QUANTITATIVE EVALUATION OF THE BIM-ASSISTED CONSTRUCTION DETAILED COST ESTIMATES

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SUMMARY: 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 study 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 study 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 types of BADE tools were tested in this study in order to differentiate the impact of the visualization factor on estimating performance from the compounded impact of both visualization and aggregation functions. A set of test cases with different levels of estimate complexity was designed and tested on entry-level estimators using both traditional manual estimating and BADE approaches. Results obtained from the test cases at several complexity levels 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 multi-attribute 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 study concluded that the BIM-assisted estimate demonstrated better performance over traditional estimating methods for the entry-level user. Both the visualization and aggregation functions of the BADE tool had significant impact on the performance of the detailed estimate. The study further indicated that the more complex the estimating tasks, the clearer the advantages were of using BADE tools instead of traditional estimating methods. The limitations of the test cases and the test subjects will affect the extrapolation of the conclusions of this research to the broad construction industry. Further study on industry-level cases and subjects is needed to obtain more conclusive findings.

KEYWORDS: Detailed Estimate, Performance Evaluation, BIM, Utility Model, Design Complexity

1. INTRODUCTION

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® 2009) 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. The details of the limitations are presented in Sections 2 and 3 of this paper.

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) in this study. 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.

Based on their own knowledge and related studies (Card 1999; Kamat and Martinez 2001; McKinney and Fischer 1998; Shen et al. 2007; Staub-French and Fischer 2003), the authors conducted this pilot study with a goal of better understanding: 1) how the visualization functions affect the detailed cost estimate; and 2) how the combination of visualization and aggregation functions affect the detailed cost estimate. In order to achieve the goal of this research, one control and two experimental groups were used:

- Group 1, the control group, used traditional 2D drawings and a Microsoft® (MS) Excel® spreadsheet.

- Group 2, the first experimental group, 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).

- Group 3, the second experimental group, 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.

The purpose of using the two different BADE tools was 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. The performance of the control group and the two experimental groups was evaluated based on four key performance criteria deemed important (Issa et al. 2003; RIBA 2001; Rivard 2000) to detailed estimates: generality, flexibility, accuracy, and efficiency.

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).

Comparisons between the BADE methods and the traditional manual estimating method were conducted using the individual criterion and the utility model developed.

The same set of test cases was used to compare the generation of estimates using the manual method (control group) and using the two BADE tools (experimental groups). Group 2 used an off-the-shelf, Industry Foundation Classes (IFC), viewer-assisted estimating tool (IFC Viewer 2005). IFC Viewer assisted with visualization and dimensional values for individual building components. A calculator was used to do aggregated quantity calculations. Group 3 used the IFC Viewer-Database-Excel (IVDE) prototype tool developed for this study, which provided functions for visualization, querying, and aggregated calculations of quantities.

The effects of design complexity on the performance comparisons were also evaluated in this study as an external factor. The test cases were designed with three levels of design complexity (i.e., simple, medium, and complex) in order to find out how this external factor impacts the efficiency of BADE tools. Table 1 provides an overview of how the performance tests were designed with the design complexity treated as an external factor when comparing the performances of the three cost estimating methods.

All users, both control and experimental group members, participating in the tests were junior level construction students who had entry-level estimating experience on the parts tested. Although the overall proficiency level of users impacted the absolute value of the tests, the results of the comparisons among the three cost estimating methods still provided us with useful indications of relative performance using different estimating tools.

TABLE 1: Performance matrix based on the estimating methods and the complexity levels.

Performance of Estimating		Estimating Methods		
		Manual	IFC Viewer	IVDE Prototype
Complexity Level of the Test Cases	Simple	Result 1.1	Result 1.2	Result 1.3
	Medium	Result 2.1	Result 2.2	Result 2.3
	Complex	Result 3.1	Result 3.2	Result 3.3

It should be noted that several limitations exist due to the idealized small-scale test cases and the representativeness of the test subjects (junior construction students who had completed estimating courses). These limitations will affect extrapolations of the test results to broad industry applications. Future studies using more diverse test cases with a more inclusive category of estimators could lead to more conclusive findings. Nevertheless, as a pilot study on the impact of 3D BIM technology on detailed construction estimates, these findings will be helpful for further explorations in this area.

2. DETAILED CONSTRUCTION ESTIMATE

In the traditional paper-based, detailed estimating process, the time spent on quantity takeoff can be broken down into three categories: 1) identifying items and their interrelationships on the drawings and specs (by marking and searching drawings and specs); 2) finding dimensions (reading directly or inferring from other drawings); and 3) calculating and aggregating the quantities, lengths, areas, and volumes of the identified items.

Detailed cost estimates include estimating product/procurement quantities (PPQ), which are physical quantities of design components, as well as estimating process quantities (PCQ), which are related to specific construction processes. Examples of PPQ include length and weight of rebar, volume of concrete beams, and areas of metal decking. Examples of PCQ include quantities of shoring/scaffolding, areas of formwork, labor hours for hanging drywall, and excavation quantities for earthwork.

One significant difference between PPQ and PCQ is that PPQ is determined by the design, and the quantity is fixed as long as the design is finalized. On the other hand, PCQ quantities depend on the construction process/construction methods and specific conditions of the job. So the PCQ could vary significantly from one contractor to another depending on the domain/trade knowledge of each individual contractor. PCQs are often based on a more detailed breakdown of the associated PPQs based on productivity factors, such as locations, geometric characteristics, and/or

construction methods (Sanders and Thomas 1991; Thomas et al. 1990). A more detailed illustration of the PPQ and PCQ is presented in the following case example.

2.1 Case Example for PPQ and PCQ

A simple case example of brick veneer quantities is presented here to illustrate how construction methods and trade knowledge affect detailed quantity breakdowns. Figure 1 shows a tilt-up concrete wall with brick veneer. Figure 1(b) shows how this tilt-up panel is cast on the casting bed. Figure 1(d) shows how the panel is being cast using the brick veneer as an embedded casting bed.

The PPQ, the brick material quantity, equals the summation of the areas of Side A and Side B. The PCQ, which is the labor hours in this case, is determined by the procedure of casting a brick-veneered tilt panel. The calculation of the PCQ requires breakdown of PPQ based on the respective construction approaches. The casting procedure is as follows:

1. The brick veneer is laid face down on the casting bed.

2. Then the panel rebar is put on top of the brick veneer.

3. The concrete is poured on the back of the brick veneer.

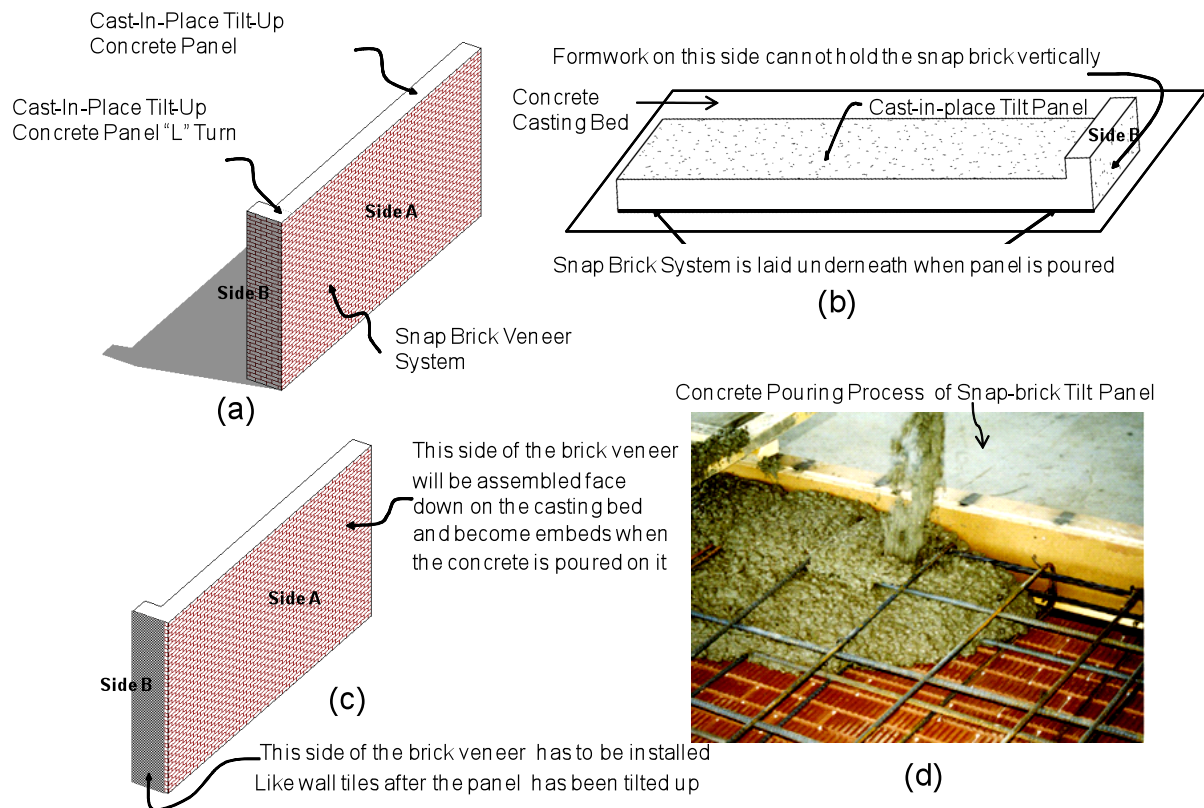4. The panel is tilted up and put it in its place.

FIG. 1: Estimating snap break veneer on a tilt-up concrete wall panel.

In this process, the brick veneer is embedded by the gravity of the concrete. However, the brick veneer on Side B of this panel, as shown in Figure 1 (a, b and c), cannot be installed the same way because the form board of the panel on Side B cannot hold the brick veneer in place during the pouring of concrete. So the brick veneer of Surface B has to be installed by masons after the panel is tilted up and put in place.

Because of the construction method used for this particular tilt panel, the installation time and waste factors of Surface B are significantly different than those of Surface A. So in order to get the correct labor hours for the veneer

installation, the estimator has to calculate the A area and the B area separately and apply their corresponding production rates and waste factors separately. As we can see from this simple example, depending on the specific construction procedure, PCQ is not the same as PPQ in many cases.

2.2 BIM-Assisted Detailed Estimating Tools

Since design models/drawings are intended to show design intentions and normally do not specify particular construction methods, there is a good chance that the quantities generated from a design model are not suitable for PCQs. This poses significant challenges for automatically generating PCQ quantities. Even with available BADE tools, the estimator's manual interpretation and analyses are still critical to extracting the right PCQs from the BIM model.

To further illustrate this observation, the L-shaped tilt-up wall panel, shown in Figure 1, will again be used as an example. For simplicity, this example focuses on the brick veneer quantities only. The designer may draw the L-shaped wall panel in a monolithic way, as shown in Figure 2 (a). Figures 2 (b), (c), and (d) illustrate the three possible ways to build this wall panel, while Table 2 shows the detailed quantity breakdowns (PCQ) for each corresponding construction method.

In Method 1, the wall was built in one pour (Figure 2 (b)); and the estimator needs to calculate the two brick surface areas and apply different labor production rates to come up with a cost estimate. In Method 2, the wall was built in two panels with a reveal joint (Figure 2 (c)); and the estimator needs to calculate the two brick surface areas and apply the same unit labor costs. In Method 3, the wall was built in two panels with flat joints (Figure 2 (d)). The cost of the construction method shown in Figure 2 (d) will be the same as that for Figure 2 (c), except for the extra cost of the reveal joint.

As this example demonstrates, the 3D BIM design model can only be created according to one of the three construction methods; and the PCQs can be generated accordingly. The actual construction method and the corresponding PCQs (Table 2) could be any of the three methods, depending on the contractor's experience and choice. Three-dimensional BIM models are capable of automatically generating PPQs, which are largely physical quantities of construction materials. Three-dimensional BIM models, which mainly reflect design intention, have significant limitations in automatically generating PCQ quantities from the contractor's trade perspective due to their lack of construction semantics.
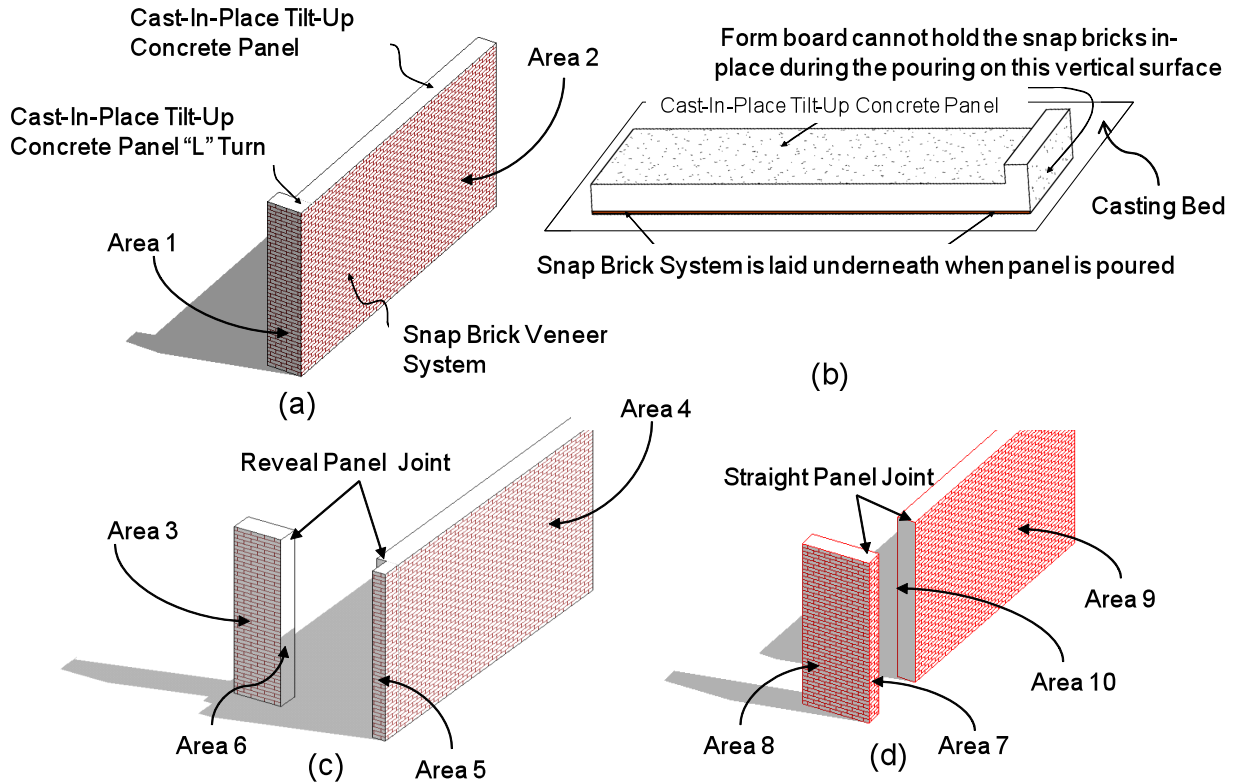
FIG. 2: *Three construction methods for an L-shape tilt panel.*

TABLE 2: *Matrix of the construction methods and the corresponding PCQs.*

Required PCQ Quantities for Calculating Labor Hours of Placing the Tilt-panel Brick Veneers				
Labor Hours Calculation Methods	Apply production rate for laying brick on the casting bed	Apply production rate for placing corner brick on the casting bed	Apply production rate for placing brick after the panel was tilted	Exclude
	The required areas of brick veneer			
Method 1 (Fig. 2a)	Area 2	n/a	Area 1	n/a
Method 2 (Fig. 2c)	Area 3, 4, and 5	Area 5	n/a	Area 6
Method 3 (Fig. 2d)	Area 8 and 9	Area 7	n/a	Area 10

This case also illustrates that even with 3D BIM models, the estimator's own interpretation and analysis (how quantities are broken down and how quantities are aggregated) still plays a critical role in extracting the right PCQs from the BIM model. However, it is anticipated that the visualization and aggregation functions of the BADE tools will help reduce the time an estimator spends on searches, clarifications, and aggregations of estimating data and will help improve the accuracy of the estimate.

3. RESEARCH DESIGN AND APPROACH

The four parameters that were used to evaluate the performance results are: generality, flexibility, efficiency, and accuracy. The parameters of generality and flexibility used ordinal scale measurement. The efficiency parameter was measured in terms of time (minutes) consumed by the estimators in accomplishing a specific task. The accuracy parameter was measured in terms of deviations (percentage) from the correct answers. The overall performance of each estimator group was evaluated based on a utility function, which incorporated the four parameters.

3.1 The Definition of Complex Levels of Estimating

To find a single metric that can precisely capture the complexity of an estimating activity is challenging and could be a research topic by itself. However, an approximate score of the complexity of estimates can be calculated based on the number of sub-procedures involved in the estimating task.

Detailed estimates (calculating detailed PCQs) for every trade start with identifying the scope of work, which involves selecting and counting the number of design components. After the scope of work is identified, the components are subcategorized based on their features (geometry, locations) that affect the construction methods and, consequently, the production rate. Three major variables are involved in the process of calculating the PCQs. The time consumed to do the detailed estimate is closely related to the number of building components in the building, the shape and geometric features of the building components, and the number of trade categories involved in constructing the building components. The following formula was developed to provide a basic measurement of the complexity of a design from an estimator's point of view.

Complexity Score = C x T x G   (Equation 1)

where

C = the number of components

T = the number of trade categories of the components

G = the number of geometric features of the components

Although there are limitations to using the complexity score to describe the complexity of estimating, it does provide some measurement of the effort involved in generating a given estimate. The validity of the measurements was verified by the test results in terms of the duration of doing the estimates manually.

3.2 Test Cases

The three test cases used are based on estimating the different parts of a building. The 3D model and the 2D drawings of the building are shown in Figure 3. Case 1 involved estimating PCQs of the concrete footings, foundation walls, slabs, and the masonry walls. Case 2 involved estimating the PCQs of interior drywall. Case 3 involved estimating PCQs of the ceilings and roof. Since more test cases of different complexity levels can provide more convincing comparison results and due to the constraint of available resources, permutations of Cases 1-3 were used to create seven different cases. Table 3 shows the case permutations and complexity scores for each case. An approximately linear correlation between the complexity score using the above mentioned definition and the actual time consumed using the manual estimating method is shown in Figure 4. The estimate sheets used in Test Cases 1-3 are found in the Appendix.

TABLE 3: Complexity level of test cases.

Items	Case 1	Case 2	Case 3	Cases 1+2	Cases 2+3	Cases 1+3	Cases 1+2+3
No. of Components	18	17	8	35	25	26	43
No. of Trade Categories	4	2	2	6	4	6	8
No. of Geometric Features	1	9	4	10	13	5	14
Overall Complexity Score	72	306	64	2100	1300	780	4816
Time for Manual Estimate (Minutes)	27	45	34	72	79	61	106

Note: The overall complexity score = No. of components x No. of component categories x No. of geometric features
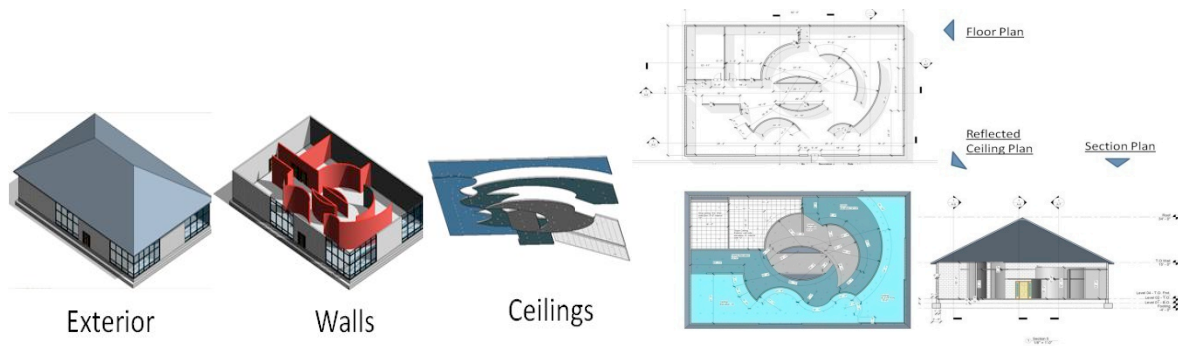
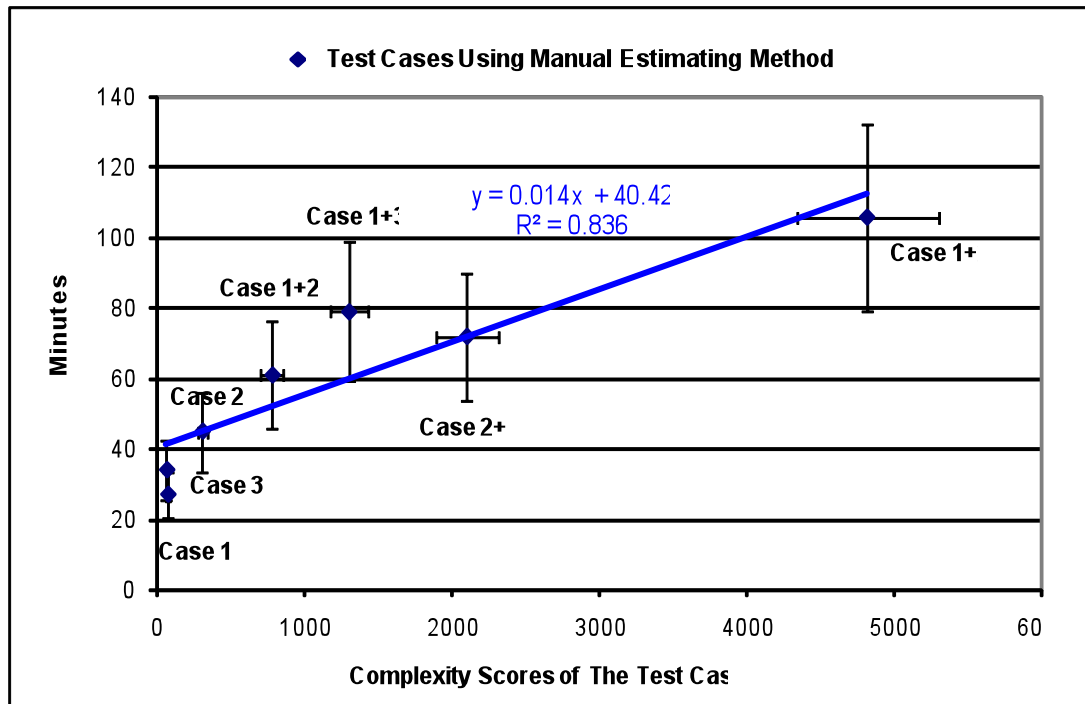*FIG. 3: The 3D model and the 2D drawings of the test cases.*

FIG. 4: Approximate linear relationship between time consumed and the case complexity.

3.3 BADE Tools Used in the Study

Two types of BADE tools were used in this study in order to evaluate: 1) the impact of the visualization factor and 2) the compound impact of the visualization plus aggregated calculation factor. The first BADE tool used in this study was the IFC Viewer (IFC Viewer 2005), which is a free, off-the-shelf application. The second BADE tool used in this study was developed by using a combination of the 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 (Figure 5).

The IFC Viewer is 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 in this study 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. Figure 5 shows the user interface: the selected roof line in the 3D model

corresponds to the dark-band item in the building assembly tree on the left-hand side of the user interface. Users need to manually read and enter each individual estimate quantity into the MS Excel spreadsheet in order to determine the PCQ and PPQs.
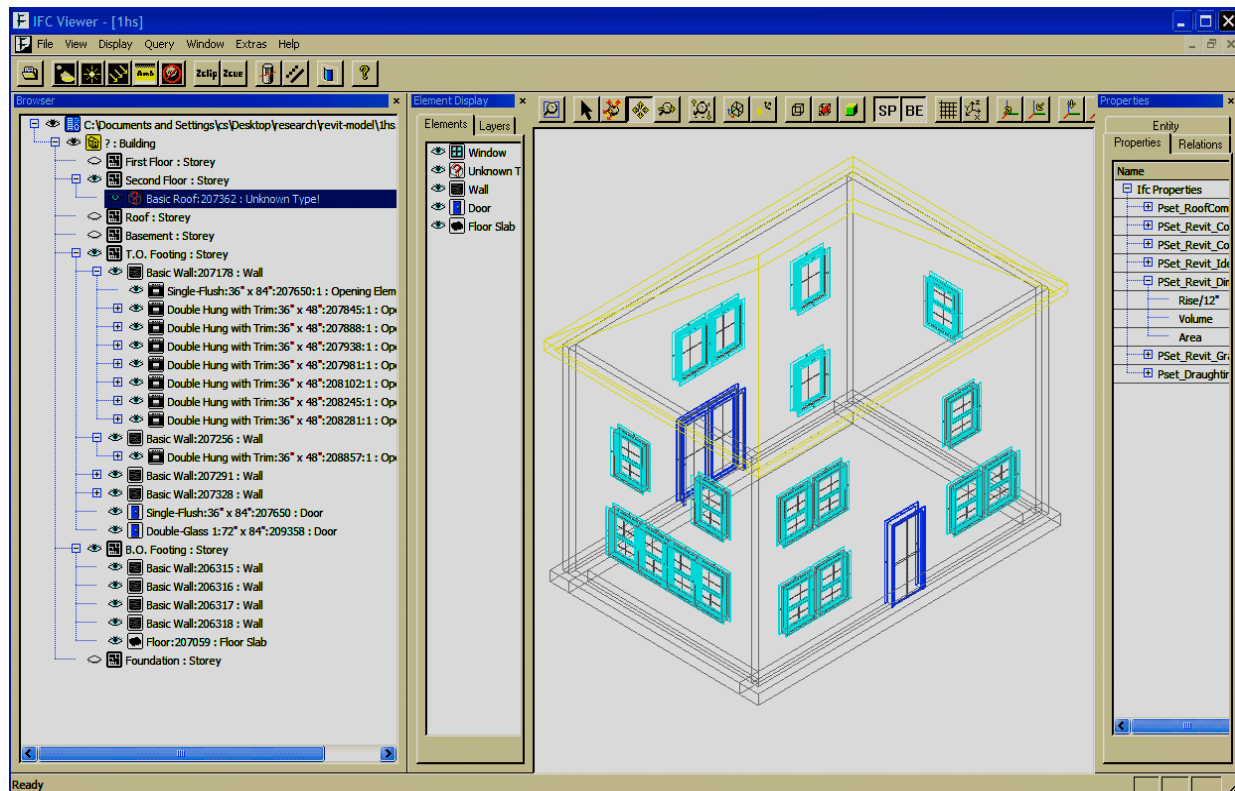

FIG. 5: IFC Viewer user interface.

The second BADE tool (the IFC Viewer-Database-MS Excel (IVDE) prototype, Figure 6) was developed 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
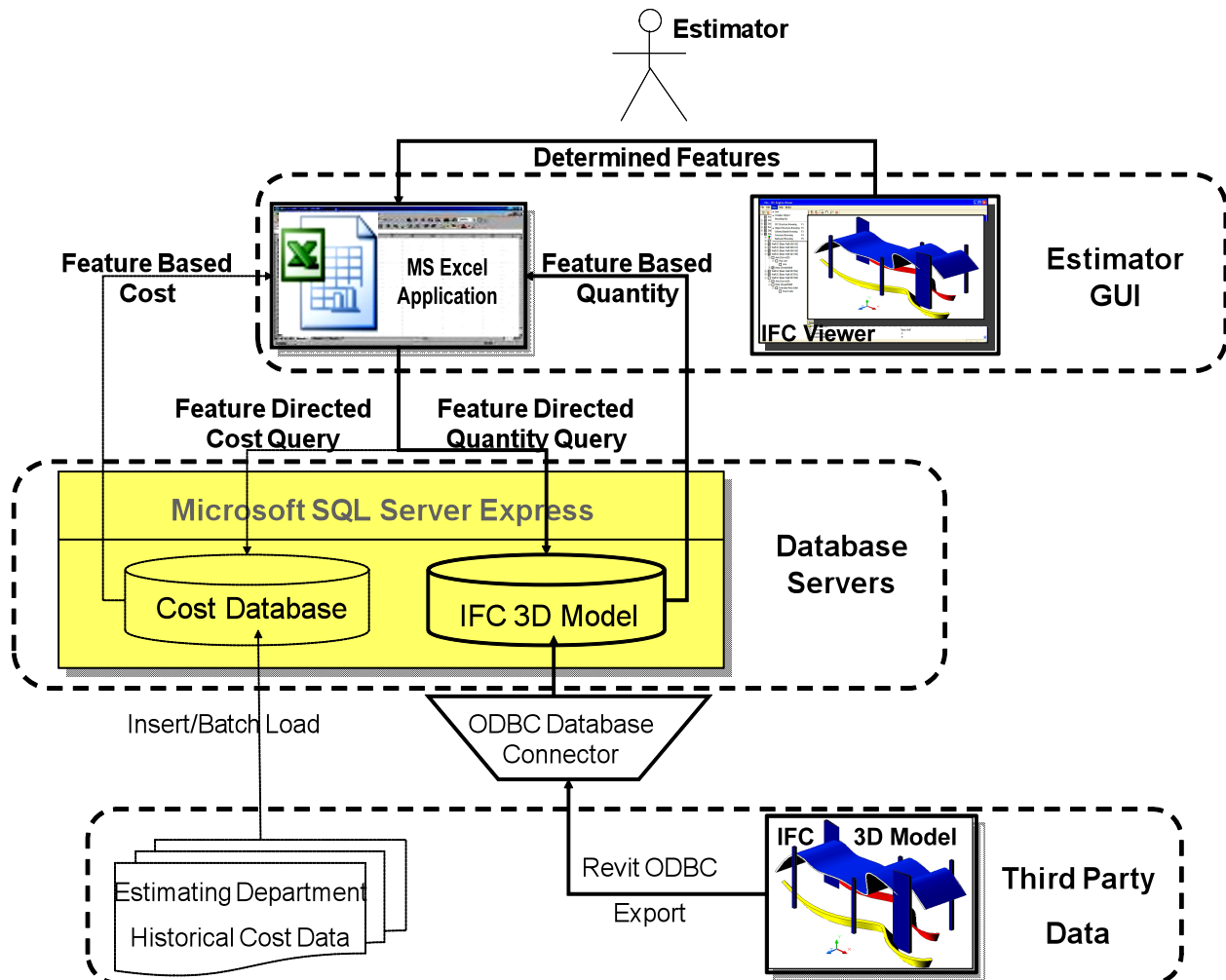
FIG. 6: The IVDE tool implementation diagram.

3.4 Test Procedures

Thirty-six (36) participants from a junior level university estimating class were selected at the end of the estimating class. At that point, they had learned the basic concepts and skills to perform entry level estimating jobs. A short training session on how to use the BADE tools was provided for each group. The participants were randomly divided into three groups with 12 students in each group. Group 1 used the traditional manual method of paper drawings and MS Excel spreadsheets. Group 2 used the IFC Viewer-aided tool to help with the estimate. Group 3 used the system developed for this study to perform the estimates. Each group estimated three test cases. The estimating sheets used in Test Cases 1-3 are shown in the Appendix.

It was assumed that the competence levels of the participants were roughly homogenous for the three groups of participants. Since the participants were randomly assigned to groups, it is unlikely that there was much difference in competency level between the groups. In addition, a statistical F-test was conducted on the data collected from the compared groups to check whether there was a significant difference in the variances between the compared groups.

An alternate testing method would be to ask each student to do one case estimate using each of the three methods. This alternate procedure avoids the limitations of the first procedure. However, it induces learning effects due to repetition, which might create more bias in the results. Accordingly, the first procedure was adopted for these test cases. In each test case, the participants were required to record the time it took to complete the estimating tasks.

4. 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 test results. For each performance criterion, a utility function was developed.

The generality parameter was measured by the number of trade estimates the evaluated method can generate. Since five trades were used in the test (exterior wall, interior wall, curtain wall, ceilings, and roofs) the maximum score would be five and the minimum score would be zero.

The *generality* parameter was measured by the number of subcontractor trade categories the estimating method being evaluated can accommodate. The test cases include five trade categories: foundation, exterior wall, interior wall, ceilings, and roofs. The maximum score is 5, and the minimum score is 0. As shown in Table 4, the estimating method evaluated was assigned one point for each trade for which it was able to perform the estimating task.

TABLE 4: Generality score comparison among the three estimating methods.

Estimating Methods	Estimated Subcontractor Trade Categories					
	Foundation	Exterior Wall	Interior Wall	Ceilings	Roof	Generality Score
Manual	1	1	1	1	1	5
IFC Viewer	1	1	1	0	1	4
Prototype	1	1	1	1	1	5

4.1 Flexibility Evaluation

The *flexibility* parameter was measured based on the number of special design features (Figure 7) the evaluated estimating method could differentiate. The number of special design features needed to be determined individually for each test case. In Test Case 1, the concrete cost estimate had no special design features involved. In Test Case 2, the interior drywall estimate included 12 different design features. Test Case 3 included four special ceilings features. The flexibility score is the number of features the estimating method can differentiate. The maximum score is 16 and the minimum score is 0.

Table 5 shows that the manual method and the prototype method are the most flexible estimating methods for handling design features. The IFC Viewer was not able to differentiate ceiling features.
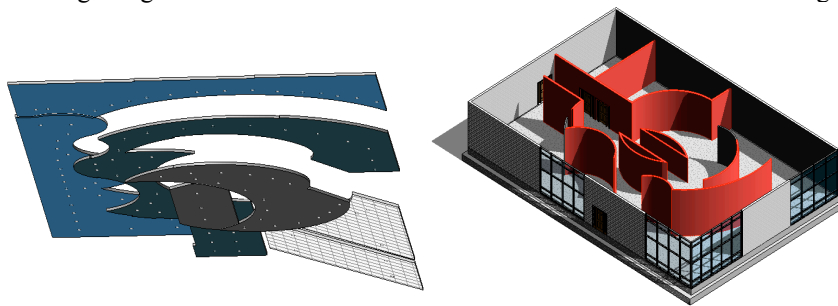

FIG. 7: Ceiling and the interior drywall features in the test cases.

TABLE 5: Flexibility comparison among three estimating methods.

	Special Design Features	Manual	IFC Viewer	Prototype
Case 1	0	0	0	0
Case 2	12	12	12	12
Case 3	4	4	0	4
Total identified special design features		16	12	16

4.2   Efficiency Evaluation

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

Since the goal was to evaluate the estimating task performance of the prototype implemented, two performance comparisons were conducted: the first comparison was between the manual and prototype implemented methods; the second comparison was between the IFC-Viewer-aided and prototype implemented methods. If an F-test showed that there was no significant difference between their variance, a t-Test with unequal variances was also conducted to compare the mean value of the data sets. This comparison method was used on every test case and on combinations to increase confidence in the test results. By doing the pairwise comparison test, the hypothesis that the differences between the compared pairs were significant in terms of performance of the estimating tasks was tested. All the hypothesis tests were conducted at the P=5% (or $\alpha=0.05$) significance level. Figures 8 through 12 show the test results of the three estimating methods for each test case.

The IFC Viewer does not have the functionality to get the ceiling data from the IFC model. Accordingly, Test Case 3 can only test the manual and prototype methods.
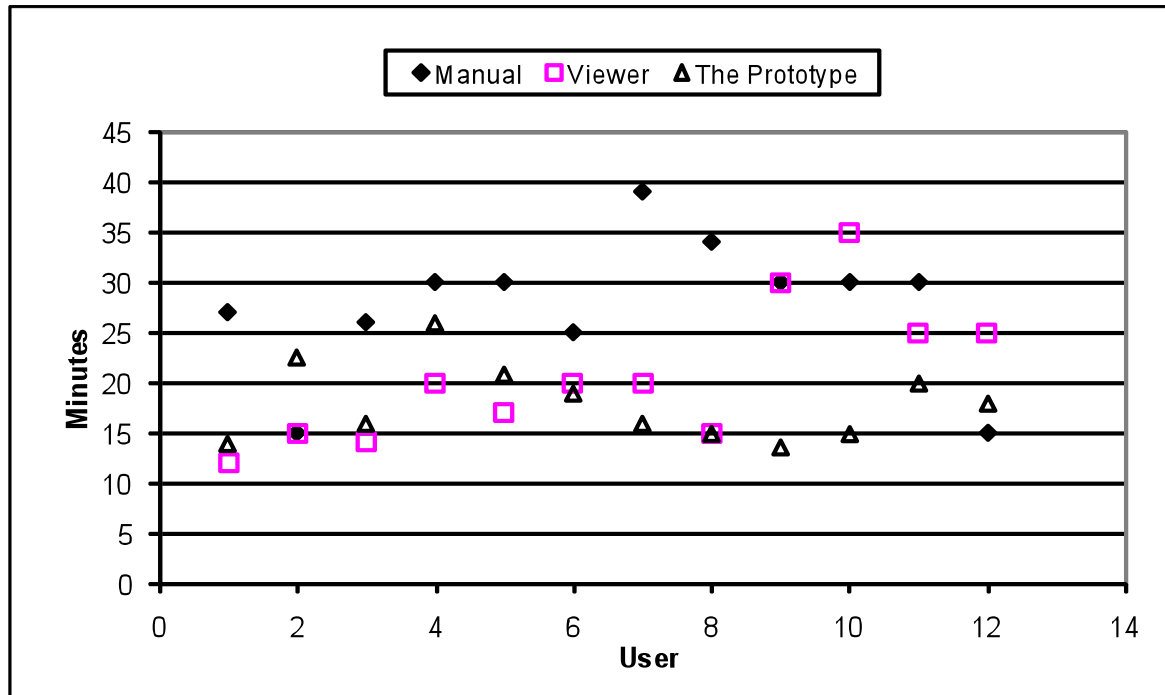
FIG. 8: Test Case 1—Durations for estimating task performances using three methods.
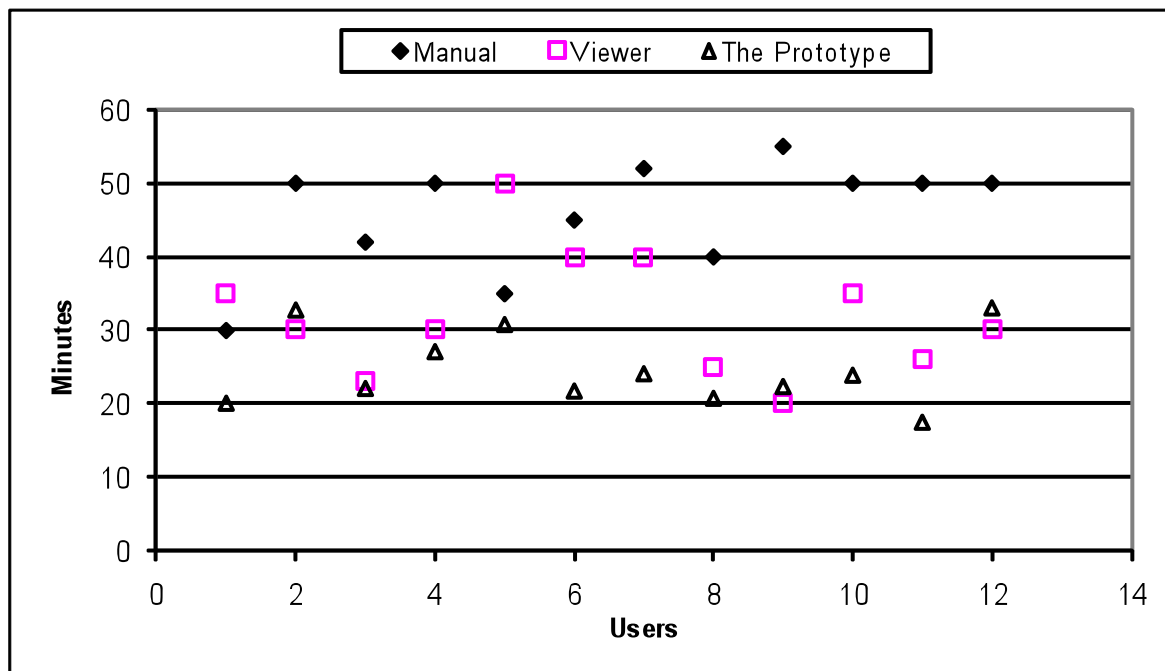

FIG. 9: Test Case 2–Durations for estimating task performances using three methods.
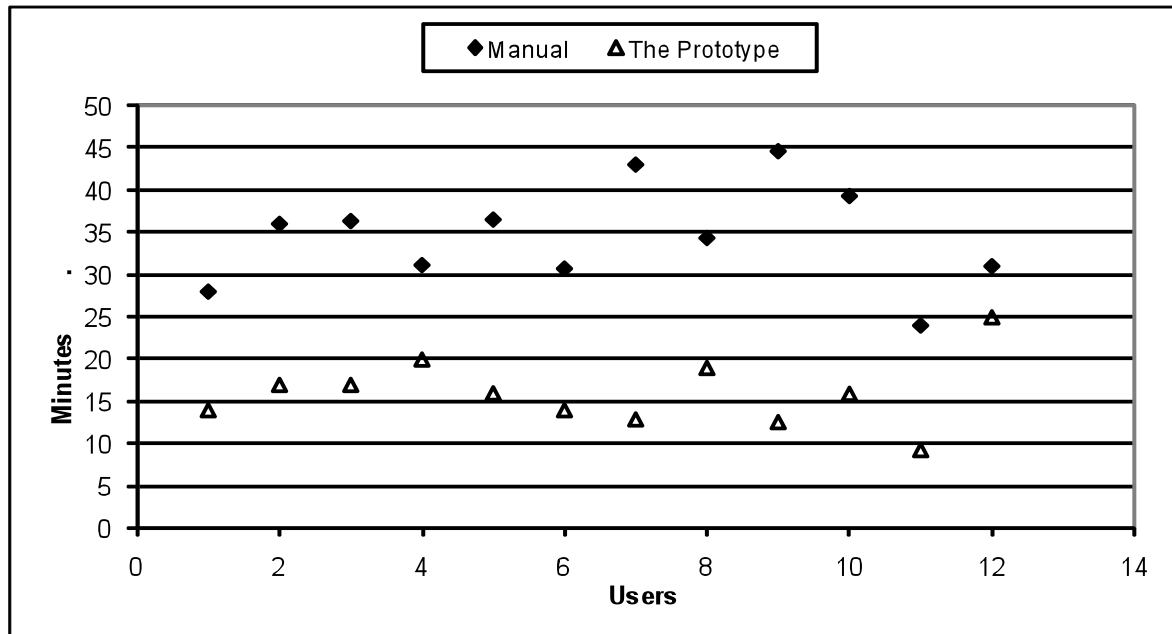
FIG. 10: Test Case 3—Durations for estimating task performances using two methods.

In order to further evaluate the performance efficiency among the three estimating methods, Test Cases 1 and 2 were merged into another test case. The advantage of doing this was that system performance could be further evaluated under a new level of complexity without testing a new case.
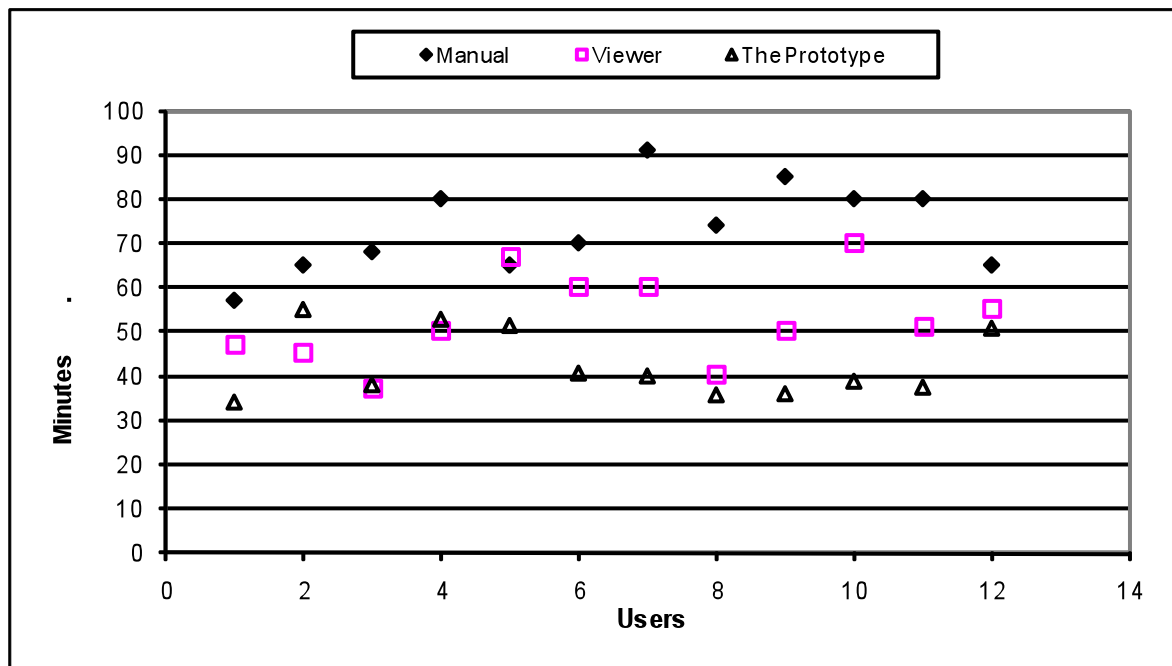

FIG. 11: Test Cases1+2—Durations for estimating task performances using three methods.
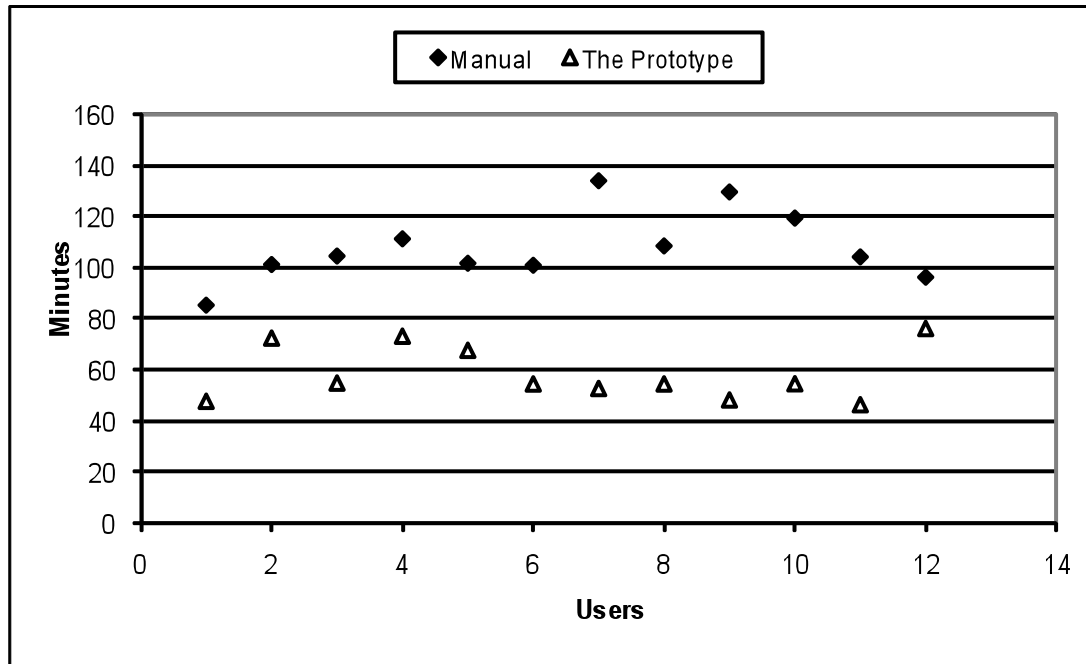
FIG. 12: Test Cases 1+2+3—Durations for estimating task performances using two methods.

Test Cases 1, 2, and 3 were combined to form a new case with a higher level of complexity. Due to functional constraints of the IFC Viewer, no comparison could be made between the performance of the IFC Viewer and the implemented prototype.

Table 6 summarizes the efficiency of generating the estimate using the three estimating methods. From the t-Test conducted on each of the cases and the combination of cases, it can be concluded with 95% confidence that the implemented prototype requires less time from an estimator in generating an estimate as compared to the manual method and the IFC Viewer method.

A linear regression analysis for the complexity scores of each estimate case and the time consumed to do the estimates (see Figure 13) shows that the more complex the building model, is the more time the prototype will save compared to the manual method. Figure 13 shows that when the building model is simple, the advantage of using the prototype is not significant. However, the trend line indicates that as the complexity score increases, the time saved by using the prototype increases. A similar conclusion was reached based on the case performance evaluation when comparing the IFC Viewer and prototype methods.

TABLE 6: Mean value of the duration of the estimating task performance for all test cases.

Test Case(s)	Mean Value (Minutes)		
	Manual Estimating Method	**IFC Viewer Estimating Method**	**The Implemented Prototype Method**
1	27.58	20.67	18.00
2	45.75	32.00	24.59
3	34.57	N/A	16.06
1+2	73.33	52.66	42.60
1+2+3	107.90	N/A	58.65

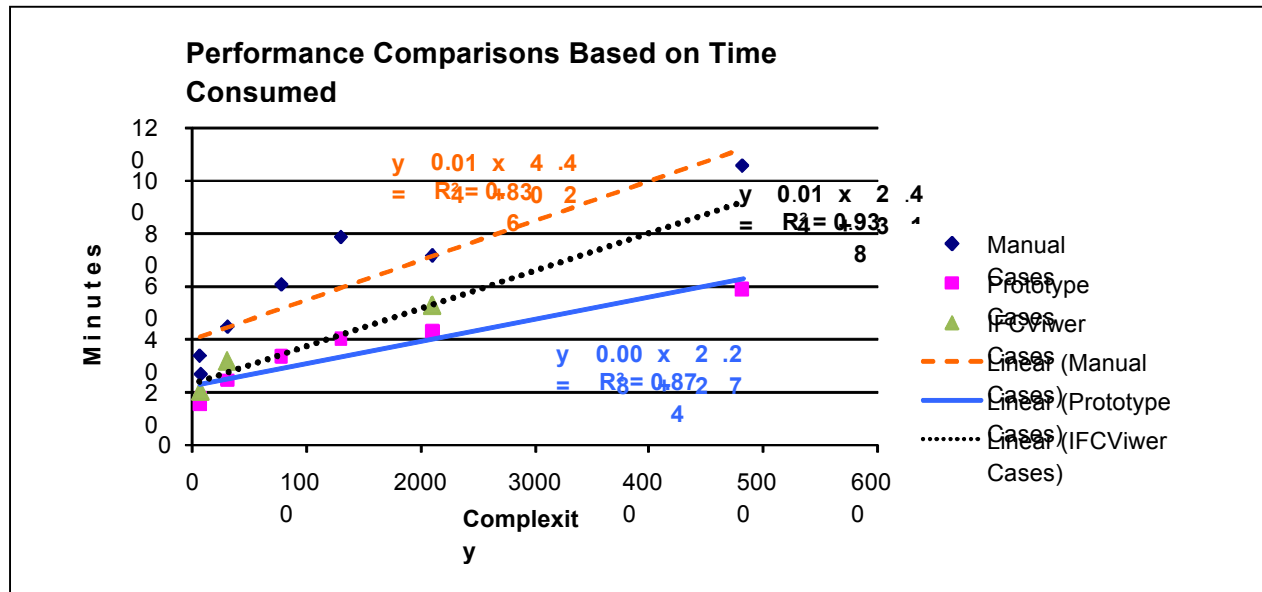**Performance Comparisons Based on Time Consumed**

FIG. 13: Comparing times taken to complete estimate tasks with complexity factor.

4.3 Accuracy Evaluation

The accuracy parameter was measured by the deviations of the estimate from the correct values. The data distribution and deviation were used to measure the accuracy. The smaller the deviation, the better the method will perform in the accuracy test. The accuracy of the estimating results was measured by the deviations from the correct value expressed as a percentage. The formula is:

ED (Estimate Deviation)=|((Value of the Estimate-Correct Value)|/Correct value)x100%   (Equation 2)

In order to compare the accuracy of the three estimating methods, the group performance (mean, STD deviation, variance, and distributions) was used in the evaluation. The comparisons are between the manual method, IFC Viewer method, and the IVDE prototype method.

The source of the error may not be due to the estimating method itself and may be due to some external factors, such as the participant's construction experience and level of knowledge of construction estimating, the level of training in construction estimating, the motivation to do the test estimates, and the proficiency level in mathematics. However, the overall evaluation of group performance is still able to provide useful information to allow for a relative evaluation of the three estimating methods.

The ED value was measured on a total of 20 estimated quantities for each student (see Appendix). Since there were 12 students in each group, a total of 240 EDs were measured using the manual method and IVDE group. Since the IFC Viewer cannot estimate the four quantities in Case 3, only 204 EDs were measured in the IFC Viewer group. The percentage and frequency of ED values were recorded to view their distributions in each estimating method. Based on industry standard practices, a 5% or less deviation was used as the threshold of good accuracy.

Figures 14 through 16 show the deviations of the estimate values and the frequencies and percentages of the ED for each of the three estimating methods used in this study. In the manual estimating method (Figure 14), about 40% of the deviations were less than 5%. In the IFC Viewer method (Figure 15), about 50% of the estimate deviations were less than 5%. In the IVDE (Figure 16) prototype method, about 87% of the deviations were less than 5%. Figures 14 and 15 also show that between the 5% and 25% ED value, there were mixed results when comparing the manual method and the IFC Viewer method. The IVDE prototype method showed significant improvement at the 5% ED value when compared to both the manual and IFC Viewer method. As shown in Figures 14-16, in general, using the BADE tools helps to increase the accuracy of the estimates while requiring shorter periods of time for completing the estimates.
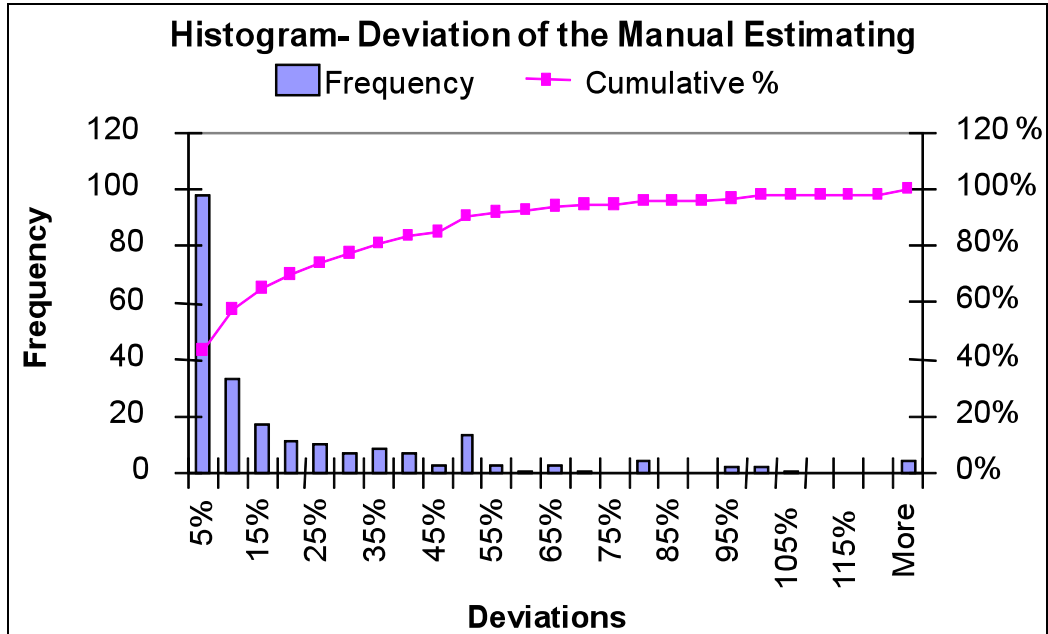
FIG. 14: *Deviations from the correct estimate value using the manual estimating method.*
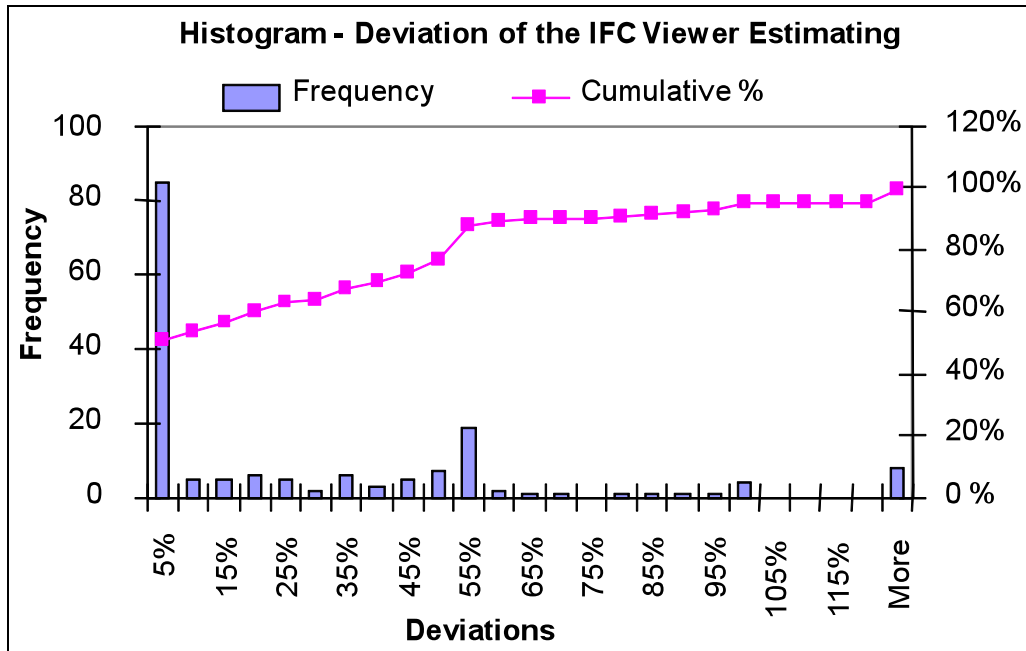

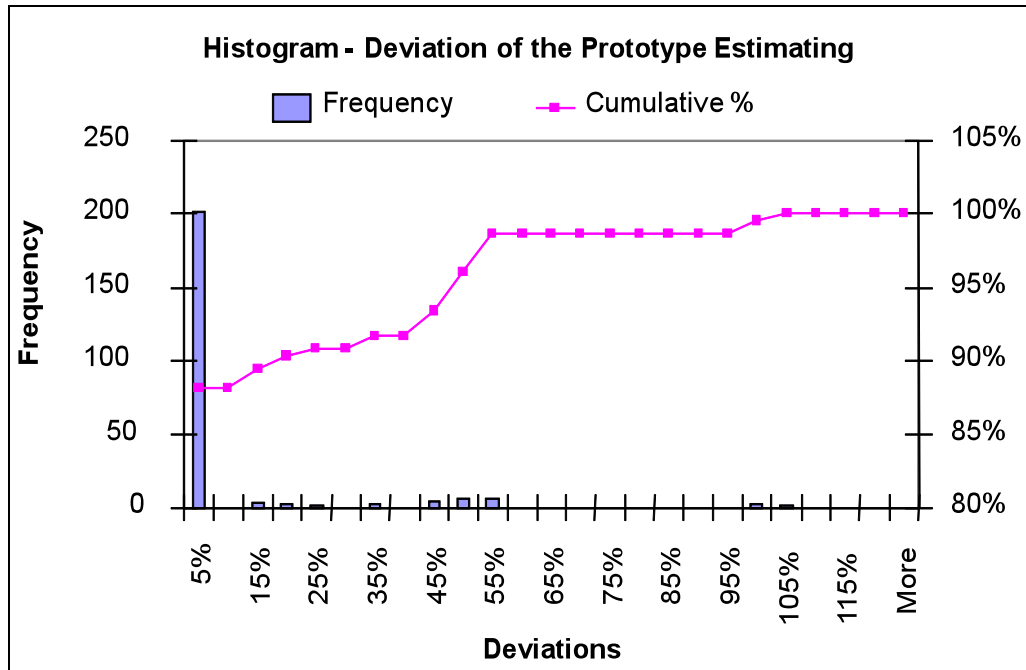FIG. 15: *Deviations from the correct estimate value using the IFC Viewer method.*

FIG. 16: Deviations from the correct estimate value using the prototype estimating method.

4.4 Overall Performance Evaluation Using the Multi-attributes Utility Function

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,...,n represents the utility of the ith 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

$$U(x_i) = c_i x_i + d_i \quad \text{where } c_i \text{ and } d_i = \text{constants.} \qquad \text{(Equation 3)}$$

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

$$U(x_1,x_2,x_3,\ldots,x_n) = W_1 U_1(x_1) + W_2 U_2(x_2) + W_3 U_3(x_3) + \ldots + W_n U_n(x_n) \qquad \text{(Equation 4)}$$

where W_i is the weight value assigned to individual attribute.

In this study, 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 Figure 17, 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 Figure 17.
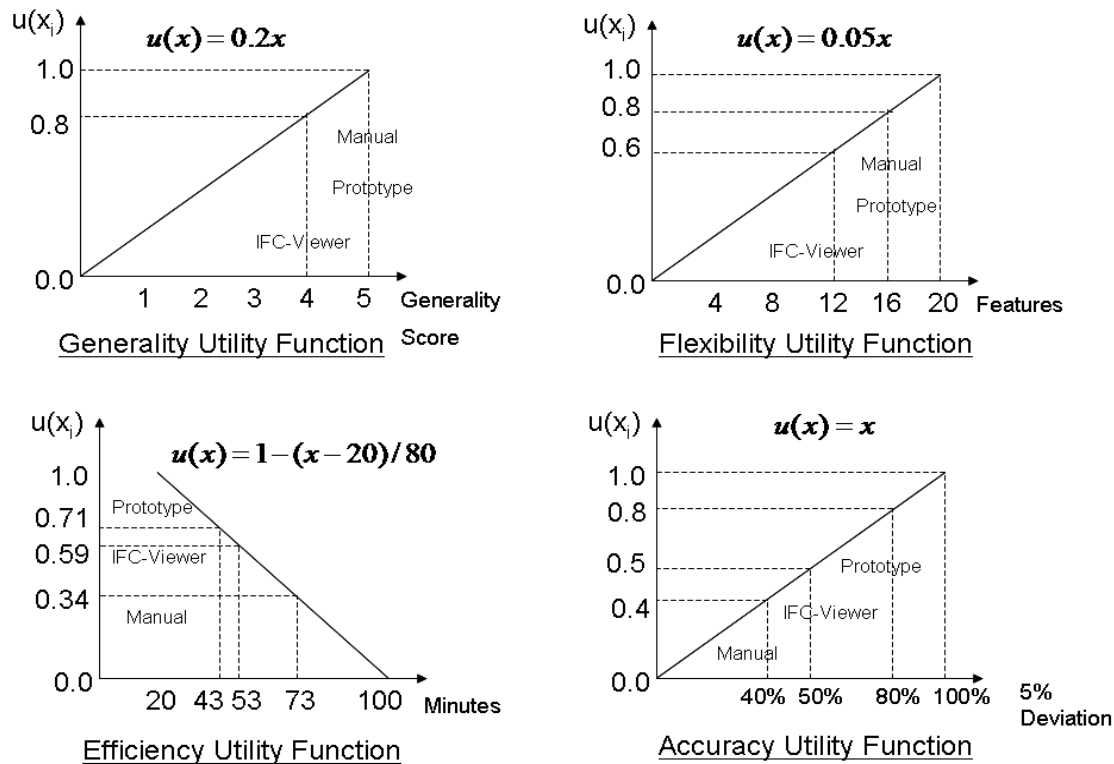
FIG. 17: The utility functions of the four evaluation attributes.

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 (Table 7) are established based on the authors' industry experience and related studies (Issa et al. 2003; RIBA 2001; Rivard 2000).

TABLE 7: 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).

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

(Equation 5)

where $\alpha_{x,y}$ represents the importance factor derived from the attributes comparison (Table 7). 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:

1. Accuracy (A) is equally as important as efficiency (E), i.e. $a_{AE} = 1$ and $a_{EA} = 1$
2. Accuracy (A) is strongly important over generality (G), i.e. $a_{AG} = 5$ and $a_{GA} = 0.2$
3. Efficiency (E) is strongly important over generality (G), i.e. $a_{EG} = 5$ and $a_{GE} = 0.2$
4. Accuracy (A) is strongly important over flexibility (F), i.e. $a_{AF} = 5$ and $a_{FA} = 0.2$
5. Efficiency (E) is strongly important over flexibility (F), i.e. $a_{EF} = 5$ and $a_{FE} = 0.2$
6. Flexibility (F) is moderately important over generality (G), i.e. $a_{FG} = 3$ and $a_{GF} = 0.3$

$$[A]_{4x4} = \begin{vmatrix} \begin{bmatrix} 1, a_{EA}, a_{GA}, a_{FA} \\ a_{AE}, 1, a_{GE}, a_{FE} \\ a_{AG}, a_{EG}, 1, a_{FG} \\ a_{AF}, a_{EF}, a_{GF}, 1 \end{bmatrix}_{4x4} \end{vmatrix} = \begin{bmatrix} 1 & 1 & 0.2 & 0.2 \\ 1 & 1 & 0.2 & 0.2 \\ 5 & 5 & 1 & 0.3 \\ 5 & 5 & 3 & 1 \end{bmatrix}_{4x4}$$

(Equation 6)

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 $[A_{norm}]_{4x4}$:

$$[A_{norm}]_{4x4} = \begin{bmatrix} \dfrac{1}{1+1+0.2+0.2} & \dfrac{1}{1+1+0.2+0.2} & \dfrac{0.2}{1+1+0.2+0.2} & \dfrac{0.2}{1+1+0.2+0.2} \\ \dfrac{1}{1+1+0.2+0.2} & \dfrac{1}{1+1+0.2+0.2} & \dfrac{0.2}{1+1+0.2+0.2} & \dfrac{0.2}{1+1+0.2+0.2} \\ \dfrac{5}{5+5+1+0.3} & \dfrac{5}{5+5+1+0.3} & \dfrac{1}{5+5+1+0.3} & \dfrac{0.3}{5+5+1+0.3} \\ \dfrac{5}{5+5+3+1} & \dfrac{5}{5+5+3+1} & \dfrac{3}{5+5+3+1} & \dfrac{1}{5+5+3+1} \end{bmatrix}_{4x4}$$

$$= \begin{bmatrix} 0.417 & 0.417 & 0.083 & 0.083 \\ 0.417 & 0.417 & 0.083 & 0.083 \\ 0.442 & 0.442 & 0.088 & 0.027 \\ 0.357 & 0.357 & 0.214 & 0.071 \end{bmatrix}_{4x4}$$

(Equation 7)

Then the elements of the Eigenvector are calculated as follows:

$$[W]_{4x1} = \begin{bmatrix} w1 \\ w2 \\ w3 \\ w4 \end{bmatrix} = \begin{bmatrix} (0.417+0.417+0.083+0.083)/4 \\ (0.417+0.417+0.083+0.083)/4 \\ (0.442+0.442+0.088+0.027)/4 \\ (0.357+0.357+0.214+0.071)/4 \end{bmatrix} = \begin{bmatrix} 0.25 \\ 0.25 \\ 0.27 \\ 0.25 \end{bmatrix}$$

(Equation 8)

Then the multiple attribute utility function takes the form

$$U(x_1,x_2,x_3,x_4) = 0.25 \cdot U_1(x_1) + 0.25 \cdot U_2(x_2) + 0.27 \cdot U_3(x_3) + 0.25 \cdot U_4(x_4)$$

(Equation 9)

where the $U_1(x_1)$ is the generality utility function; $U_2(x_2)$ is the flexibility utility function; $U_3(x_3)$ is the accuracy utility function; $U_4(x_4)$ is the efficiency utility function (Figure 17).

The overall utility score of each estimating method was determined by applying Equation 9 to the manual estimate method, IFC-Viewer estimate method, and the prototype method. The greater the utility score, the better the performance of the estimate method.

Using data from Figure 17 the utility scores of the three estimating methods were as follows:

$U_{(Manual)}$ = 0.25 x 1+ 0.25 x 0.8 + 0.27 x 0.4 + 0.25 x 0.34 = 0.643

$U_{(IFC-Viewer)}$ = 0.25 x 0.8+ 0.25 x 0.6 + 0.27 x 0.5 + 0.25 x 0.59 = 0.633

$U_{(Prototype)}$ = 0.25 x 1+ 0.25 x 0.8 + 0.27 x 0.8 + 0.25 x 0.71 = 0.843

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.

5. CONCLUSION

Conclusions and discussions of the BADE tool's impact on the estimator's performance were limited only to the entry-level estimators who participated in the tests using the test cases developed with different complexity levels. The test results in this pilot study showed significant improvement using BADE tools in terms of accuracy and efficiency when compared to the traditional manual estimating method. The test results also showed that the 3D visualization function alone, as provided by the IFC Viewer, 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 even though the prototype tested was still primitive. 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. Although improvements are anticipated, quantifying those improvements using the parameter of complexity of estimating tasks, increases our knowledge on how BADE tools affect the performance of construction estimating.

The research project was a pilot study, and it was limited in many ways. These limitations might affect extrapolations of the test results. Major limitations included the nature of the test cases and the subjects participating in the tests. First of all, the scale and scope of the test cases was limited to the junior-level student estimator's knowledge. 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. Second, the sample size of the subjects (junior construction students) in this pilot study was small. Further tests on a larger scale, with a broader scope of projects, and on a more diversified and larger number of construction estimators are needed for more conclusive findings. 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.

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APPENDIX

Estimating Sheet used in the Testing Cases

The following estimating sheet was used for the test cases. Only quantities were generated in the tests. Each estimating case represents part of the estimating job of the entire building.

			Quantities	Unit	Unit Cost	Extended Cost	Sub Total
Case 1 Estimating							
	Concrete Footing						
		Volume		Cubic Ft.			
		Surface Area		Sq. Ft.			
	Foundation Wall						
		Volume		Cubic Ft.			
		Surface Area		Sq. Ft.			
	Masonry Wall (8" concrete block)						
		Surface Area		Sq. Ft.			
	Concrete Slab						
		Volume		Cubic Ft.			
		Top surface area		Sq. Ft.			
Case 2 Estimating							
		Dry wall					
		6" Dry wall Surface area					
		Straight wall		Sq. Ft.			
		Curve wall radius less than 10'		Sq. Ft.			
		Curve wall radius less than btw 10'-15'		Sq. Ft.			
		Curve wall radius greater than 15'		Sq. Ft.			
		4" Dry wall Surface area					
		Straight wall		Sq. Ft.			
		Curve wall radius less than 10'		Sq. Ft.			
		Curve wall radius less than btw 10'-15'		Sq. Ft.			
		Curve wall radius greater than 15'		Sq. Ft.			
Case 3 Estimating							
		Ceiling					
		Area elevation 8		Sq. Ft.			
		Area elevation 12		Sq. Ft.			
		Area elevation 15		Sq. Ft.			
		Sloped Ceiling		Sq. Ft.			
		Roof					
		Surface Ares		Sq. Ft.			