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Developing an Integrated Evaluation Technology for Energy- and Cost-Efficient Building Design Based on BIM in the Real-time Manner

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Abstract Existing BIM(Building Information Modeling) based energy evaluation tools cannot be utilized enough for the potential performance of BIM because most of them have not provided the integrated model for energy evaluation, assessment of the material, cost of the construction, and so on. This research aims to propose and develop a new application, EcoBIM, to support an integrated evaluation of the energy and cost efficiencies of the design alternatives within the design process. The proposed application functions as a BIM-based evaluation system that calculates energy-savings performance as well as the construction cost of the alternatives at the design stage. This study mainly focuses on the possibilities of developing the proposed technology. We also suggest an advanced design process using the proposed system, corresponding to changes of national regulations in Korea. This study deduce that EcoBIM can allow architects to make suitable decisions regarding energy- and cost-efficient designs. The proposed design process will allow architects not only to check the eco-friendly performance of design alternatives but also predict the operation cost in a certain period in the future. EcoBIM can prevent large-scale design changes required to obtain environmental certification and enable the owner to make an informed decision about the initial investment of construction according to the result of the analysis of the energy requirement at the design stage.

Keywords: Building Information Modeling, Eco-Friendly Building, Real-Time Evaluation, Integrative Evaluation

1. INTRODUCTION

Today, the requirement of reducing energy expenditure is one of the most important issues in Asia and throughout the world (Na et al., 2010). Normally, buildings that are responsible for about 40% of the total energy consumption might be regarded as an energy problem. Buildings in Korea account for 25% of the total national energy consumption. Thus, the Korean government established several regulations to reduce the amount of energy that buildings consume (An et al., 2011). In line with these regulations, several technologies have been developed to analyze the energy consumption of buildings. In particular, there have been attempts to predict the energy savings performance of building design alternatives in the design process, since the buildings that are considered to conserve energy in the process of design generally sustain their environmental performance for a long time.

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In the design process, architects make various decisions, for example, regarding shapes, sizes, materials, and so on. These considerations in the design process directly affect the total energy consumption of the building life cycle (Oh et al., 2011) and furthermore city scale(Kim et al, 2012). Therefore, a building's energy savings performance should be evaluated during the early design stage(Schlueter & Thesseling, 2009).

Although this energy savings performance evaluation at the design stage is needed to minimize a building's energy consumption during its life cycle, architects must normally spend tremendous time and money to undertake the evaluation process. For example, in order to evaluate the energy savings performance of the design alternatives, architects should develop additional digital models that account for 80% of the total cost of evaluation. Furthermore, it is not easy to reflect the result of such an evaluation in the design, because the evaluation process is separated from the design process (Ko, 2010).

Recently, the costs of construction and maintenance have become the most significant factors for architects to consider in their eco-friendly building design(Azhar, 2011). Although the initial investment cost for an eco-friendly building is higher than that of a ordinary one, the cost cutting in the operation and maintenance in an eco-friendly building can reduce the total cost throughout the life cycle of the building as compared to a standard building. In order to facilitate this eco-friendly design process, the architect must predict and compare costs between eco-friendly and standard buildings during the design stage.(Brown, 2009, Larsen 2011) For this, there are several attempts to evaluate the life cycle cost of the design alternatives for eco-friendly buildings.(Leigh 2004, Azhar 2010, Carlton 2010) However, these attempts focused on energy analysis using BIM, rather than an integrative analysis of energy performances and material cost. In result, they were not enough to resolve the workloads of the architect's decision making, due to the time delay and labor-based task of calculating the total cost (Song, 2010).

In this situation, BIM is regarded as one of the most appropriate solution which is a kind of platform for the integrative evaluation process in the architectural design stage because BIM can enhance the interoperability of each design stages and alternatives(Lee et al, 2006). That's why the representative BIM software companies are pursuing to develop the BIM-based evaluation system supporting the eco-friendly design process.(Oh et al, 2011)

Thus, this research aims to propose a technology capable of realizing the integrative and real-time evaluation of the energy and cost efficiencies of the design alternatives. This research develop a BIM-based evaluation system, EcoBIM, to calculate the energy savings performance as well as the construction cost of the design alternatives during the design process. This study mainly focuses on the possibilities of developing the proposed technology. In addition, this research proposes an advanced design process along with the system, corresponding with the amended design process, on the basis of the changes to Korea's regulations concerning energy performance evaluations. However, this study is limited to the heat transmission coefficient of walls, which is one of the fundamental elements of the building performance evaluation, because it might be inefficient to include the whole method for evaluating building performance.

2. RELATED STUDIES AND TECHNOLOGIES

Recently, several studies have been conducted in relation to building energy evaluation, energy and cost evaluation, and BIM-based energy evaluation.

Eastman (2009) proposed energy analysis using BIM in the early stage design. Schulueter and Thesseling (2009) also examined energy evaluation using BIM. These studies focused on energy analysis via BIM's assembling powers of semantic geometry. They have not reached the integrative evaluation which architects feel difficulty to handle. Leigh and Won (2004) applied life cycle cost (LCC) analysis to evaluate the economic performance of building service systems. They proposed a cost-effective design decision using LCC analysis and provided an example of its appropriate use for designing HVAC systems in the Community Center and Congress Hall of a local government. It was quite a successful example of LCC analysis and its usage. However, it is not easy for architects to employ this method, as the analysis is complicated and separate from the design process (Leigh and Won, 2011). Prior to this, Leigh et al. (2005) conducted a study of managing and predicting the energy of office buildings also revealed the importance of energy evaluation and prediction. However, their evaluation was also not related to the design process.

Kim et al. (2012) suggested a BIM-based energy performance assessment tool for use at the early stage of the design process. They also proposed an Industry Foundation Classes (IFC)-based input data file (IDF) converter that is middleware for reducing the loss of information for the energy performance evaluation. The use of IFC, regarded as the mutual data format of BIM, to evaluate energy performance is meaningful for its potential worldwide influence. However, the proposed system is still not connected to the whole design process.

Song et al. (2010) researched the cost efficiencies of the design variables related to the energy efficiency of an apartment complex. They considered the life cycle cost, net present value, internal rate of return, and payback period of each alternative and suggested the order of cost-efficient alternatives (Song, 2010). The basic idea of this research is similar to our research that evaluates and predicts the cost and energy efficiency of a building before its construction. However, this study provides complex equations that are not easy for architects to learn and use.

Lee et al. (2010) proposed a prediction and evaluation method based on BIM, for the wind environment at the design stage. Furthermore, Lee et al. (2011) predicted the CO2 in the building life cycle using a database connecting building material and carbon emissions (Lee et al., 2011). The previous research is meaningful for the prediction of environmental performance at the design stage using the interoperability of BIM. However, since these evaluation methods are also separated from the design tool, they do not appear to provide real-time feedback to architects.

Moreover, there are several commercial applications for evaluating building energy performance, and some of them are already connected with BIM modeling tools, such as EnergyPlus, Ecotect, Esp-r, and TRANSYS. These tools play a quite significant role in architects' decision making regarding eco-friendly building design (Oh et al., 2011) Recently, Autodesk introduced Vasari, which is the beta version and is connected to BIM. It will be released as soon as a commercial product has been developed. Moreover, Revit Architecture 2013 has been equipped with a Conceptual Energy Analysis (CEA) module to analyze the energy performance of the mass shape of the building alternatives. This software highlights the need for a real-time evaluation tool that is connected to design tools. In spite of these efforts, it is not easy the architects to evaluate the energy performance because there is no appropriate technologies which simultaneously execute the integrative analysis for several variables related to the energy performance of the designed building.

As the global interest in eco-friendly building evinces, efforts have been mobilized to institutionalize architectural design including energy performance. For example, the so-called Green Building Certification Criterion in Korea is the regulation that evaluates the eco-friendly performance of buildings. Its purpose is to realize sustainable development in which humans and nature can coexist. It evaluates the factors of the building in its life cycle that affect nature, such as the building's locations, materials, construction methods, management, and so on (CreBiz QM, 2013). Furthermore, according to Article 66-2 of the Korean National Building Code, architects must submit their Energy Saving Plan to the government for official approval of their building design. In order to do so, architects should devote additional time and effort to their project, regardless of the design task. Recently, Korea's Energy-Saving Building Design Standard has been strengthened. The Ministry of Land, Infrastructure, and Transport proclaimed this enhanced standard in May 2013, with a plan to apply it to the practical field of architecture as of September 2013.

3. STRATEGIES FOR DEVELOPING ECOBIM

Through the previous survey, This research build several strategies for developing the design system that supports energy performance evaluation, EcoBIM, as follows.

(1) Real-time evaluation at the design stage

First, the proposed system should evaluate the energy performance in real time. Since the existing evaluation system analyzes the designed alternatives after the competition of the design task, architects cannot determine the building's energy performance during the design process. For this reason, This research propose a process-centered, eco-friendly building evaluation that will enable architects to design a building and calculate its energy savings simultaneously (Oh et al., 2011). Once a design alternative is fixed in the design process, it is unlikely to change. If the architect can intuitively preview and check the energy performance of the design alternatives within the design process, he or she can generate a better design that is in harmony with the optimized result.

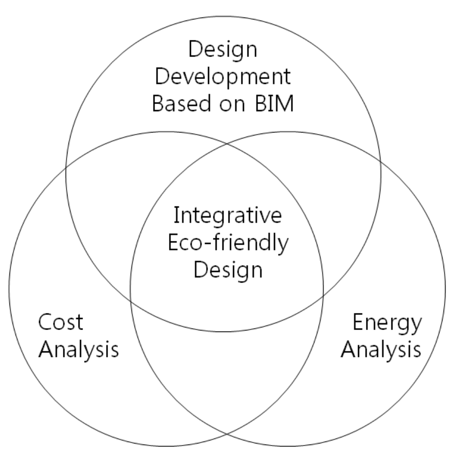

Figure 1. The Concept of the integrative eco-friendly design with EcoBIM

(2) Integrative evaluation for energy- and cost-efficient building design

In order to obtain environmental certification from the government, architects must calculate the energy performance of the design alternatives. These are crucial data for obtaining the permission for the construction. However, high-quality energy performance generally elevates the construction cost. Therefore, architects are often required to calculate both the environmental performance and the construction cost during the design stage. Furthermore, the operation cost of the design alternatives is one of the most important factors for the decision making concerning the building design. Thus, this research proposes a system for calculating not only the energy performance but also the initial construction cost and the operation cost simultaneously.

(3) BIM-based application running within the design process

As stated above, in order to evaluate the performance of the design alternatives, architects require additional digital models that can account for 80% of the total cost in the evaluation. Recently, the advent of BIM has revealed the possibility of minimizing the unnecessary effort required for extra modeling. If architects use a BIM-based authoring tool, the design alternative, represented by a 3-dimensional parametric data model, can be used for the evaluation model and easily modified in accordance with the result of the evaluation. Moreover, most BIM-based authoring tools provide a software development kit (SDK) that has many functions for managing the model information, to develop a plug-in module. Hence, to develop EcoBIM, This research use an SDK that is based on a commercial BIM-based authoring tool.

4. IMPLEMENTATION OF ECOBIM

(1) Overview of EcoBIM

The goal of this research is to develop a technology that evaluates the energy performance of design alternatives by calculating the life cycle cost for its operation in real time. In order to develop it, This research propose a BIM-based application that evaluates the energy and cost efficiencies of the design alternatives. Within the design process, our EcoBIM enables architects to calculate the energy requirement and the operation cost of the design alternatives simultaneously. Furthermore, architects using EcoBIM can compare the resultant data of each alternative and choose the more efficient alternative. In order to realize this idea, This research first develop the function of calculating the heat transmission coefficients of the designed wall, roof, and slab, which can compose the envelope of the building's surface. Further, This research develop the function for calculating the energy requirement on the basis of these heat transmission coefficients. The energy requirement is used to calculate the operation cost according to the designated operation time and outer and inner temperatures.

EcoBIM is a kind of add-on module for the commercial BIM modeling tool, Revit Architecture 2012. As such, EcoBIM is developed using the SDK provided by Autodesk with Visual Studio 2008, which is a Windows-based development tool using C# language. Revit reads the "addin" file and executes EcoBIM.

(2) System Structure

Figure 1 shows the system structure of EcoBIM. Revit is used for the modeling platform and EcoBIM is deployed in Revit as a plug-in module. The authoring tool contains the libraries of building components based on BIM. To calculate the heat transmission coefficient, the energy requirement, and the operation cost, information is transmitted to EcoBIM, such as the type of material, density, thermal conductivity, and so on. Revit, as the authoring tool, delivers the geometrical information of the design alternatives to EcoBIM, and EcoBIM, as the evaluation module, delivers to Revit the visualized result of the calculations.

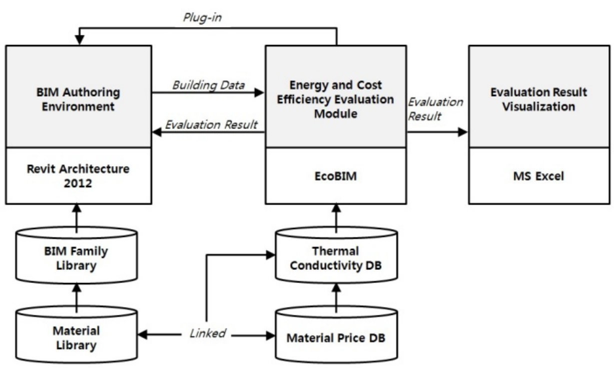

Figure 2. The Structure of the Proposed System

(3) Database

Figure 3 displays the database of the proposed system conceptually. As shown in the figure, the names of the architectural materials in the BIM family, which are composed of several materials, are linked to the database according to TCR (Thermal Conduction Rate), DEN (Density), the price of materials, and so on. EcoBIM can retrieve the needed information for the calculation in this database by using the keyword associated with the name of the required material.

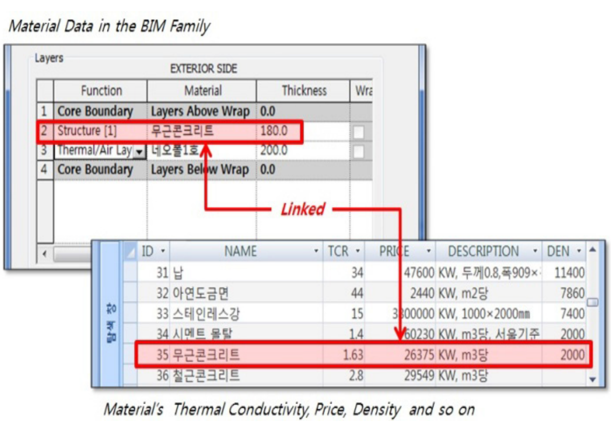

Figure 3. The Relation of Data for the Proposed System

(4) Interface

Figure 4 illustrates the user interface of EcoBIM plugged into Revit. The icon for activating EcoBIM is deployed on the sub-menu of "External Tools" in the menu of the "Add-ins" category. In order to deploy the external EcoBIM module, the file "EcoBIM.addin" should be located in the designated folder, as shown in Figure 5. This file makes the connection between Revit and EcoBIM (*.dll) when Revit starts. Figure 4 shows us the codes defined in "EcoBIM.addin."

(5) Calculation

EcoBIM performs three calculation tasks to determine the heat transmission coefficient, the energy requirement, and the operation cost of the design alternatives. To that end, EcoBIM uses algorithms based on equations authorized by the official organization.

In order to calculate the heat transmission coefficient of each building component, such as the wall, slab, and roof, EcoBIM must first calculate the thermal resistance of the materials composing them. EcoBIM must also calculate the thickness of each building component, because the heat transmission coefficient is the value of the thermal conduction rate divided by the thickness. Since the thermal resistance is the reciprocal of the heat transmission coefficient, the heat transmission coefficient of the building component can be calculated by retrieving each material's thermal conduction rate and thickness.

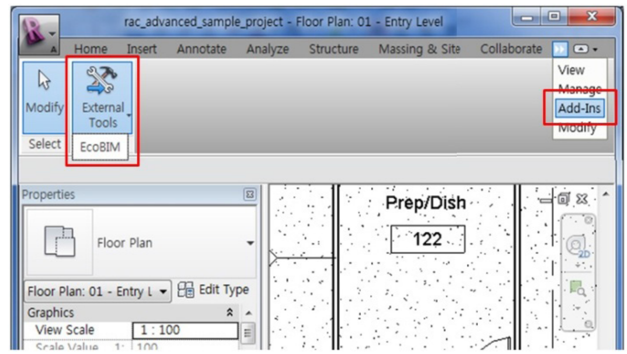

Figure 4. The Interface of EcoBIM Added in Revit

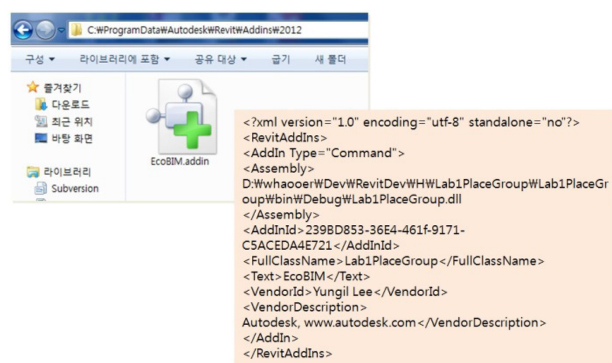

Figure 5. The Add-in File of Revit for EcoBIM

Energy Requirement (Kwh/m^2) =

(Outer temperature – Inner temperature) * The area of surface

* The heat transmission coefficient of surface * Time

Figure 6. The Equation for Calculating the Energy Requirement

```
LocationCurve floorLoc = floor.Location as LocationCurve;

Autodesk.Revit.DB.Parameter param = floor.get_Parameter("Area");

double area = param.AsDouble();
```

Figure 7. The Codes of the Function for Calculating the Area of Floor

To calculate the energy requirement, This research use the equation in Figure 6. The energy requirement is defined as the sum of the energy required to sustain the designated indoor temperature for a certain period of time in the designed space. Without the parametric modeler, it is difficult to measure the area of surfaces and calculate each heat transmission coefficient. However, Revit's SDK provides the functions to obtain the needed information pertaining to each component. Figure 7 is an example of the codes of the function for determining the area of the floor. Within the limited scope of this research, This research focus on the potential for the automatic calculation of the energy requirement. In further research concerning the practical application, This research need to consider the direction of the surface, the opening, the heating/cooling equipment, etc., in order to calculate the energy requirement.

To calculate the operation cost, This research need to set the assumption of the operation situation. Since This research endeavor to compare the cost and energy efficiencies of the design alternatives, it is useful to calculate the operation cost under a fixed situation. We fix the inner/outer temperature and operation time to calculate the energy requirement and develop the function for calculating the operation cost according to the calculated energy requirement. To calculate the operation cost, This research use the data of electricity rates provided on KEPCO(Korea Electronic Power Corporation)'s website.

(6) Execution Examples

Figure 8 illustrates the execution of EcoBIM as a plug-in module in Revit to evaluate the energy and cost efficiencies of the design alternatives. EcoBIM calculates the heat transmission coefficients of the components that constitute the surface of the room, the energy requirement, and the operation cost, and allows the architect to compare the results of the calculations in order to choose the suitable alternative in a real-time manner. Figure 8 shows two execution examples that contain the different thicknesses of the insulation in a wall component. Figure 9 shows the different thicknesses of the insulation. EcoBIM can show the calculated value of the heat transmission coefficient on the designed wall component in Revit and also save the results of the calculations as an MS Excel file (*.xls), as shown in Figure 8. The insulation thickness of the highlighted alternative on the left is 100 mm and the one on the right is 200 mm. After the execution of EcoBIM, the generated Excel files show the different results of the calculations. The result of the energy requirement on the left is higher than the one on the right, and the electricity rates on the left are higher than those on the right.

According to the result in Figure 8, the double size of the wall insulation might save about 1,000 WON a month as compared to the other wall insulation option. It might be hard to compare the initial cost and the operation cost, because the construction cost

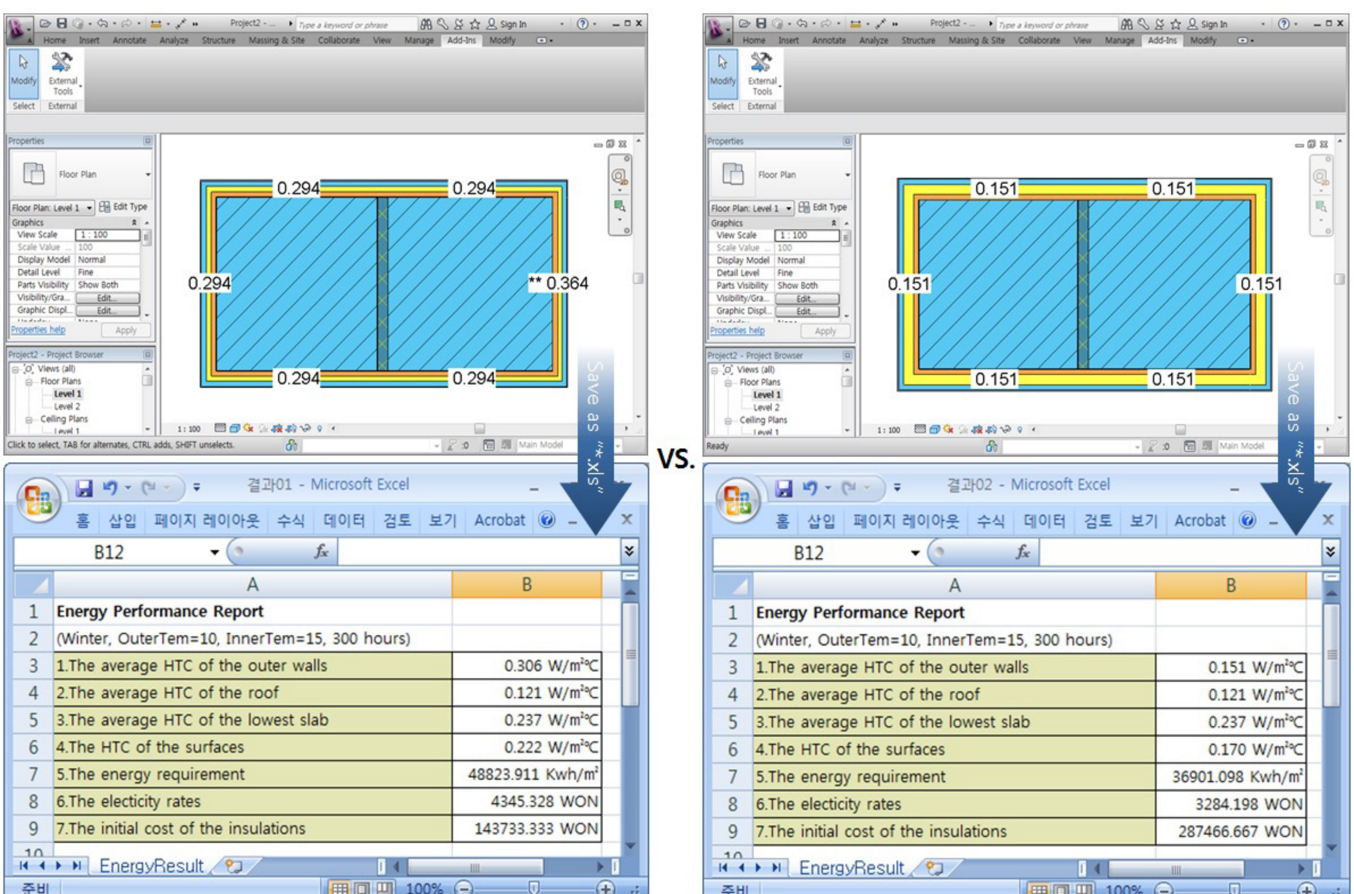

Figure 8. The Execution Examples of EcoBIM

is related to many factors, such as the size and type of building, the construction methods, and so on. However, in this example, the figure on the left is lower than that the right, and the cost difference is about 140,000 WON. That means that the extra cost compared to the alternative on the left can be compensated if the right alternative is constructed and operated for 10 years. By this result, This research cannot say which is better than the other. However, EcoBIM can provide the information to make an informed decision.

(7) The Eco-friendly Design Process with EcoBIM

In order to create an energy- and cost-efficient building design environment, This research propose a design process using EcoBIM. Figure 10 shows the proposed design process with EcoBIM as compared to the conventional design process. Normally, the task of the eco-friendly evaluation of the design alternative is performed at the later stage of the design process, making it difficult to change the design alternatives that have already been finalized. However, in the proposed design process using EcoBIM, since the architect can check the eco-friendly performance from the early design stage, it is easier to compensate the lack of eco-friendly performance and modify the design alternative. This means that the proposed design process using EcoBIM enables architects to minimize the large-scale change of adopting another design alternative at the end of the design process and maximize the eco-friendly performance of the design alternatives. If architects use BIM authoring tool for the architectural design like Revit, they can easily set up and change a lot of specific things related to the designed building such as shape, size, material and so on. That's why EcoBIM can be used in the early as well as later stage of building design process because it works with BIM authoring tool as a add-on module. The latest version of Revit provide a function for the eco-friendly evaluation. However, it cannot work with the design process because it is a kind of data exporting module which can generate the data for evaluation of energy performance like gbXML. With EcoBIM, architects can evaluate the energy performance of the alternatives in any stage of design process and they can make decision the designed building in detail based on the result of evaluation in the real-time manner. (Figure 10)

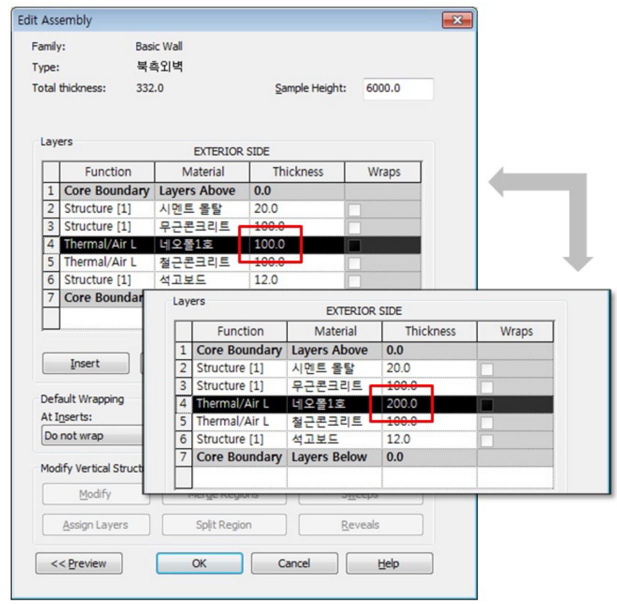

Figure 9. The Change of the Insulation Thickness

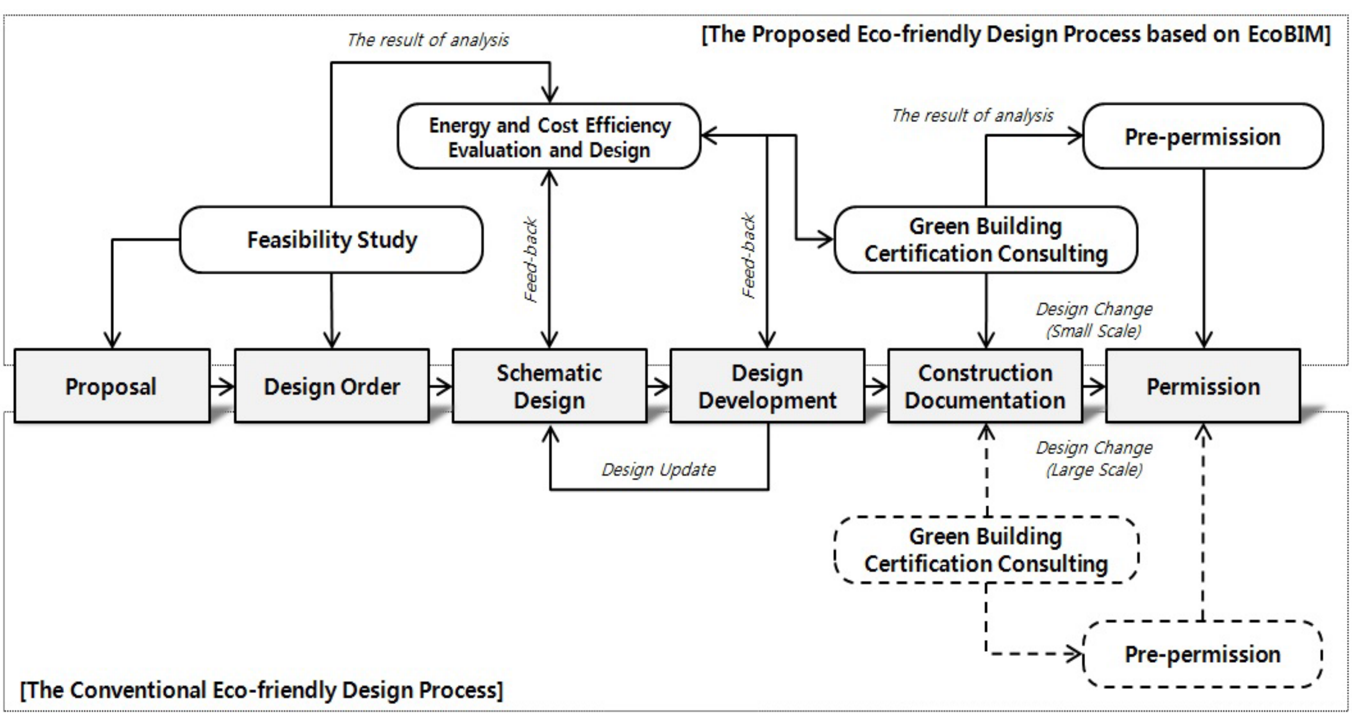

Figure 10. The Comparison between the Conventional and Proposed Eco-friendly Design Processes

5. CONCLUSION AND DISCUSSION

This study proposes a technology that realizes the integrative and real-time evaluation of the energy and cost efficiencies of design alternatives. This research provide the BIM-based evaluation system, EcoBIM, which calculates the energy savings performance as well as the cost of construction of alternatives during the design phase. This research mainly focuses on the possibilities of developing the proposed technology. Moreover, This research suggest an advanced design process with the proposed system that corresponds with the changes to Korea's national regulations. EcoBIM can help architects make suitable decisions for energy- and cost-efficient designs. The proposed design process will enable architects to assess the eco-friendly performance of the design alternatives as well as predict the operation cost in a certain period in the future. This process can prevent large-scale design changes in order to receive environmental certification, and allow the owner to make a reasonable decision about the initial investment in construction according to the result of the analysis of the energy requirement at the design stage. EcoBIM as an expert system can be valuable for supporting to design decision making and can be developed to the official reporting system for the certification related the eco-friendly building design.

Future research must examine the following. First, a study of the various criteria for eco-friendly performance is needed because many different factors affect the environmental performance of a building. Second, in the same manner, This research must consider the surroundings of the building in the eco-friendly performance evaluation. Although the situation of a building itself related to the materials, the sizes of openings, the equipped facilities, and so on is crucial to the building's eco-friendly performance, the situation of the surroundings related to the direction of the building, its location, the situation of nearby buildings, and so on can influence the ultimate performance of the building. Third, it is necessary to find a practical solution for eco-friendly design. Now, most of the eco-friendly design behaviors are aimed at obtaining the official certification. However, the standard of such a certification is not enough to realize an eco-friendly building environment, because this will only satisfy the minimum standards. Furthermore, the solution must facilitate the architects' eco-friendly design and certification processes. Fourth, although this study focuses on the possibilities of development, This research need further development and practical testing to determine the accuracy of the evaluation results.

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