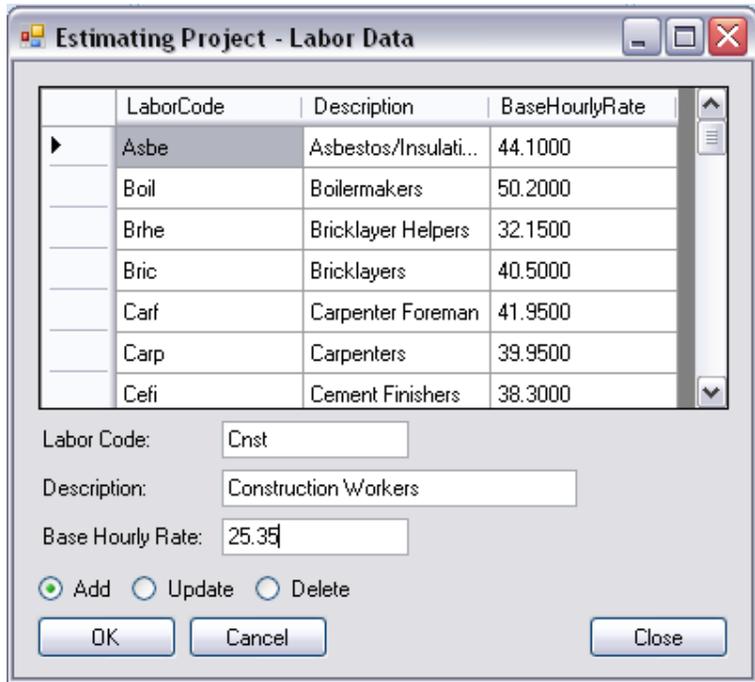


FIGURE 7-6: After the “add” button is clicked, textboxes, “OK”, and “Cancel” buttons are enabled.

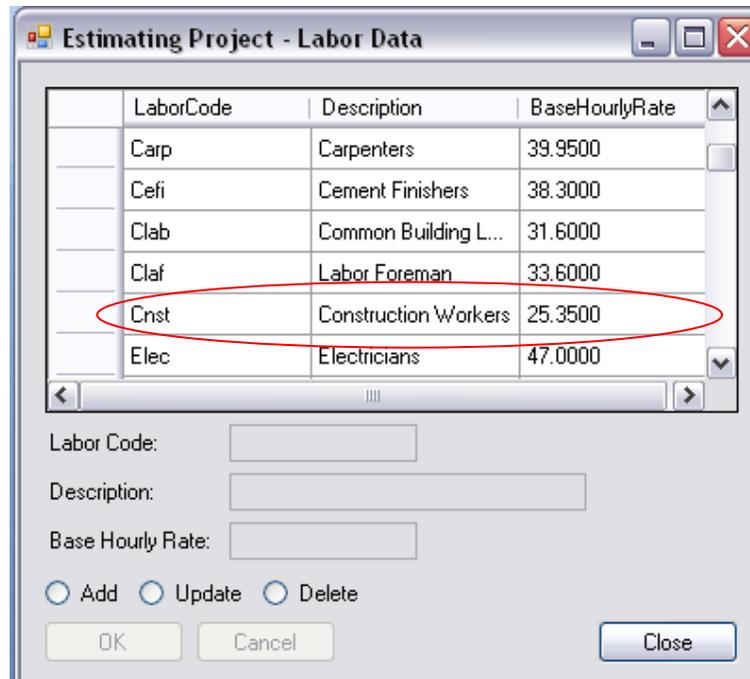


FIGURE 7-7: After the estimator has clicked “OK” and the list will be updated automatically.

### Editing or Updating Data

To edit or update data in the estimating database, data has to be selected first. The selection can be done using the data grid view that shows content from the database. Selected data and its attributes are then shown in textboxes. Figure 7-8 illustrates that “Roof” has been selected for update. The description for “Roof” will be changed to “Asphalt Roof” and a picture will be added to this assembly.

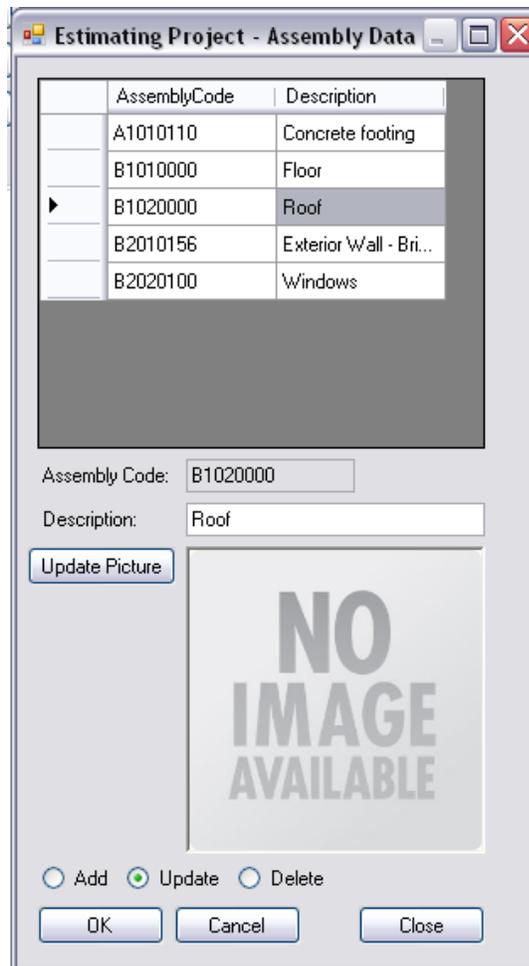


FIGURE 7-8: Roof is selected and the update button is clicked.

To update the picture, the “Update Picture” button has to be selected. A dialog box will appear, as shown in Figure 7-9. Figure 7-10 shows the Assembly table dialog box after the “Asphalt Roof” has been updated to the database.



FIGURE 7-9: Update picture dialog box. Asphalt roof picture was selected.

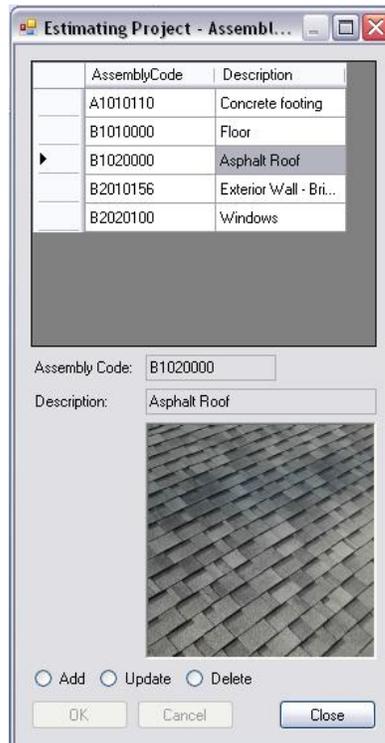


FIGURE 7-10: After “Roof” has been updated to “Asphalt Roof”. A picture was also added.

## Deleting Data

To delete data, user has to select a row to be deleted and click on “Delete” radio button. This is shown in Figure 7-11 where an item in the dialog box is selected to be deleted.

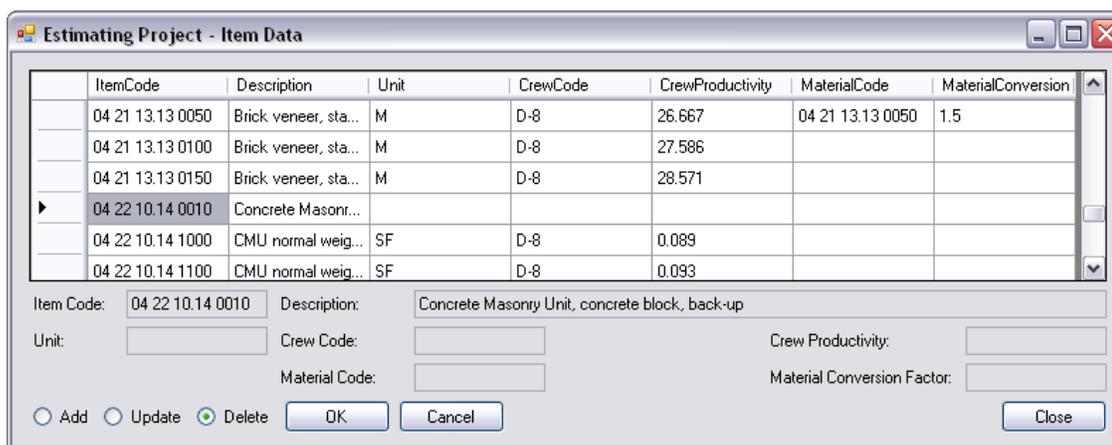


FIGURE 7-11: An item is selected to be deleted.

## **7.4 STEP-BY-STEP DESCRIPTION OF THE ESTIMATING MODULE**

After building the estimating database, the estimator has all the data necessary for creating an estimate. This section provides a step-by-step procedure to describe the visual method to construction cost estimating.

### Step 1: Element Extraction

All pertinent information for an element must be extracted from a Revit model before the element’s cost can be estimated. The Revit Architecture menu is customized for element information extraction. Figure 7-12 shows Revit Architecture’s interface and the menu item (named My Menu) added to the Revit tool bar for this purpose.

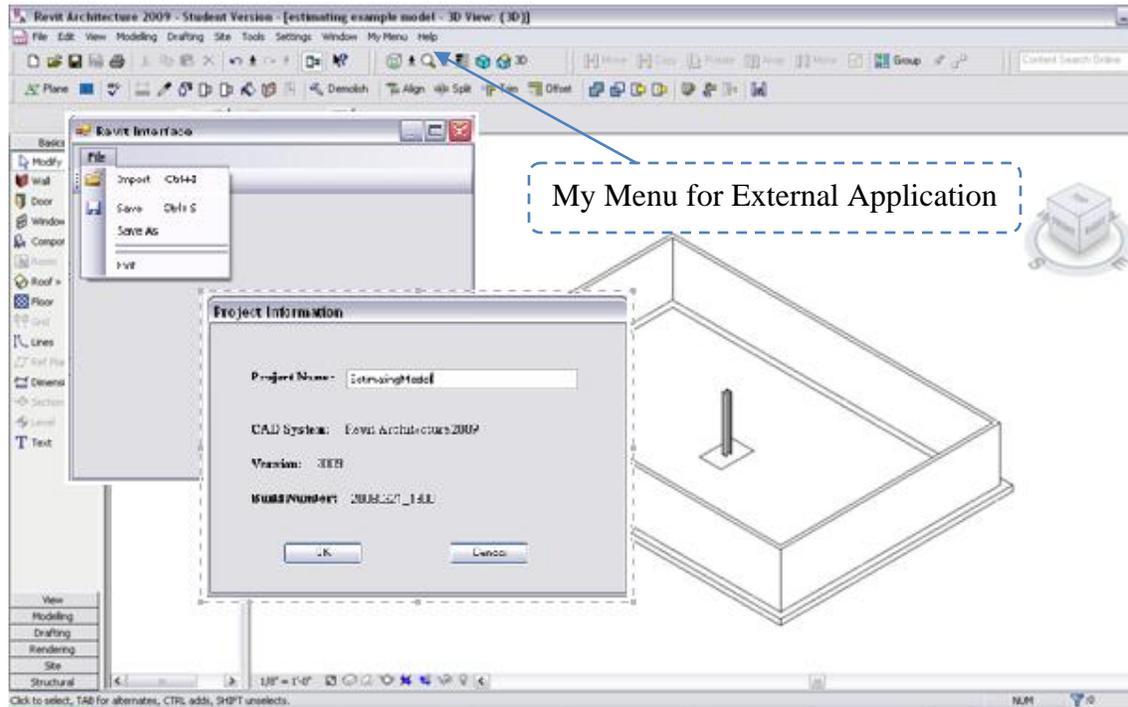


FIGURE 7-12: “My Menu” added on the top tool bar. It is used to extract element properties into an XML file.

### Step 2: 3D Model in the Visualization System

Users can create a 3D model in the visualization system using the element properties extracted from the CAD model. Figure 7-13 shows a few elements drawn in the visualization system.

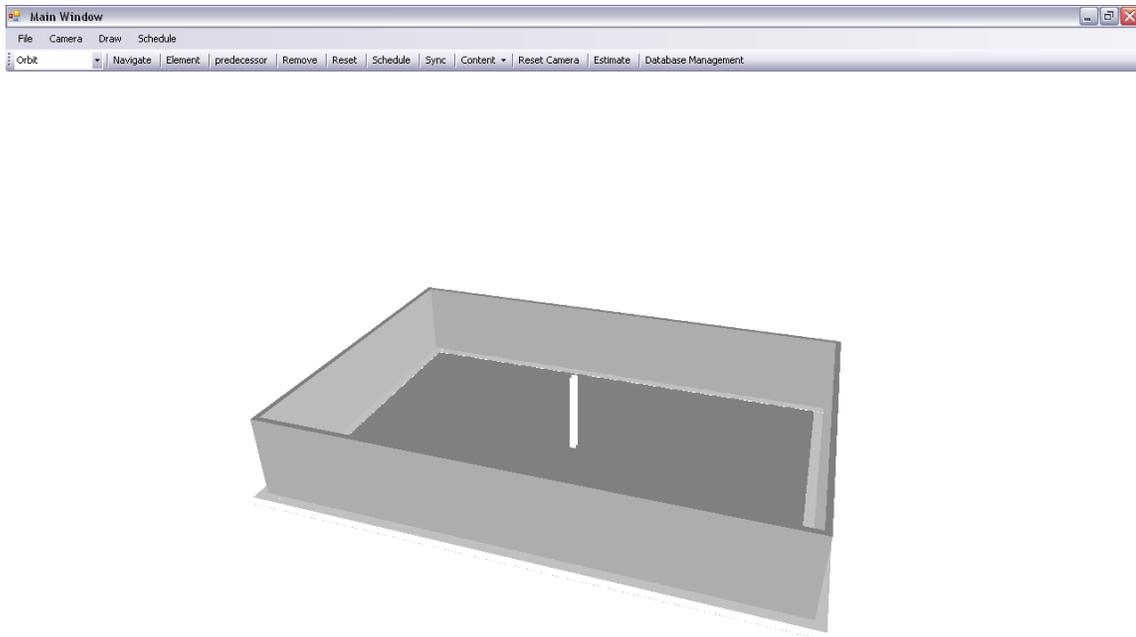


FIGURE 7-13: Model shown in the visualization system module.

### Step 3: Selecting an Element for Estimating

After a 3D model of a building is created in the visualization system, estimating can start by selecting an element from the model. Since element's information has been extracted and saved in an XML file, when an element is selected its information necessary for estimating becomes available.

The estimator can change the application's state to "Select" by toggling the "Navigate" button. This will change the button's text to Select. In Select state, an element can be selected by clicking the element. When an element is selected, it will turn to a pink color. This can be seen in Figure 7-14 where a wall has been selected.

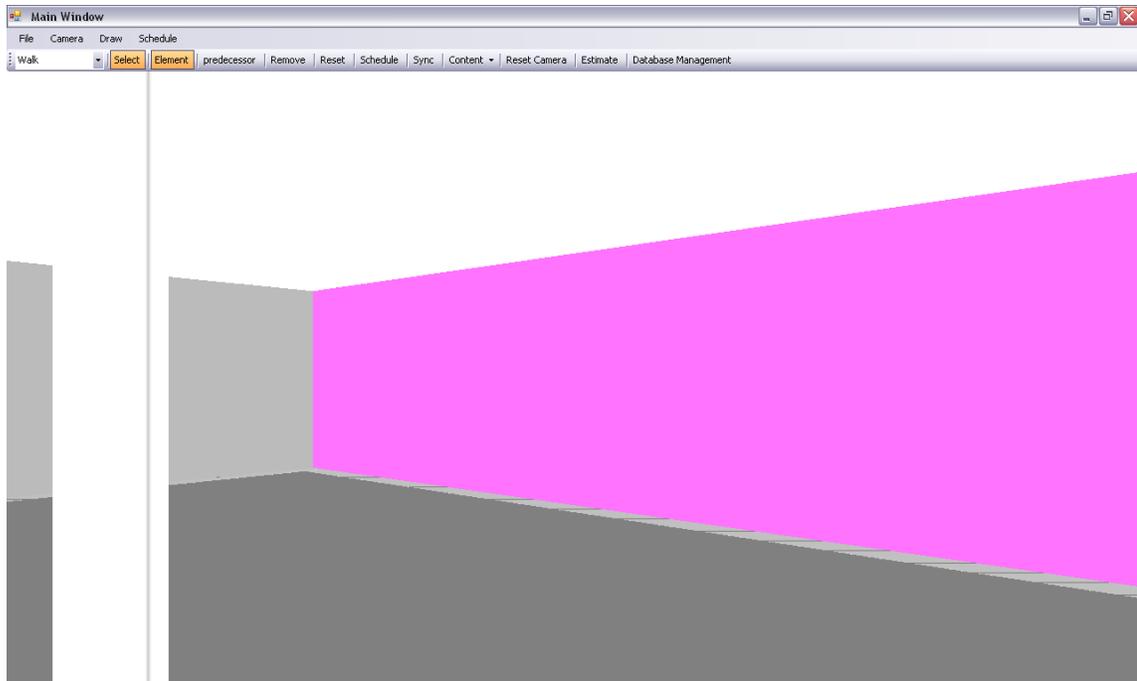


FIGURE 7-14: A wall is selected using the walkthrough camera.

#### Step 4: Review the Geometry and Matching a Building Element to an Assembly from the Database

After an element has been selected, the estimator can click on the “Estimate” button on the toolbar. An estimating dialog box will appear with information regarding the selected element. This information includes element’s category, name, and geometry. Geometry information could include width, length, height, area, and volume depending on the kind of element that has been selected for estimating. The estimator can then select the database assembly that matches the element for estimating. Figure 7-15 shows an assembly is being selected for the selected element for estimating.

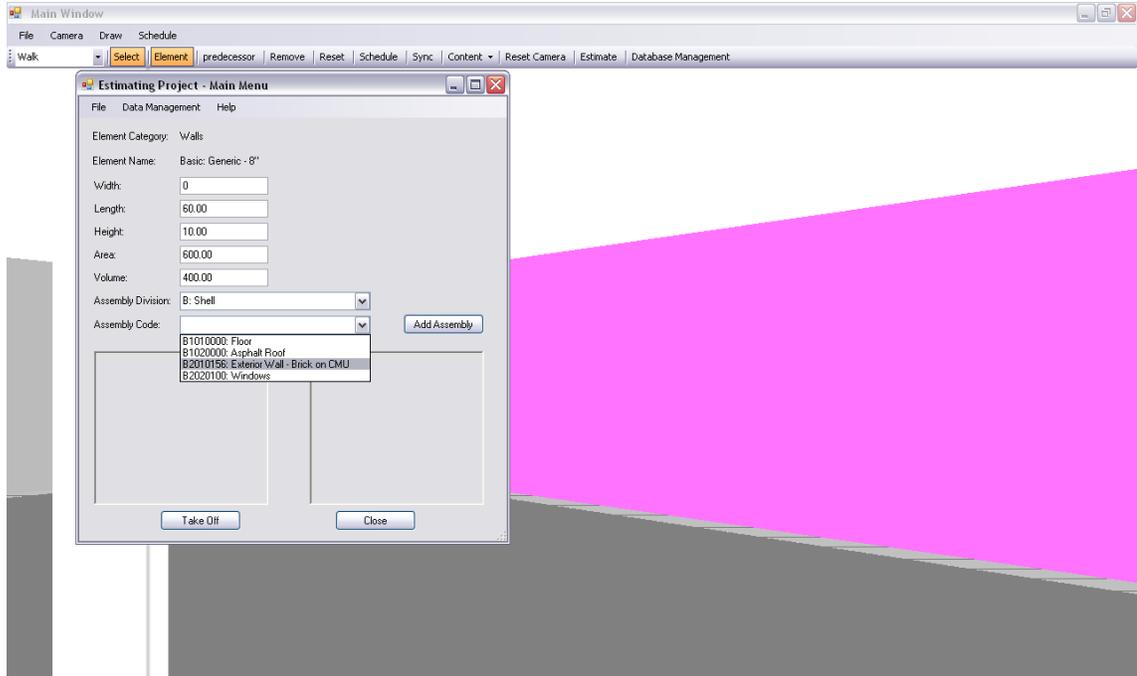


FIGURE 7-15: Estimating dialog box shown during an assembly is being selected.

### Step 5: Adding Quantities for Items

After an element has been matched to an assembly from the cost estimating database, the estimator can review the quantity takeoff for the element by selecting the “Takeoff” button. Clicking the Takeoff button shows a dialog box with items that are included in the assembly, as shown in Figure 7-16. Each item has to be adjusted for the element being estimated. For example, number of bricks needed depends on the size of the brick used. This can be done by selecting the property for the item. A dialog box will appear after the property has been selected. After the dialog box appears and the estimator has made the necessary adjustments, item quantity will be shown in the “Quantity” column. The estimator must also provide waste percentages for each item.

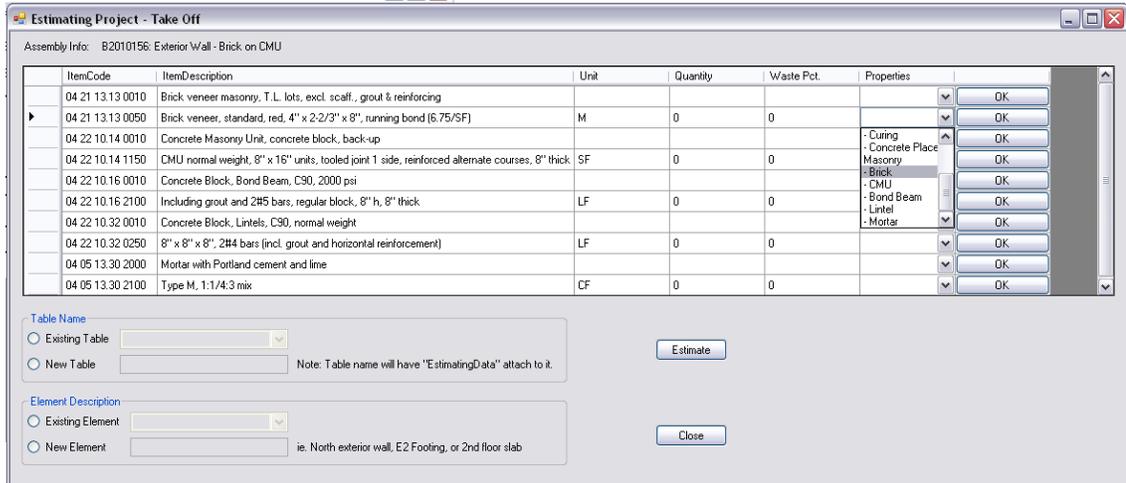


FIGURE 7-16: Different Items for the Assembly is shown in the dialog box.

### Step 6: Saving Items and item Quantities to the Database

After items in the assembly have been adjusted, it can then be saved. The estimator can choose whether to save the assembly in an existing project or a new project. If the estimator wants to save the element in an existing project, the application will check whether the element has already been estimated. If the element has already been estimated, a warning will be pop-up and ask whether to replace the previously saved data.

### Step 7: Reviewing an Estimated Item and Creating an Estimating Report

After all model elements have been estimated, the estimator can review the estimate by using the Review Dialog Box, as shown in Figure 7-17. The estimator can edit the data in this dialog box before an estimate report is created.

Estimating Project - Item Cost Estimating

Sort by Element Description | Sort by Assembly Code | Sort by Item Code | radioButton4

ElementDescription	AssemblyCode	ItemCode	ItemDescription	Quantity	Waste	TotalQuantity	MaterialCost	LaborCost
North Wall	B2010156	04 21 13.13 0010	Brick veneer mas...	0	0	0	0	0
North Wall	B2010156	04 21 13.13 0050	Brick veneer, sta...	4.050000190734...	15	4.657500219345...	5658.862766504...	4615.3299
North Wall	B2010156	04 22 10.14 0010	Concrete Mason...	0	0	0	0	0
North Wall	B2010156	04 22 10.14 1150	CMU normal weig...	600	10	660	591789	2477.0856
North Wall	B2010156	04 22 10.16 0010	Concrete Block, ...	0	0	0	0	0
North Wall	B2010156	04 22 10.16 2100	Including grout a...	60	5	63	82782	311.36364
North Wall	B2010156	04 22 10.32 0010	Concrete Block, ...	0	0	0	0	0
North Wall	B2010156	04 22 10.32 0250	8" x 8" x 8", 2#4 ...	0	0	0	0	0
North Wall	B2010156	04 05 13.30 2000	Mortar with Portl...	0	0	0	0	0
North Wall	B2010156	04 05 13.30 2100	Type M, 1:1/4:3 ...	23.08500099182...	20	27.70200119018...	30700.74281902...	49.874682

OK Edit Cancel

FIGURE 7-17: Item Cost Estimating Summary

Figure 7-18 shows an estimate report. Estimate reports can be saved in PDF file format for future use.

Estimating Project - Estimating Report

Main Report

10/19/201

ElementDescription	AssemblyCode	ItemCode	ItemDescription	Quantity	Waste	TotalQuantity	MaterialCost	LaborCost	Equipment	TotalCost
<b>North Wall</b>										
North Wall	B2010156	04 21 13.13 0010	Brick veneer ma	0.00	0.00	0.00	0.00	0.00	0.00	0.00
North Wall	B2010156	04 21 13.13 0050	Brick veneer, sts	4.05	15.00	4.66	868.86	315.33	0.00	274.19
North Wall	B2010156	04 22 10.14 0010	Concrete Mason	0.00	0.00	0.00	0.00	0.00	0.00	0.00
North Wall	B2010156	04 22 10.14 1150	CMU normal wei	300.00	10.00	660.00	789.00	477.09	0.00	266.09
North Wall	B2010156	04 22 10.16 0010	Concrete Block,	0.00	0.00	0.00	0.00	0.00	0.00	0.00
North Wall	B2010156	04 22 10.16 2100	Including grout a	60.00	5.00	63.00	782.00	311.36	0.00	393.36
North Wall	B2010156	04 22 10.32 0010	Concrete Block,	0.00	0.00	0.00	0.00	0.00	0.00	0.00
North Wall	B2010156	04 22 10.32 0250	8" x 8" x 8", 2#4	0.00	0.00	0.00	0.00	0.00	0.00	0.00
North Wall	B2010156	04 05 13.30 2000	Mortar with Portl	0.00	0.00	0.00	0.00	0.00	0.00	0.00
North Wall	B2010156	04 05 13.30 2100	Type M, 1:1/4:3	23.08	20.00	27.70	700.74	49.87	3.34	753.95
<b>North Wall</b>				<b>710,930.61</b>			<b>7,453.65</b>		<b>3.34</b>	<b>387.59</b>
<b>South Wall</b>										
South Wall	B2010156	04 21 13.13 0010	Brick veneer ma	0.00	0.00	0.00	0.00	0.00	0.00	0.00
South Wall	B2010156	04 21 13.13 0050	Brick veneer, sts	4.00	0.00	4.00	866.05	368.72	0.00	334.76
South Wall	B2010156	04 22 10.14 0010	Concrete Mason	0.00	0.00	0.00	0.00	0.00	0.00	0.00
South Wall	B2010156	04 22 10.14 1150	CMU normal wei	593.33	0.00	593.33	1,009.34	226.86	0.00	236.21
South Wall	B2010156	04 22 10.16 0010	Concrete Block,	0.00	0.00	0.00	0.00	0.00	0.00	0.00
South Wall	B2010156	04 22 10.16 2100	Including grout a	60.00	0.00	60.00	840.00	296.54	0.00	136.54
South Wall	B2010156	04 22 10.32 0010	Concrete Block,	0.00	0.00	0.00	0.00	0.00	0.00	0.00
South Wall	B2010156	04 22 10.32 0250	8" x 8" x 8", 2#4	0.00	0.00	0.00	0.00	0.00	0.00	0.00
South Wall	B2010156	04 05 13.30 2000	Mortar with Portl	0.00	0.00	0.00	0.00	0.00	0.00	0.00
South Wall	B2010156	04 05 13.30 2100	Type M, 1:1/4:3	22.83	0.00	22.83	299.54	41.10	2.75	343.39
<b>South Wall</b>				<b>641,014.94</b>			<b>6,533.21</b>		<b>2.75</b>	<b>550.90</b>
<b>Grand Total:</b>							<b>945.54</b>	<b>986.87</b>	<b>6.08</b>	<b>938.49</b>

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FIGURE 7-18: Estimating report created by the Visual Estimating Application

## CHAPTER 8

### SUMMARY, CONTRIBUTIONS, LIMITATIONS, AND FUTURE RESEARCH

This chapter provides a brief description of research summary, contributions, limitations, and recommendations for future research in the area of visual construction cost estimating.

#### 8.1 RESEARCH SUMMARY

The goal of this research was to make the process of construction cost estimating simpler and more intuitive. It also introduced the use of visualization in estimating. The developed application digitally transfers project information from a BIM model to the estimating application; this reduces the manual data entry which is a very time consuming process. This study provided a visual approach for estimating that allows an estimator to walk inside a virtual building and select elements for estimating interactively.

The developed Visual Estimating Application helps ease the estimating process by utilizing 3D CAD models and information extracted from a 3D CAD model. A visualization module is used to help the estimator navigate and interact with the model. A cost estimating database is used to store cost data for the Visual Estimating Application. Although several database models can be used for storing cost data, the relational database model was adopted in this study.

The developed visualization module interfaces with Revit Architecture using Revit API via C# programming language. The visualization module extracts from a Revit

model not only a building element's geometry, but also element material properties. The visualization module uses Microsoft DirectX graphical library to generate a virtual prototype of the project.

The Visual Estimating Application matches an element extracted from a Revit model to an assembly from the cost estimating database for preparing an estimate. An estimate report could also be generated.

Although some of the tedious estimating tasks have been eliminated, the estimator input is still a must. Different project has different methods of construction and circumstances. Even though computers can assist some process during estimating, it could only do so much while judgment and experience of estimator is also needed.

## **8.2 RESEARCH CONTRIBUTIONS**

The following are the main research contributions:

1. *Visual Interface for Cost Estimating*: Visual approach to construction cost estimating provides visual aids to the estimator, making the estimating process more intuitive and simple. This application transfers the necessary information from a BIM model to the estimating software. This eliminates the tedious and time consuming process of manual data entry quantity takeoff.
2. *Visual Cost Estimating as an Educational Tool*: The Visual Estimating Application can be used as an effective educational tool for students who have no experience in construction cost estimating. According to Karshenas (2009), during estimating, “students must perform less repetitive, mechanical

activities and spend more time observing, thinking, discussing, reflecting, and solving problems. This requires:

- i. Making access to cost estimating information intuitive and fast.
  - ii. Automating extraction of building element geometry and material from CAD models.
  - iii. Exposing student to as many actual construction operations as possible.”
3. *Foundation for Future Research and Improvements:* This research provides a good foundation for developing not only an educational tool, but also a new way to approach cost estimating commercially. Future research and improvements for the Visual Estimating Application is provided in more detail in section 8.4.

### **8.3 RESEARCH LIMITATIONS**

1. Estimating the cost of a building project consists of determining the cost of a large number of building elements made of different material. However, the database was developed to a limited number of elements such as concrete and masonry show the methodology of the Visual Estimating Application.
2. There are many BIM packages available in today’s market. One of the leading BIM software company is Autodesk. This study is primarily focused on Autodesk Revit Architecture. Although Revit Structure and Revit MEP are available as part of Autodesk BIM package, they were not included in this study.

3. Extraction of information from a 3D CAD model provides the Visual Estimating Application with geometry and materials information needed for cost estimate. However, elements extracted from Revit Architecture do not contain information that can be used to automatically match to an assembly provided by the cost estimating database. This process still requires manual input from an estimator.
4. Since this is a visual approach to construction cost estimating, estimating is done by navigating and selecting elements from inside a virtual building. Navigating a 3D model using a 2-button mouse maybe difficult for some users. A navigating device such as a 3D mouse may be more helpful for navigation.

#### **8.4 FUTURE RESEARCH**

Future improvements to the Visual Estimating Application could be implemented as follows:

1. Elements from the 3D CAD model have to be matched to an assembly from the cost estimating database. Automating this process could provide the estimator with an easier task of searching for an assembly in the database.
2. Since cost of equipments and materials changes on a regular basis. Cost estimating database should be updated automatically from remote resources such as suppliers' web sites. This would help save time by not having to update individual entries in the cost estimating database.

3. Computer network capability can be added to facilitate collaboration among estimators. For example, an estimator can work on project walls while another estimator works on footings.

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**APPENDIX 1****ASSEMBLY DIVISION CODE**

A: Substructure

B: Shell

C: Interiors

D: Services

E: Equipment and Furnishings

F: Special Construction

G: Building Sitework

**APPENDIX 2****CSI ITEM DIVISION CODE**

Division 00 – Procurement and Contracting Requirements

Division 01 – General Requirements

Division 02 – Existing Conditions

Division 03 – Concrete

Division 04 – Masonry

Division 05 – Metals

Division 06 – Wood, Plastics, and Composites

Division 07 – Thermal and Moisture Protection

Division 08 – Openings

Division 09 – Finishes

Division 10 – Specialties

Division 11 – Equipment

Division 12 – Furnishings

Division 13 – Special Construction

Division 14 – Conveying Equipment

Division 21 – Fire Suppression

Division 22 – Plumbing

Division 23 – Heating, Ventilating, And Air-Conditioning (HVAC)

Division 25 – Integrated Automation

Division 26 – Electrical

Division 27 – Communications

Division 28 – Electronic Safety and Security

Division 31 – Earthwork

Division 32 – Exterior Improvements

Division 33 – Utilities

Division 34 – Transportation

Division 35 – Waterway and Marine Construction

Division 40 – Process Integration

Division 41 – Material Processing and Handling Equipment

Division 42 – Process Heating, Cooling, and Drying Equipment

Division 43 – Process Gas and Liquid Handling, Purification, and Storage Equipment

Division 44 – Pollution Control Equipment

Division 45 – Industry-Specific Manufacturing Equipment

Division 48 – Electrical Power Generation