

## Construction Cost Prediction by Using Building Information Modeling

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### Abstract

The increased interest in using Building Information Modeling (BIM) in detailed construction cost estimates calls for methodologies to evaluate the effectiveness of BIM-Assisted Detailed Estimating (BADE) tools in generating detailed construction cost estimates. The focus of this research is on developing a quantified evaluation method to measure the impact of these BADE tools. Further, in order to understand the cognitive details of the estimator, this research also tested and evaluated the impact of the visualization factor and the compound impact of the visualization factor and aggregated calculation factor on the construction cost estimating process. Two cases study were tested, building and bridge. Three methods were applied on each case study, method 1 the manual estimating method, method 2 used a BADE tool without a calculation function (i.e., the quantities of the individual building components can be read as properties of the component), method 3 used a BADE tool with calculation functions that allowed the user to directly calculate/aggregate the query results of the BIM database in the MS Excel spreadsheet. Results obtained from the test cases helped to reinforce the reliability of the observations and the evaluation. Four parameters were used to evaluate the performance results individually in the first step: generality, flexibility, efficiency, and accuracy. Then a multiattribute utility model, which took into account the four individual parameters, was developed and used to evaluate the overall performance of BIM assisted estimating versus the performance of the traditional estimating method on quantity takeoffs. The research concluded that the BIM-assisted estimate demonstrated better performance over traditional estimating methods. Both the visualization and aggregation functions of the BADE tool had significant impact on the performance of the detailed estimate.

### I. Introduction

During cost estimating process, estimators typically begin by doing manual takeoffs from their drawings. This method increases the chance of human error and follows any inaccuracies there may be in the original drawings. The time spent by the estimator on quantification varies by project, but perhaps 50-80% of the time needed to create a cost estimate is spent just on quantification. Given those numbers, the huge advantage of using a building information model for cost estimating is clear.

Miner and Thompson (2006) explained the importance of BIM for 3D, 4D and 5D modeling which include scheduling and cost estimation. By using a building information model instead of drawings, the takeoffs, counts, and measurements can be generated directly from the model. BIM Software packages have built-in cost estimating features. Material quantities are automatically extracted and changed when any changes are made in the model (Azhar et al., 2008). When manual takeoffs are not required; time, and cost can be saved, and the human error is reduced. Cost estimation can be done in Building Information Modeling (BIM) Software packages in different manners: connecting the model objects to cost databases so that cost estimation can

be done in an automated manner, or exporting the quantity takeoff lists to Excel spreadsheets where costs are inserted and cost estimation is performed.

Shen et al. (2007) explained that BIM models are not rich enough to cover the richer details of the real trade practices, and that they lack the mechanism to provide multiple trades views at various detailed levels. There are significant limitations when BIM applications are applied to generate detailed construction estimates due to the lack of a configurable construction knowledge base in BIM's data model. BIM applications are able to generate accurate physical quantities of materials used in the design. However, due to the lack of context for construction methods and procedures, these material quantities cannot be used directly to generate labor and equipment quantities (Shen & Issa, 2010). In order to overcome this problem, they applied BIM-Assisted Detailed Estimating (BADE) approach which allows estimators to apply their own domain-specific judgments to the design features with the assistance of 3D visualization and quantity data from BIM models.

Building Information Modeling (BIM) is the development and use of a computer software model to simulate the construction and operation of a

facility (AGC, 2006). The resulting model, a Building Information Model, is a data-rich, intelligent, and parametric digital representation of the facility, from which data appropriate to various users' needs can be extracted and analyzed to generate information to make decisions and improve the process of facility delivery. BIM is a building industry development that represents a shift from electronic drafting to a model-based process. The main concern of BIM is the development of an integrated model that can be used in all stages of a project's life cycle. A BIM model has many uses, including the following: it can be connected to time schedules, be used to generate accurate shop drawings, perform quantity surveys and cost estimates, and be used in facility management. BIM has many benefits that assist the project participants during the project's life cycle.

A number of benefits, as presented by ASHARE (2010), are: Parametric modeling, which is an important feature of BIM that enables objects and components within a model to be parametrically related; Time saving and cost reduction in all stages of the project; Automation of off-site fabrication; Enables better cost estimates and procurement management; and Assists in sustainable construction and climate protection. Coordinating construction sequencing by integrating schedule data with the 3D model creates the 4D aspect in BIM. The fifth dimension (5D) uses the 3D model data to quantify materials and apply cost information (McCuen, 2008).

Applying BIM technology on bridges is named Bridge Information Modeling (BrIM) that has widely become an effective tool in bridges engineering and construction industry. BrIM is not just a geometrical representation of bridges, but it is an intelligent representation of bridges since it contains all information needed about bridges throughout their life cycle. Different models were developed for bridge cost estimation in literature (Kim, 2011, Fragkakis et al., 2011; Fragkakis et al., 2010; Kim et al., 2009; Sirca & Adeli, 2005; Morcoux et al., 2001; Skamris & Flyvbjerg, 1997). The models presented in literature are not bridge specific models. They do not include bridge construction knowledge that could affect the detailed cost estimation. Bridge Information Modeling (BrIM) has great effect on the improvements of the three main concerns of bridges stakeholders which are quality, schedule, and cost and it is needed for bridges since it creates consistency in information in different phases from design to maintenance (Marzouk et al., 2010). The 3D bridge model can be used for: Up-to date shop drawings; Quantity takeoffs and bills of materials; CNC (computer – numerically – controlled) input files to drive automated shop equipment such as robotic welders or beam-line hole – punching

machines for steel members, splice plates, etc.; Fabrication labor and material estimating and shop material management, etc. (Chen & Shirole, 2007). Marzouk and Hisham (2011a) utilized BrIM with the main components of bridge management systems in order to obtain efficient decisions related to maintenance and rehabilitation. Marzouk and Hisham (2011b) integrated BrIM with Genetic Algorithms to optimize the locations of mobile cranes during the construction phase of bridges, taking into consideration existing conditions of site, surrounding areas, safety, and schedule constraints.

## II. BIM-Assisted Detailed Estimating (BADE)

Visualization has been recognized in many areas as an effective tool for enhancing the understanding of complex relationships and complex systems (Card 1999; Kamat 2001; McKinney 1998). This is especially true with regard to understanding complex spatial relationships, such as building structures and systems. Detailed construction cost estimates require a comprehensive and thorough understanding of the relationships among building systems. Generating a detailed construction cost estimate is a critical and time-consuming task in construction operations. Poor cost estimates were identified as one of the major factors contributing to the high failure rate of construction companies (Surety Information Office 2007). In detailed cost estimates, a significant amount of time is spent on visualization, interpretation and clarification of drawing and specification information and calculations of aggregated quantities of labor, materials, and equipment.

Many tools have been developed to help the estimator get the job done quicker and more accurately. Those tools range from color markers, digitizers, and two-dimensional (2D), on-screen takeoffs, to the latest Building Information Modeling (BIM) software. BIM tools have addressed the significant limitations of 2D drawings that lack the rich three-dimensional (3D) context which estimators need in order to identify important cost-sensitive design features (Froese et al. 1999; Staub-French and Fischer 2003).

Major computer-aided design (CAD) software developers, such as Autodesk®, have included bill of material (BOM) functions in their BIM applications (Autodesk® Revit®) to help with construction estimating and procurement. While helpful, there are significant limitations when BIM applications are applied to generating detailed construction estimates (O'Brien et al. 2002; Shen et al. 2007) due to the lack of a configurable construction knowledge base in BIM's data model. In other words, current BIM applications are able to generate fairly accurate physical quantities of materials used in the design. However, due to the lack of context for construction

methods and procedures, these material quantities cannot be used directly to generate labor and equipment quantities.

An alternative to the predefined-data-model approach is to allow estimators to apply their own domain-specific judgments to the design features with the assistance of 3D visualization and quantity data from BIM models. This approach is called BIM-Assisted Detailed Estimating (BADE). An alternative to the text-based ontology approach (Staub-French and Fischer 2003), this visualization based approach provides flexibility when design features are difficult to describe in text.

Despite increased interest and progress in the BIM area, a quantified assessment framework is needed for evaluating the impact of BADE tools on detailed construction estimates. Few publications were found in this area. There is a need to study some key factors that contribute to the performance of BADE tools.

This research was conducted with a goal of better understanding, how the visualization functions affect the detailed cost estimate; and how the combination of visualization and aggregation functions affect the detailed cost estimate.

In order to achieve the goal of this research, three methods were used:

- ♣ Method 1, the manual estimating method, used traditional 2D drawings and a Microsoft® (MS) Excel® spreadsheet.
- ♣ Method 2, used a BADE tool without a calculation function (i.e., the quantities of the individual building components can be read as properties of the component).
- ♣ Method 3, used a BADE tool with calculation functions that allowed the user to directly calculate/aggregate the query results of the BIM database in the MS Excel spreadsheet.

Two types of BADE tools were used in order to evaluate the impact of the visualization factor and the compound impact of the visualization plus aggregated calculation fact, and to test the hypothesis that the visualization function alone, even without a calculation function, is enough to help improve the estimating process in terms of accuracy and speed.

These three methods will be applied in two cases study, Building Information Modeling (BIM), and Bridge Information Modeling (BrIM). The different two cases study are used to compare the generation of estimates using the manual method and using the two BADE tools, these comparisons were conducted using the individual criterion and the utility model developed for each case study.

The performance of the three methods was evaluated based on four key performance criteria deemed important to detailed estimates: generality, flexibility, accuracy, and efficiency. (Issa et al. 2003; RIBA 2001; Rivard 2000). The parameters of generality and flexibility used ordinal scale measurement. The efficiency parameter was measured in terms of time (minutes) consumed in accomplishing a specific task. The accuracy parameter was measured in terms of deviations (percentage) from the correct answers. The overall performance of each method was evaluated based on a utility function, which incorporated the four parameters. Further, a utility function was developed for each individual criterion. The overall performance of each method was measured by both the individual criterion and the Multiple Attributes Utility-Function Model (MAUFM).

### III. Case Study 1 (The Building)

The presented case is a four-storey building (Ground floor, 3 typical floors) of an area of 500 m<sup>2</sup> located in Damietta governorate, Egypt. There are three methods were used:

#### 3.1 Method 1 (Manual)

The manual method used traditional 2D AutoCAD drawings and a Microsoft® (MS) Excel® spreadsheet.

#### 3.2 Method 2 (BADE tool without a calculation function)

The first BADE tool used 3D Structural Modeling and parametric design by Revit structure software and an off-the-shelf, Industry Foundation Classes (IFC), viewer assisted estimating tool (IFC Viewer). IFC Viewer assisted with visualization and dimensional values for individual building components. A calculator was used to do aggregated quantity calculations. The Revit Structure software and the IFC Viewer are able to display the 3D building model along with a tree data structure. Users can see and turn around each building component with its individual properties, including dimensions, displayed. The function of the IFC Viewer was to enable estimators to see the 3D model, assembly structures, and design features of the building components. This IFC Viewer is able to display the 3D building assembly and data structure and allows users to highlight building components. Users need to manually read and enter each individual estimate quantity into the MS Excel spreadsheet in order to determine the PCQ and PPQs. Figure1 shows a 3D BIM model.

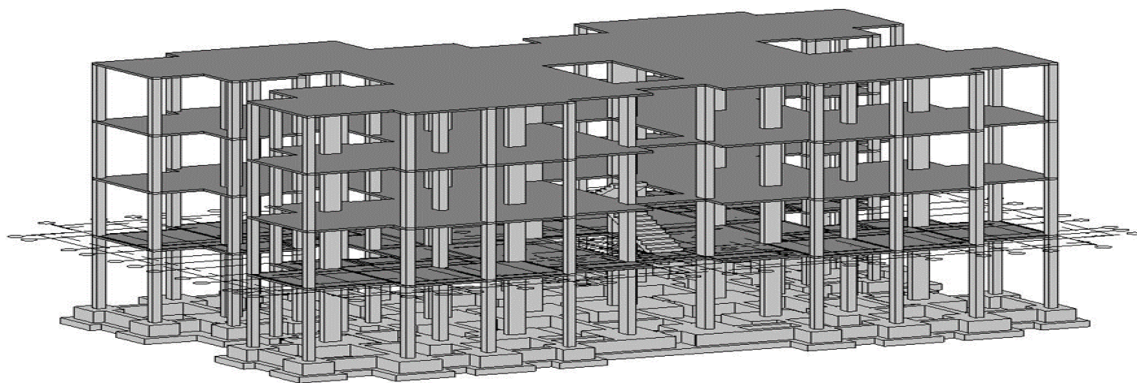


Figure1 3D BIM Model

### 3.3 Method 3 (BADE tool with calculation functions)

The second BADE tool was developed by using a combination of the Revit structure software, IFC Viewer and MS Excel connected to a customized MS SQL Server® Express system, which served as a repository for all of the data for the building components. Used the IFC Viewer-Database-Excel (IVDE) prototype tool which provided functions for visualization, querying, and aggregated calculations of quantities, and customized from off-the-shelf applications, namely, the IFC Viewer, MS Excel, and MS SQL Server Express. The key function provided

by the IVDE is that it allows the estimators to create PCQs flexibly using MS Excel by differentiating and/or aggregating quantities provided by the 3D design file while visualizing and examining the 3D model for special features, which may affect labor and/or equipment productivity. MS Excel was connected through the MS Open Database Connectivity (ODBC) interface to the BIM database that resides on the MS SQL Server. PCQs were created in MS Excel by aggregating and/or differentiating the PPQs that were brought into MS Excel. Figure2 shows the IVDE tool implementation diagram.

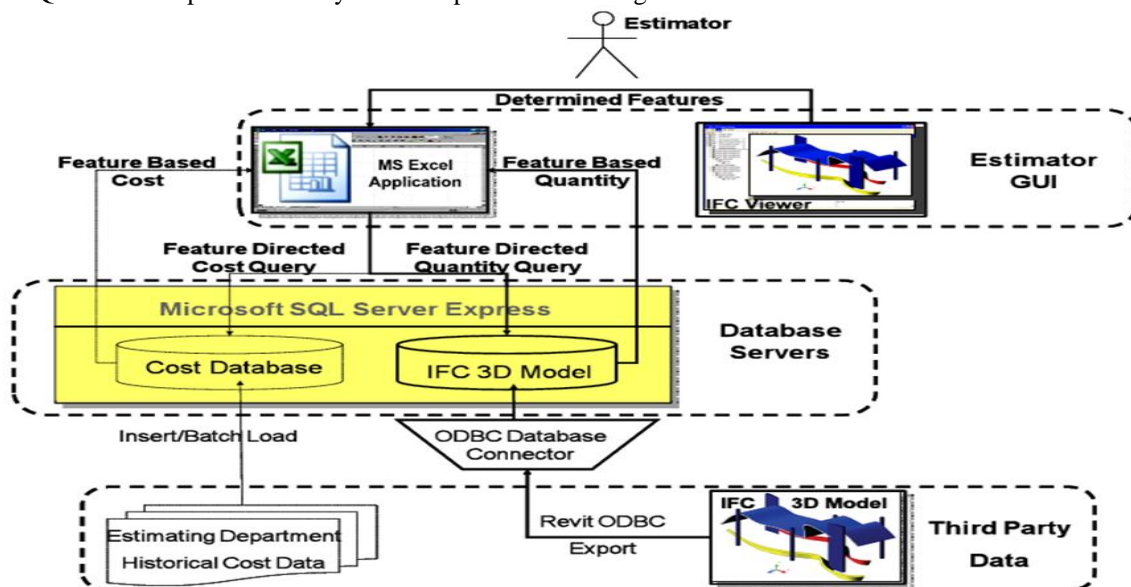


Figure2 the IVDE Tool Implementation Diagram

### IV. Case Study 2 (The Bridge)

The presented case is a bridge located in Albeherah governorate, Egypt. The bridge length is 170 meters divided into three parts which are:

- ♣ Part 1: the length of this part is 75 meters divided into 3 equal spans. The superstructure is composed of 2 cast in place concrete box sections.

- ♣ Part 2: the length of this part is 45 meters. The superstructure is composed of steel beams and bracings, and concrete deck slab.

- ♣ Part 3: the length of this part is 50 meters divided into 2 equal spans. The superstructure is the same as part 1.

There are three methods were used for detailed estimates:

#### 4.1 Method 1 (Manual)

The manual method used traditional 2D AutoCAD drawings and a Microsoft® (MS) Excel® spreadsheet.

#### 4.2 Method 2 (BADE tool without a calculation function)

The first BADE tool used 3D Structural Modeling and parametric design by Tekla structures software, the 3D bridge model is not only a geometrical representation of the bridge, but it also contains attributes such as material type, cross section area, and volumes. The construction visualization is achieved by integrating: the 3D BrIM model, and the construction methods' modeling tools and libraries. In order to integrate the 3D BrIM model with these models, Navisworks Manage

software is used. The visualization feature helps in obtaining accurate cost estimates because it assists in determining the required equipment, temporary structures and coordinating their interaction to determine any conflicts that could affect productivity during construction. In cases of integrating the representation of site conditions, bridge model, and equipment and temporary structures models; more accurate productivity estimates could be obtained. A calculator was used to do aggregated quantity calculations. Users need to manually read and enter each individual estimate quantity into the MS Excel spreadsheet in order to determine the PCQ and PPQs. Figure3 shows a 3D BrIM model, Figure4 show the 3D representation of different construction methods using Bridge Information Modeling.

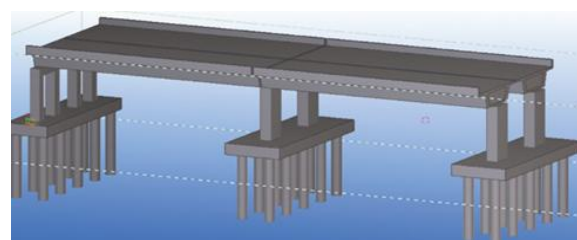
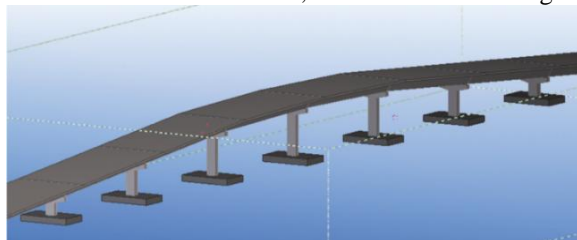


Figure3 3D BrIM Model

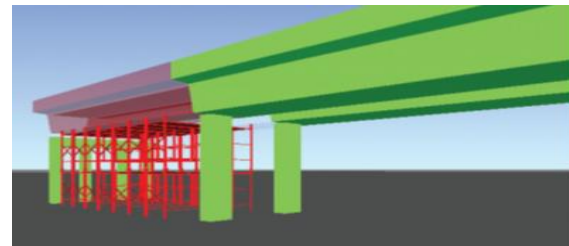
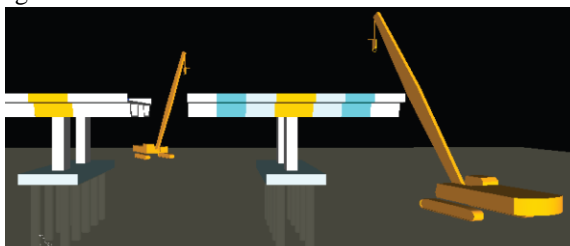


Figure4 3D Visualization of Different Construction Method Using BrIM

#### 4.3 Method 3 (BADE tool with calculation functions)

The second BADE tool was developed by using a combination of the Tekla structures software, Navisworks Manage software and MS Excel connected to a customized MS SQL Server® Express system, which served as a repository for all of the data for the bridge components. The information and conclusions obtained from the visualization process, or the estimator's knowledge and experience, are added as user defined information to their associated model objects. These added information include: the construction method (for slabs and beams only), and comments. Another information which is dependent upon the contract documents are added. This information is: contractor/subcontractor/vendor name, and the numbering of item (the object related to) in Bill of Quantities (BOQ). Figure5 shows the connectivity between different software packages and methods to achieve the proposed BrIM. The user defined information and other components' attributes are represented using Express G diagrammatic modeling notation as shown in Figure6.

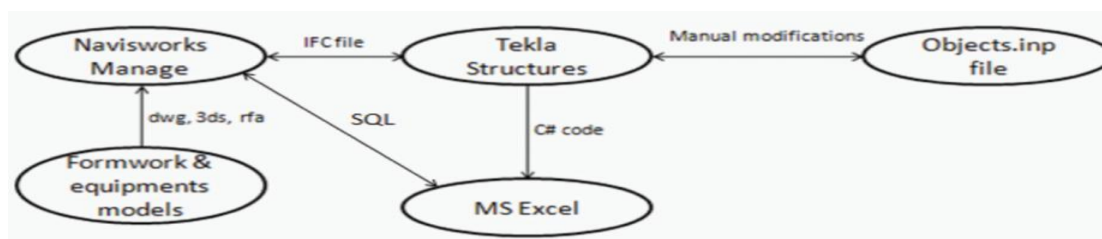


Figure5 Connectivity to Achieve the Proposed BrIM in Cost Estimation

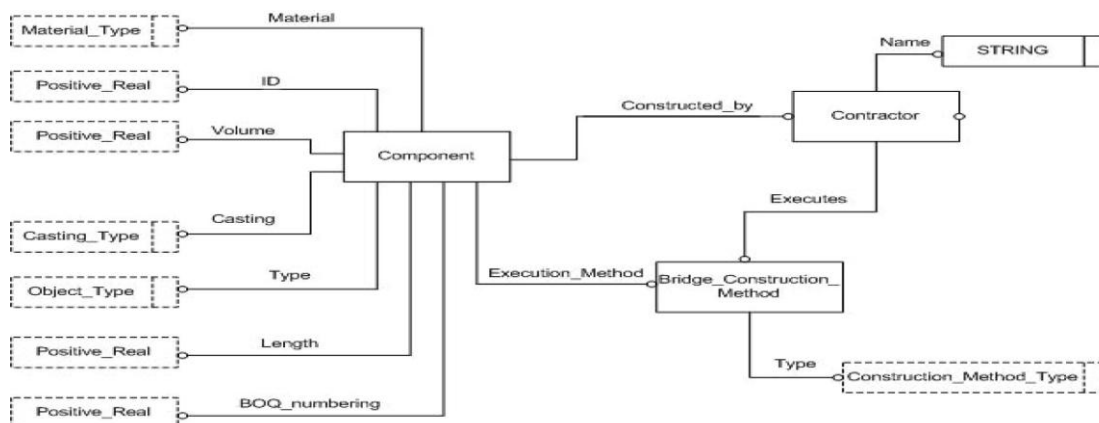


Figure6 Information Representation Using Express G

Most of Bridge Information Modeling software allow API (Application Programming Interface) which allows extending the uses of the software by creating new features and applications related to the 3D bridge information model by using several programming languages such as C# and Visual Basic. A program was created using C# programming language to extract: the added information and conclusions; and other intelligent objects attributes (e.g., objects' IDs, material, profile, casting type, volumes, and lengths). The estimator has to use these information and attributes to obtain material costs, labor costs, and equipment costs. These costs that have to be filled by the estimators are influenced by the information and conclusions obtained from the visualization of construction methods, and information added to the model objects based on users' knowledge.

## V. Analysis of Results

The evaluation of the results was based on a utility model that was used to quantify the efficacy of BADE programs in assisting with detailed construction estimates. The utility model included four performance criteria which were deemed important to detailed estimates: generality, flexibility, accuracy, and efficiency. The generality and flexibility scores were based on the functions of the compared estimating method. The efficiency and accuracy evaluation were based on the actual results. For each performance criterion, a utility function was developed. Table1 provides an overview of how the performance were designed when comparing the performances of the three cost estimating methods for each case study.

Table1 Performance Matrix Based on the Estimating Methods

Estimating Methods	Method1	Method2	Method3
Case Study 1 (BIM)	Result 1.1	Result 1.2	Result 1.3
Case Study 2 (BrIM)	Result 2.1	Result 2.2	Result 2.3

### 5.1 Generality Evaluation

The generality parameter was measured by the number of trade estimates the evaluated method can generate. Since five trades were used in each case study. The maximum score is 5, and the minimum

score is 0. As shown in Table2, the estimating method evaluated was assigned one point for each trade for which it was able to perform the estimating task.

Table2 Generality Comparison among the Three Estimating Methods  
 For Case Study1 (The Building)

Estimating Methods	Estimated Subcontractor Estimating Trade Categories					Generality Score
	foundations	columns	floors	framing	stairs	
Method1	1	1	1	1	1	5
Method2	1	1	1	0	1	4
Method3	1	1	1	1	1	5

For Case Study2 (The Bridge)

Estimating Methods	Estimated Subcontractor Estimating Trade Categories					Generality Score
	abutment	pier	bearing plinth	girder	slap	
Method1	1	1	1	1	1	5
Method2	1	1	1	0	1	4
Method3	1	1	1	1	1	5

### 5.2 Flexibility Evaluation

The flexibility parameter was measured based on the number of special design features the evaluated estimating method could differentiate. The flexibility score is the number of features the estimating method can differentiate. But the concrete cost estimate had no special design features involved. So this parameter did not take into consideration in these cases study.

### 5.3 Efficiency Evaluation

The efficiency parameter was measured by the time consumed to complete each estimate as shown in Table3. The shorter time the estimate required, the more efficient the method.

Table3 Efficiency Comparison among the Three Estimating Methods  
 For Case Study1(The Building)

Estimating Methods	Method1	Method2	Method3
Time consuming (Minutes)	125	97	85

For Case Study2(The Bridge)

Estimating Methods	Method1	Method2	Method3
Time consuming (Minutes)	130	105	95

### 5.4 Accuracy Evaluation

The accuracy parameter was measured by the deviations of the estimate from the correct values expressed as a percentage. The smaller the deviation, the better the method will perform in the accuracy

test. Based on industry standard practices, a 5% or less deviation was used as the threshold of good accuracy. The formula is:

$$ED \text{ (Estimate Deviation)} = (\text{Value of the Estimate} - \text{Correct Value}) / (\text{Correct value}) \times 100\%$$

Table4 Accuracy Comparison among the Three Estimating Methods  
 For Case Study1(The Building)

Estimating Methods	Method1	Method2	Method3
Correct Value	712606.5	712606.5	712606.5
Value of the Estimate	766052	748236.8	744673.8
Estimate Deviation%	7.5%	5%	4.5%

For Case Study2(The Bridge)

Estimating Methods	Method1	Method2	Method3
Correct Value	9534492.6	9534492.6	9534492.6
Value of the Estimate	10297252	10011217	9915872.3
Estimate Deviation%	8%	5%	4%

### 5.5 Overall Performance Evaluation Using the MUFM

The multiple attribute utility function model (MAUFM) (Georgy et al. 2005) provides a methodology for evaluating performance for multi-

attribute systems. In this section, MAUFM is employed to compare the system performance between using the manual estimating method and the two estimating methods using BADE tools. The basic method of the MAUFM is to assign certain weights

to each system attribute based on the experts' opinions on the importance of each attribute. Each individual attribute has a usefulness function (utility) included in the overall system performance. The overall system performance will be assessed based on the values from the MAUFM.

For example, the function  $U(x_i)$   $i = 1, 2, 3 \dots n$  represents the utility of the  $i$ th attribute in the system performance. The value of the function  $U(x_i)$  has a range with a low score=0 and high score=1, depending on the evaluator's risk attitude (Georgy et al. 2005). The function  $U(x_i)$  is defined as:

$$U(x_i) = c_i x_i + d_i \quad (\text{Equation 1})$$

Where  $c_i$  and  $d_i$  = constants

The overall value of the function  $U(x_i)$  is a weighted function of each individual attribute value. The weight assigned to individual attributes is based on the evaluator's or expert's experience and knowledge. The multi-attribute score takes the form of:

$$U(x_1, x_2, x_3 \dots x_n) = W_1 U_1(x_1) + W_2 U_2(x_2) + W_3 U_3(x_3) + \dots + W_n U_n(x_n) \quad (\text{Equation 2})$$

Where  $W_i$  is the weight value assigned to individual attribute

In this research, the performance of estimating tasks using different estimating methods was evaluated. Four attributes were included in the evaluation: generality, flexibility, efficiency, and accuracy of the evaluated estimating methods. The first step was to establish the individual attribute utility functions, as shown in Figure7, based on evaluators' and/or experts' knowledge and experience. For example, the value of Generality Utility Function=1 when the estimating method can estimate five subcontractor trades. The value=0 when the estimating method is unable to generate estimating quantities for any of the five trades. In the Efficiency Utility Function, if the estimate can be 1 in 20 minutes, its value=1. If the estimate took more than 100 minutes, its value=0. The intermediate attribute values will generate utility values between 0 and 1, as shown in Figure7.

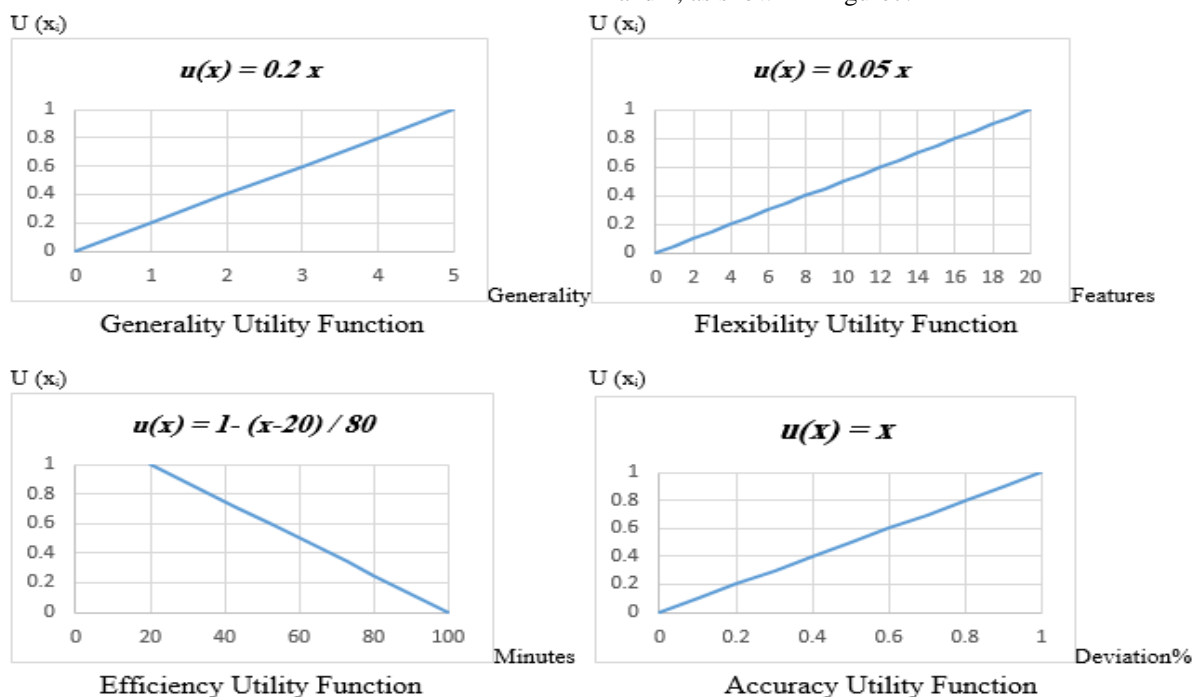


Figure7 the Utility Functions of the Four Evaluation Attributes

The next step is to determine the weight factor for each individual attribute. The Eigenvector Prioritization Method (Saaty 1980) was used to determine the weight factor of the four attributes. The importance factors (Table5) are established based on the authors' industry experience and related studies (Issa et al. 2003; RIBA 2001; Rivard 2000).

Table5 Importance Factor for Pairwise Comparison of the Four Evaluated Attributes (Georgy et al. 2005)

Importance	Rating
Equally important	1
Moderately important	3
Strongly important	5
Very strongly important	7
Extremely important	9

Note: 2,4,6,8 are intermediate values.



The Eigenvector Prioritization Method uses a pairwise comparison matrix to determine the weight factor of the multiple attributes (Georgy et al. 2005).

$$[A]_{n \times n} = \begin{bmatrix} 1, a_{12}, a_{13}, a_{14}, \dots, a_{1n} \\ a_{21}, 1, a_{23}, a_{24}, \dots, a_{2n} \\ a_{31}, a_{32}, 1, a_{34}, \dots, a_{3n} \\ \dots \\ a_{n1}, a_{n2}, a_{n3}, a_{n4}, \dots, 1 \end{bmatrix}_{n \times n}$$

(Equation 3)

Where  $a_{x,y}$  represents the importance factor derived from the attributes comparison (Table5). Based on their own industry experience and related studies (Issa et al. 2003; RIBA 2001; Rivard 2000), the four attributes were given the following relative importance:

Accuracy (A) is equally as important as Efficiency (E), i.e.  $a_{AE} = 1$  and  $a_{EA} = 1$   
 Accuracy (A) is strongly important over Generality (G), i.e.  $a_{AG} = 5$  and  $a_{GA} = 0.2$

Accuracy (A) is strongly important over Flexibility (F), i.e.  $a_{AF} = 5$  and  $a_{FA} = 0.2$

Efficiency (E) is strongly important over Generality (G), i.e.  $a_{EG} = 5$  and  $a_{GE} = 0.2$

Efficiency (E) is strongly important over Flexibility (F), i.e.  $a_{EF} = 5$  and  $a_{FE} = 0.2$

Flexibility (F) is moderately important over Generality (G), i.e.  $a_{FG} = 3$  and  $a_{GF} = 0.3$

$$[A]_{4 \times 4} = \begin{bmatrix} 1, a_{EA}, a_{GA}, a_{FA} \\ a_{AE}, 1, a_{GE}, a_{FE} \\ a_{AG}, a_{EG}, 1, a_{FG} \\ a_{AF}, a_{EF}, a_{GF}, 1 \end{bmatrix}_{4 \times 4} = \begin{bmatrix} 1 & 1 & 0.2 & 0.2 \\ 1 & 1 & 0.2 & 0.2 \\ 5 & 5 & 1 & 0.3 \\ 5 & 5 & 3 & 1 \end{bmatrix}_{4 \times 4}$$

(Equation 4)

Mollaghasemi and Pet-Edwards (1997) calculated the Eigenvector of the matrix [A] 4x4 using the following procedure:  
 First, the matrix [A] 4x4 is normalized to [Anorm] 4x4:

$$[A_{norm}]_{4 \times 4} = \begin{bmatrix} \frac{1}{1+1+0.2+0.2} & \frac{1}{1+1+0.2+0.2} & \frac{0.2}{1+1+0.2+0.2} & \frac{0.2}{1+1+0.2+0.2} \\ \frac{1}{1+1+0.2+0.2} & \frac{1}{1+1+0.2+0.2} & \frac{0.2}{1+1+0.2+0.2} & \frac{0.2}{1+1+0.2+0.2} \\ \frac{5}{5+5+1+0.3} & \frac{5}{5+5+1+0.3} & \frac{1}{5+5+1+0.3} & \frac{0.3}{5+5+1+0.3} \\ \frac{5}{5+5+3+1} & \frac{5}{5+5+3+1} & \frac{3}{5+5+3+1} & \frac{1}{5+5+3+1} \end{bmatrix}_{4 \times 4}$$

$$= \begin{bmatrix} 0.417 & 0.417 & 0.083 & 0.083 \\ 0.417 & 0.417 & 0.083 & 0.083 \\ 0.442 & 0.442 & 0.088 & 0.027 \\ 0.357 & 0.357 & 0.214 & 0.071 \end{bmatrix}_{4 \times 4}$$

(Equation 5)

Then the elements of the Eigenvector are calculated as follows:

$$[W]_{4 \times 1} = \begin{bmatrix} w1 \\ w2 \\ w3 \\ w4 \end{bmatrix} = \begin{bmatrix} (0.417 + 0.417 + 0.083 + 0.083) / 4 \\ (0.417 + 0.417 + 0.083 + 0.083) / 4 \\ (0.442 + 0.442 + 0.088 + 0.027) / 4 \\ (0.357 + 0.357 + 0.214 + 0.071) / 4 \end{bmatrix} = \begin{bmatrix} 0.25 \\ 0.25 \\ 0.27 \\ 0.25 \end{bmatrix}$$

(Equation 6)

Then the multiple attribute utility function takes the form:

$$U(x1, x2, x3, x4) = 0.25 \cdot U1(x1) + 0.25 \cdot U2(x2) + 0.27 \cdot U3(x3) + 0.25 \cdot U4(x4)$$

Where the  $U1(x1)$  is the generality utility function;  $U2(x2)$  is the flexibility utility function;  $U3(x3)$  is the accuracy utility function;  $U4(x4)$  is the

efficiency utility function (Figure7). The overall utility score of each estimating method was determined by applying Equation 7 to the three methods. The greater the utility score, the better the performance of the estimate method. Using data from

Figure the utility scores of the three estimating methods were as follows:

For case study1 (The Building):

$$U (\text{Manual})= 0.25 \times 1+ 0.25 \times 0 + 0.27 \times 0 + 0.25 \times 0.925 = 0.48$$

$$U (\text{BADE1}) = 0.25 \times 0.8+ 0.25 \times 0 + 0.27 \times 0.04 + 0.25 \times 0.95 = 0.45$$

$$U (\text{BADE2}) = 0.25 \times 1+ 0.25 \times 0 + 0.27 \times 0.2 + 0.25 \times 0.955 = 0.54$$

For case study2 (The Bridge):

$$U (\text{Manual})= 0.25 \times 1+ 0.25 \times 0 + 0.27 \times 0 + 0.25 \times 0.92 = 0.48$$

$$U (\text{BADE1}) = 0.25 \times 0.8+ 0.25 \times 0 + 0.27 \times 0 + 0.25 \times 0.95 = 0.44$$

$$U (\text{BADE2}) = 0.25 \times 1+ 0.25 \times 0 + 0.27 \times 0.06 + 0.25 \times 0.96 = 0.51$$

Based on the utility score of the three estimating methods, it was concluded that the BADE tool with aggregated calculation function demonstrated better performance than the other two estimating methods when the four evaluation attributes were taken into account together.

## VI. Limitations and Future work

The research project was a pilot study, and it was limited. This limitation is the nature of the test cases, the scale and scope of the test cases was limited. These test cases were relatively simple and were created for verification purposes only. A larger number of more complex test cases is needed in order to develop a more accurate regression model. Further tests on a larger scale, with a broader scope of projects are needed for more conclusive findings. And for case study2 (the bridge) although the proposed methodology facilitate the processes related to cost estimation, this methodology is limited for bridges executed with the defined construction methods only as the available 3D models required for visualization are limited to these construction methods only. For future research efforts, it is recommended to add 3D models so that other construction methods could be included. Despite its limitations, this research provides solid, quantified evidence that using a BADE tool can provide significant improvement in generating detailed construction estimates. Due to limited resources, this study did not address the detailed cognitive factors of 3D visualization, which contribute to performance improvements when estimating tasks. Future study in this area will help extend our understanding of the cognitive mechanism of how 3D models help estimators comprehend the interdependencies, interactions, and constraints that affect detailed cost estimates.

## VII. Conclusion

The results in this research showed significant improvement using BADE tools in terms of accuracy and efficiency when compared to the traditional manual estimating method. The results also showed that the 3D visualization function alone, as provided by the Revit structure software or Tekla structure software was sufficient to generate perceivable improvements in both estimating efficiency as well as estimating accuracy. The test results further demonstrated the power of integrating the 3D visualization functions with the aggregated calculation function. The performance improvement was significant in terms of both accuracy and efficiency. The results of this research, through the quantified evaluation of the contributing factors of 3D visualization and aggregation, provided many insights and motivations for further studies in this area.

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