A BIM-based Conceptual Cost Estimation Model Considering Structural Analysis and Design

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Abstract:

In recent years, considerable concern has arisen over the application of Building Information Modeling (BIM). BIM has been widely utilized for solving the drawbacks of traditional preliminary cost estimation by creating a cost-estimation model. However, since the function of structural analysis and design in BIM is still in its developing stage, the model still lacks precise information of the structural engineering. As a result, the model hypothesizes the structural engineering quantity on the basis of the empirical formula, contributing to a slight inaccuracy in its approximation. Hence, to overcome these shortcomings, this research presents a conceptual cost-estimation model created by linking ETABS (a software used for structural analysis and design of buildings) to the BIM-based model. With the integration of the ETABS and the BIM model, the proposed model can simultaneously consider the two factors (the budget, and the structural analysis) for cost estimation in the early stages of the project: (1) establishing a BIM model on Revit, (2) applying ETABS to conduct structural analysis and design on the BIM model, (3) obtaining quantity takeoffs of the BIM model by Navisworks, (4) retrieving unit price data from PCCES software through results of the quantity takeoffs, and (5) ratifying whether the projected cost meets the owner's budget. The proposed model is tested via a building located on a certain university campus in northern Taiwan. The results show that the proposed conceptual model is significantly superior to the original BIM-based model, and demonstrate that the proposed model can be practically implemented and provide adequate results for the projected cost.

Keywords –

Building Information Model; Cost-Estimation; ETABS; Structural Analysis and Design

1 Introduction

Cost estimation is one of the most critical tasks concerned by all participants in the architecture, engineering, construction, and facilities management (AEC/FM) industry throughout the lifecycle of a building project [1]. In the early stages of conventional construction, there is always enormous and complex information for the cost estimation, causing each cost item can not be calculated and shared accurately in time [2]. Therefore, the management of cost estimation is not only time-consuming but also prone to error. To address the issues, recent years have seen growing importance placed on research in the management of cost estimation.

Building Information Modeling(BIM) as an emerging process and technology has been widely adopted in the building construction industry. BIM is a new approach to design, construction, and facilities management, in which a digital representation of the building process used to facilitate the exchange and interoperability of information in digital format [3]. Through object-oriented concept of BIM, BIM is able to establish the information of each building item and connects it to the cost items to form a BIM-based cost-estimation model. With the increasing usage of BIM, the BIM-based model has been a popular solution for the drawbacks of traditional cost estimation.

However, the BIM-based cost-estimation model still lacks precise information of structural engineering, since functions of structural analysis and design in BIM are still in its developing stage [4]. For example, in the aspect of structural analysis, though it can conduct basic static analysis, and display moment diagrams and structural reactions on the model, advanced analysis is still beyond its ability. As a result, the BIM-based model has trouble with defining the accurate information of structural engineering (beam, column, slab, and wall) crucial to preliminary cost estimation. To overcome the disadvantages, a conceptual model to link ETABS, a professional software used for structural analysis and design of buildings, with BIM is presented in this paper. With the benefits of ETABS, the functions of structural analysis and design of BIM can be enhanced dramatically.

In the paper, we present a conceptual cost-estimation model for linking ETABS and BIM. The paper firstly confers how to integrate the information of ETABS and the BIM software based on the exr. file extension created by Application Programming Interface(API), and discusses the methods of modifying the BIM model when the projected cost doesn't meet the owner's budget. It is hoped that the proposed model will solve the problems about the integration of the accurate information of structural engineering into the BIM-based cost-estimation model, and contribute to a more comprehensive assessment for the civil engineering in the preliminary stages.

2 Review of recent studies

2.1 Structural analysis and design on the basis of BIM

Chang [4] proposed a research that Revit Structure combined ETABS to execute the integration of design. The research firstly established a Revit model subjected to the various external forces. The Revit model with related information was then transferred to ETABS to perform the mechanical analysis and structural design process. Design results were then sent back to BIM platform to renew the members. And since IFC format was not well-developed enough to transfer the structural engineering information between the two software, the research utilized the API as an information transferring interface to renew and create the members. The results found that the data of basic components, such as beams, columns, and plates, could be completely transmitted between the softwares. However, the research was only tested via a simple model, which seems too premature to apply on construction in practical. For example, when the resources in the projects are complicated, whether it will cause other errors related to information delivery between the two softwares, all of which are worthy of being investigated further.

2.2 Applying BIM to estimate construction costs in early stages of projects

Elbeltagi et al. [5] presented a comprehensive cost estimating and monitoring model based on the concept of BIM. With a visualization aid, BIM model could add the color coding help to pinpoint the element clashes, saving considerable time delays and cost wasting. Also, visualization helped construction team to absorb and realize the project information. The results showed that the proposed BIM framework could be considered as an effective tool for the cost estimation in the projects.

Lu et al. [6] thought that traditional method for cost flow analysis were based on the manual integration of time and cost, which was very time-consuming. Therefore, the research presented a BIM-based 5D model of cost estimation on the basis of Navisworks. The research firstly established a BIM model, and took off the properties of items to calculate the quantity of the cost items, which can be stored as a quantity database. The factors of time and cost were subsequently added into the quantity database to create a BIM 5D model. The research utilized this model to analyze the cash flow of the projects. The results found that compared to traditional method, the quantification in Navisworks is simplified and automated, contributing enormous benefits to the cost estimation. What's more, with consideration of time and cost, the whole framework can help contractors analyze the cash flow and make appropriate decisions for different design in construction projects.

Cheung et al. [7] pointed out that current BIM tools were less able to handle concurrency and integration at early design stages, affecting the accuracy of cost estimation; thus, the authors proposed a multi-attribute based tool to address the need to evaluate various aspects of building design, and detailed the cost estimation module that enabled quick and intuitive exploration of early stage design in a 3D environment.

3 Cost estimation of construction practice in the early stages

In the early stages of the projects, a lot of engineering information is still in an uncertain status. Under the condition of limited information, there are, however, some common approaches of preliminary cost estimation in practice, including the cost estimation of Taipei City Government, and the cost estimation of Public Construction Commission of Taiwan. In the end, the chapter will summarize the common parts of these methods to demonstrate the cost-estimation model the research presents is deserving deliberating in depth.

3.1 The cost estimation of Taipei City Government

Taipei City Government divides the cost of the project into direct cost and indirect cost. Direct cost includes structural engineering, decoration engineering, and MEP engineering. The cost of structural engineering (a part of direct cost) is calculated by the total area of the floor multiplied by an empirical value following the rules of Taipei City Government; then, the cost of the other parts of direct cost is calculated by the cost of structural engineering multiplied by an empirical value, and so is indirect cost. In other words, almost all the cost items are presumed by an empirical value (Wang, 2016) [9].

3.2 The cost estimation of Public Construction Commission of Taiwan

Public Construction Commission of Taiwan divides the cost of the project into design cost, indirect cost, price index cost, decoration engineering cost, interest cost, all of which are calculated by direct cost multiplied by an empirical value. And the direct cost is calculated by the area of the floor multiplied by an empirical value. That is to say, like the cost estimation of Taipei City Government, in the preliminary cost estimation, each cost item is involved in a hypothesized calculation (Wang, 2016) [9].

3.3 Summary

From what have been discussed above, we can safely draw a conclusion that due to severe lack of the information of the projects in the early stages, most of cost items' estimation are calculated by an empirical value, especially the cost estimation of Taipei City Government and Public Construction Commission of Taiwan, almost all the cost items are calculated by direct cost multiplied by an empirical value, and the direct cost are calculated on the basis of the cost of the previous projects. Therefore, if the conceptual cost-estimation model the research proposed can be applied into the projects, the problems of scant information in the early stages will be solved by BIM, transmitting the precise information of structural engineering into the preliminary cost estimation.

4 Proposed model

The procedure of the proposed model firstly establishes a BIM model, and then transfers the model to ETABS to conduct structural analysis and design. After analysis and design, the model is then sent back to the BIM software to renew the members, and obtains quantity takeoffs by Navisworks and retrieves unit price data from PCCES software. In the end, the research discusses how to get an alternative cost via the proposed model when the projected cost does not meet the owner's budget. The research selects Revit as the BIM modeling software since it is a commonly-used software in Taiwan. Figure 1 shows the establishment of this proposed model includes five main steps: (1) establishing a BIM model on Revit, (2) applying ETABS to conduct structural analysis and design, (3) obtaining quantity takeoffs by Navisworks, (4) retrieving unit price data from PCCES software, and (5) ratifying whether the projected cost meets the owner's budget.

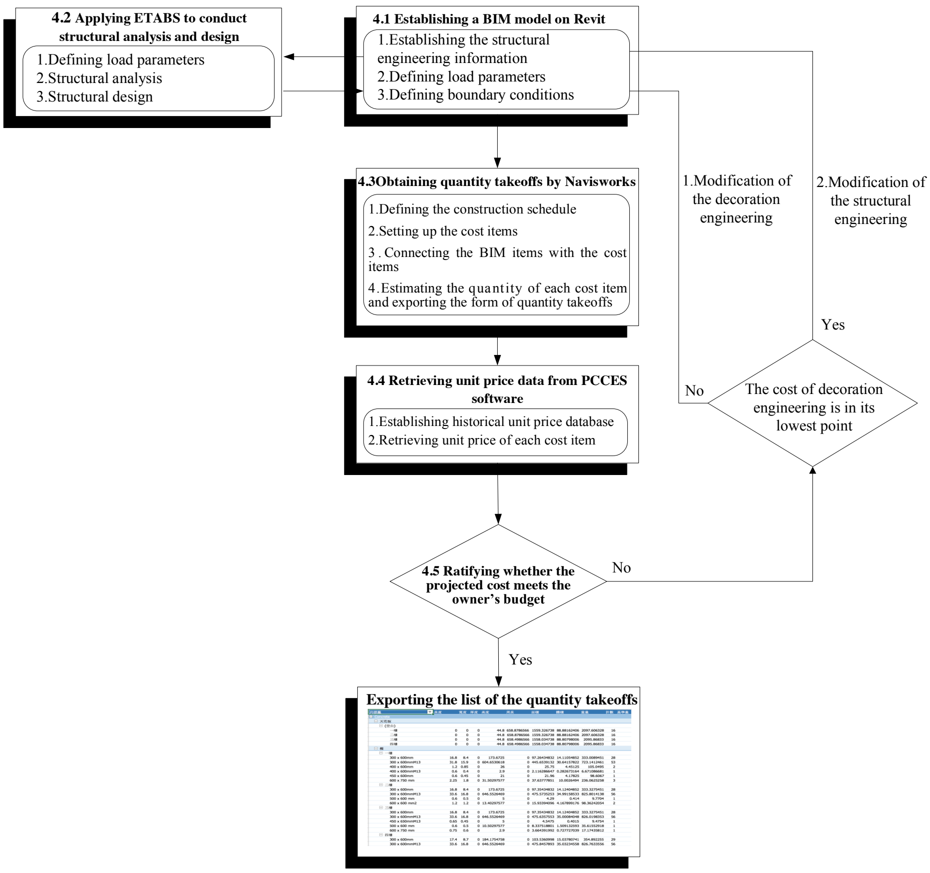

Figure 1. Proposed model

4.1 Establishing a BIM model on Revit

As the BIM handbook [10] noted, when the BIM model needs to conduct structural analysis and design, there are three requirements for the BIM model: 1. establishing the structural engineering information 2. defining load parameters 3. defining boundary conditions.

After establishing the Revit model on the basis of the three requirements, the research utilizes Application Programming Interface (API) as the intermediary of information interoperability between Revit and ETABS instead of Industry Foundation Classes (IFC), since IFC is not functional enough to transfer comprehensive information between ETABS and Revit, causing some elements, such as beams, essential to structural analysis are missed in the transferring process.

On the contrary, the API is capable of exporting the Revit and ETABS model into an exr. file extension to provide a shared format for the two softwares. The API has four functions, "Import to Create New Revit Project from ETABS SAFE or SAP2000 Model", "Import to Update Existing Revit Structure Model from ETABS", "Export to Create New ETABS SAFE or SAP2000 Model", and "Export to Update Existing ETABS Model". Through the functions of the API, the Revit and ETABS models are able to be renewed and established.

The research exports the Revit model into an exr. file extension by the function of the API, "Export to Create New ETABS SAFE or SAP2000 Model", and imports it into ETABS to create a new ETABS model.

There are two categories of the information the exr. file extension is imported into ETABS, the detectable and the undetectable category. The detectable information is the items of structural engineering, including grid, column, beam, wall, slab, boundary condition, and load while the undetectable information is mainly the items of architectural engineering (window, door…etc.) and some structural material properties (density of material and mechanical properties of material), all of which will notify the users in the form of a red signal through the window of the API.

For the undetectable information, the research adds physical properties of the material in the Revit model, or replenishes the structural properties of the undetectable information to transform information from the undetectable into the detectable one.

4.2 Applying ETABS to conduct structural analysis and design

However, to conduct complete structural analysis and design, there is still relatively little information imported from the Revit model; thus, the research needs to define more parameters in ETABS, and requires more professional functions of structural analysis and design from ETABS. The process of structural analysis and design includes three main steps: 1. defining load parameters, 2. structural analysis, 3. structural design.

After structural analysis and design, the information of the ETABS model is imported into the Revit model by the function of API, Import to Update Existing Revit Structure Model from ETABS, renewing the Revit model based on the results of structural analysis and design.

There are two categories of the information the exr. file extension imported into Revit, the detectable and the undetectable category. The detectable information includes grid, column, beam, wall, slab, boundary condition, and load while the undetectable information is nonlinear elements and parts of analysis and design data (rebar area…etc.).

For the undetectable information, the research sorts out the information of the Excel structural analysis and design summary report; then, add it into the Revit model additionally.

After importing ETABS information to Revit, the Revit model is still able to be modified and established, and the information of the Revit model established before being imported to ETABS can be preserved after the structural analysis and design.

4.3 Obtaining quantity takeoffs by Navisworks

To estimate the projected cost after structural analysis and design, the cost estimation is divided into two steps, quantity takeoffs and retrieving unit price data. The research selects Navisworks as the quantity takeoffs BIM software since the system of Navisworks is the same as Revit's, which can reduce the errors of interoperability of information.

To establish a new Navisworks model, the research imports the rvt. file created by Revit into Navisworks by the function of Navisworks, Append, which can record the path of archive and renew the information between the two softwares in time. In doing so, the results of quantity takeoffs can be updated when the Revit model is modified.

After importing the rvt. file into Navisworks, all the information is detectable, such as area and volume. And if the projects need to add additional information into the Navisworks model, the users can utilize the function of Navisworks, "Add New Property".

Through the windows of Navisworks Quantification," Quantification Workbook", "Item Catalog", and "Resource Catalog", the process of quantity takeoffs includes four main steps: 1. defining the construction schedule, 2. setting up the cost items, 3. connecting the BIM items with the cost items, 4. estimating the quantity of each cost item and exporting the form of quantity takeoffs.

After the four steps, Quantification Workbook displays a form of the quantity of each cost item, which can be exported into an Excel form. The Excel form of quantity takeoffs can be divided into different types of forms, including item-pivoted or resource-pivoted forms. For the project, the research selects resource-pivoted forms as the quantity takeoffs form.

4.4 Retrieving unit price data from PCCES software

After sorting out the results of the quantity takeoffs, the quantity takeoffs retrieves unit price from PCCES software to estimate the projected cost. The research selects PCCES as the software of unit price database. And, the process of retrieving unit price from includes two main steps: 1. establishing historical unit price database, 2. retrieving unit price of each cost item.

4.5 Ratifying whether the projected cost meets the owner's budget.

To measure up the requirements of the construction in practical, the research ratifies whether the projected cost meets the owner's budget. In this section, the research hypothesizes the projected cost does not meet the owner's budget, and modifies the model to adjust the cost. The research proposes a scheme to reintegrate the building information for an alternated projected cost on the basis of the proposed model.

Base on the condition of the construction in practice, the modification of the model can be divided into two parts, "decoration engineering" and" structural engineering", and the sequence of the two modifications is first decoration engineering and then structural engineering in the order of complication. Firstly, the modification of decoration engineering includes paint, tile…etc. Since decoration engineering is not in the consideration of structural analysis and design and interior design, the modification of decoration can skip the process of structural analysis and design. When the cost of the decoration engineering has already been decreased to its lowest point, the modification of structural engineering is the next option; the modification of structural engineering includes beam, column, slab, and wall. It requires to not only reanalyze and redesign the structure but also inspect if the interior design corresponds to the laws of the government and the request of the owner. Therefore, the research utilizes the function of API, "Export to Update Existing ETABS Model", to provide an update regarding to the modification of structural engineering to the ETABS model. In doing so, the preprocess of structural analysis and design (defining load parameters) can be skipped.

5 Case study

The proposed model is tested via a building located on a certain university campus in northern Taiwan, as presented in Figure 2 The building was finished in 1982, main building material is reinforced concrete, four floors with no basements, and total area of the floor is 5814.83 ㎡.

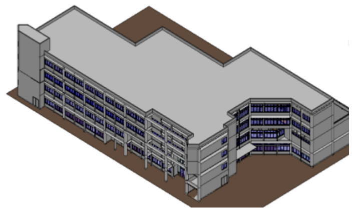

Figure 2. The tested Revit model

5.1 Establishing a BIM model on Revit

The research creates a new project on the construction template in Revit, and builds columns, beams, slabs, and walls respectively; dead load is the weight of the building, which is 0.5KN/m^2, and live load is 2.5KN/m^2, following the rules of the government, and then, assign the loads to the slabs in an uniform distribution; the research sets the boundary conditions as the fixed one at the junctions of columns and ground.

After establishment of the Revit model, the research utilizes the function of API, "Export to Create New ETABS Model", to export grid, column, beam, wall, slab, boundary condition, and load of the Revit model to create a new ETABS model. The results show the items of the Revit model are successfully detected in ETABS, and the ETABS model is able to be modified.

5.2 Applying ETABS to conduct structural analysis and design

The process of ETABS structural analysis and design includes three main steps: 1. defining load parameters, 2. structural analysis, 3. structural design.

After structural analysis and design, the research utilizes the function of API, "Import to Update Existing Revit Structure Model from ETABS", to import information of the ETABS model to update the Revit model, and export the results into an Excel summary report.

To perform the cost estimation, the research establishes the other engineering items, such as ceiling, tile, excavation, skirting, slope protection, and flooring, and then exports the Revit model into a rvt. file.

5.3 Obtaining quantity takeoffs by Navisworks

The research imports the rvt. file into Navisworks by the function of "Append". The items for quantity takeoffs includes geotechnical engineering (excavation and slope protection), structural engineering (concrete, rebar, and formwork), and decoration engineering (ceiling, skirting, flooring, paint, and tile). Furthermore, to retrieve unit price of each cost item, the quantity takeoffs unit of each cost item is the area or volume of the material.

The process of Navisworks quantity takeoffs includes four main steps: 1. defining the construction schedule, 2. setting up the cost items, 3. connecting the BIM items with the cost items, 4. estimating the quantity of each cost item and exporting the form of quantity takeoffs. After the quantity takeoffs, the results are sorted out in Table 2.

5.4 Retrieving unit price data from PCCES software

The quantity takeoffs retrieve unit price from PCCES software to estimate the projected cost. The process of retrieving unit price from includes two main steps: 1. establishing historical unit price database, 2. retrieving unit price of each cost item. Table 2 is the detail of the projected cost; the total projected cost is 38,266,229 NTD.

Table 1 The list of the projected cost

Engineering items	Quantity	Unit	Price (NTD)	Cost (NTD)
reinforced concrete 280kgf/cm^2	3,974	M^3	2,115	8,405,010
rebar SD280	395	T	15,673	6,190,835
rebar SD420	104	T	16,432	1,708,928
formwork	19,817	M^2	332	6,579,244
excavation	4,382	M^3	166	727,412
light-gauge steel frame	5,930	M^2	873	5,176,890
red paint	161	M^3	710	114,310
granitic tile	1,902	M^2	4,000	7,608,000
flooring	5,852	M^2	300	1,755,600
			Total	38,266,229

5.5 Ratifying whether the projected cost meets the owner's budget

The projected cost presented above is about thirty-eight million and three hundred thousand NTD; in contrast, the research hypothesizes the owner's budget is thirty-six million NTD, the difference is about two million and three hundred thousand NTD. Therefore, the research provides an alternated project to meet the owner's budget, which includes two modifications: 1. the modification of the decoration engineering 2. the modification of the structural engineering.

1. The modification of the decoration engineering

To decrease the projected cost, the research changes the granitic tile into cheaper tiles, grey-faced tile, and also modifies the red paint and the light-gauge steel frame of the floors into the cheaper materials.

Since the Navisworks model was established by the function, "Append", the modification can be updated to the Navisworks model by the function, "Refresh". In this way, the cost items do not have to reconnect with the BIM items; then, the results of the quantity takeoffs can be renewed.

On the condition of the lowest cost of the decoration engineering, Table 2 shows that the original projected cost decreases about sixty hundred thousand NTD, which is still a gap of one million seven hundred thousand NTD between the alternated projected cost and the owner's budget. Hence, the research modifies the structural engineering items.

Table 2 The list of the projected cost after the modification of the decoration engineering

Engineering items	Quantity	Unit	Price (NTD)	Cost (NTD)
reinforced concrete 280kgf/cm^2	3,974	M^3	2,115	8,405,010
rebar SD280	395	T	13,412	6,190,835
rebar SD420	104	T	15,000	1,708,928
formwork	19,817	M^2	332	6,579,244
excavation	4,382	M^3	166	727,412
light-gauge steel frame	5,930	M^2	873	5,176,890
red paint	161	M^3	650	104,650

granitic tile	1,902	M^2	3,700	7,037,400
flooring	5,852	M^2	300	1,755,600
			Total	37,685,969

2. The modification of the structural engineering

To decrease another one million seven hundred thousand dollars, the research deletes the partial area of the third and fourth floor, decreasing the number of columns, beams, slabs, walls and rebar, as presented in Figure 3.

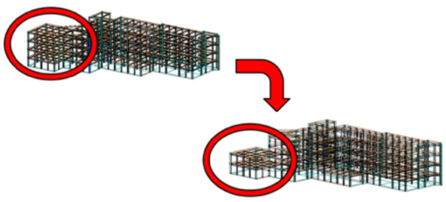

Figure 3. The modification of the structural engineering

The research updates the ETABS model by the function of API, "Export to Update Existing ETABS Model", and then conducts the structural analysis and design again.

After analysis and design, if there are deleted items in the Revit model, the steps of the quantity takeoffs are the same as the modification of the decoration engineering, which do not need to reconnect the cost items and the BIM items; however, if there are added items in the Revit model, it is necessary to reconnect the cost items and the BIM items in Navisworks.

The results show that after the structural engineering modification, the alternated projected cost decreases another two million NTD. In summary, these two modifications decrease two million and six hundred thousand NTD, which meets the budget of the owner, as presented in Table 3.

Table 3 The list of the projected cost after the modification of the decoration engineering and structural engineering

Engineering items	Quantity	Unit	Price (NTD)	Cost (NTD)
reinforced concrete 280kgf/cm^2	3,654	M^3	2,115	7,728,210
rebar SD280	379	T	15,673	5,940,067
rebar SD420	92	T	16,432	1,511,744
formwork	19,017	M^2	332	6,313,644
excavation	4,382	M^3	166	727,412
light-gauge steel frame	5,560	M^2	873	4,853,880
red paint	154	M^3	650	100,100
granitic tile	1,820	M^2	3,700	6,734,000
flooring	5,427	M^2	300	1,641,600
			Total	35,550,657

Through the hypothesis, it's proved that the proposed model is capable of developing an alternated projected cost on the basis of interoperability of information; hence, if the proposed model can be applied on the projects in practice, the projects will have the ability to adjust the cost to meet the owner's cost precisely and smoothly, and also through the comparison between the original projected cost and the alternated projected cost, the owner will have a more comprehensive understanding of the current condition of the projects, achieving the goal of the projected construction cost in the early stages.

6 Discussion of the results

The research compares the proposed model with the model of the preliminary cost estimation Wang et al. [11] proposed. In the two models, the common part is the application of BIM on the quantity takeoffs; in addition, the cost items, the unit price of the cost items, and the tested building are identical while the main difference is the consideration of structural analysis and design, which contributes to different quantity of structural engineering. Therefore, the research discusses the margin of the two projected cost to prove the proposed model has the beneficial effect on the cost estimation in the early stages.

The projected cost of Wang et al. [11] is 42,190,382 NTD, which is a 10% difference between the two projected cost. That is to say, the difference between the projected cost of structural and non-structural analysis and design can be up to 10%, which is unacceptable to the preliminary cost estimation. The difference will not only produce the difficulties on the management of the projects in the late stages, but also influence the progress of the construction. In conclusion, the preliminary cost estimation of the projects should put the structural analysis and design into consideration.

7 Conclusions and suggestions

In civil engineering, a recent surge of research on BIM has given us new opportunities and solutions for the issues of the cost estimation in the early stages. However, since the structural analysis and design of BIM is still in its infancy, there is still a strong assumption of the quantity of the structural engineering. Hence, the purpose of the research is to present a conceptual cost estimation model to better control the details of the projected cost in the early stages.

After the test, through the BIM-based conceptual cost-estimation model considering structural analysis and design, the research successfully estimates a projected preliminary cost, and is also able to alter the cost within the owner's budget. In addition, the research compares the proposed model with the preliminary cost-estimation model Wang et al. [11] proposed. The result of the comparison concludes with certainty the proposed model is feasible. In the end, the research hopes the proposed model should be of importance in the applications of constructions and provide a more comprehensive functions to the lifecycle of the projects.

Three of the suggestions are worth summarizing:(1) The interoperability of information between ETABS and Revit is still defective. For example, the damper cannot be identified in the exr. file extension. Therefore, the research suggests that an area of future research that should be considered is how to enhance the accuracy of the interoperability of information between ETABS and Revit. (2) There are a variety of BIM softwares, and so as the softwares of structural analysis and design. Perhaps future research could examine the interoperability of information between different BIM softwares and structural analysis and design softwares to refine the functions of BIM structural analysis and design. (3) In this research, the model is tested via a RC building and Taiwan architectural laws and guidelines. In the future, the research suggests the other researchers can adopt this conceptual model in different scenarios, such steel building or other countries' laws and guidelines, and accumulate all these implements to form a dynamic database. According to different scenarios, the dynamic database will enhance the ability of the proposed model by providing a wider range of applicability.

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