A Study on the Model of a Building-Envelope Structural Modification System to Increase Energy Efficiency at the Schematic Design Stage

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Abstract
The purpose of this study was to create a building-envelope structural modification system (BESMS) and an accompanying algorithm that could be used to improve a building's energy efficiency. The proposed system is capable of deciding the optimal structure of a building-envelope. Methods adopted in the study include a review of previous studies and reference literature and, interviews with relevant industry experts. As part of creating the BESMS and algorithm, a five-stage building-envelope design process (BEDP) offering a basis for the BESMS was established. A model using BIM-based design software programs as platforms was proposed as well. The decision-making system for designing the proposed model was developed by combining the FLs (AI technique) and AHP (decision-making method). Based on these outcomes, components of the BESMS were defined, an inference-deciding structure was determined for each decision-making item as required by the BESMS, related design factors were identified, and the degree of importance was calculated. Lastly, using these results, the model for the BESMS was created.

Keywords: building envelope; energy efficiency; schematic design; algorithm; fuzzy logic

1. Introduction
1.1 Purpose of Study
Given the demand for eco-friendly architecture in this environmentally-conscious age, there has been a drive in the architecture and the construction industries to improve the energy efficiency of buildings (Peter, 2006). Improvement in efficiency is determined by optimal, efficiency-related values of design factors that are adopted during the design process. Designing an optimal building envelope is of particular importance since the design affects the building's energy consumption and has close relationships with the indoor environment created. Implemented at the schematic stage where design factors are decided, optimal envelope design affects both energy performance and maintenance of the building (the result). As such, it is vital that the building's architect or designer decide the structure of the envelope during the schematic design stage based on energy performance levels of the building and directly incorporate this structure into the design.

To ensure that all relevant factors are decided in consideration of the inter-factorial effects at the schematic design stage where the optimal envelope structure is created to help achieve the building's energy efficiency improvement goal, it is imperative to develop a building-envelope structural modification system capable of assisting the design team. The purpose of this study was to establish a system architecture and algorithm that would be the basis of the development of such a modification system.

1.2 Scope and Methods
This study aimed to improve architectural design quality and promote technical development in BIM (Building Information Modeling). The scope of the study and methods used are summarized below.

First, a design process of building-envelope structure was established, and optimal modeling was proposed to help increase the energy efficiency of a building. Conventional envelope design processes were collected, analyzed and standardized, with an emphasis on the schematic stage. Based on the standardization results, a structural design process was developed in which an envelope structure is defined with logic to increase the energy efficiency of the building. An optimal model was then proposed, that is capable of utilizing the developed design process in BIM-based design.

Second, a decision-making system for design was established in which architects can decide
design values by considering relevant factors while working on the structure of the building-envelope. Existing decision-making methods and AI (Artificial Intelligence) techniques that had been either theoretically solidified or applied in other disciplines, were collected and analyzed. Based on the results of this analysis, the organization and content of the optimal decision-making system were defined and identified as suitable for the envelope structural design process to be implemented during the schematic stage.

Third, based on the results of the preceding stages, this study proposed an architecture of and an algorithm for a building-envelope structural modification system (BESMS). This assists designers in their selection of an optimal envelope structure that satisfies the energy efficiency improvement goals for the building during the schematic design stage.

2. Analysis and Establishment of the Design Process of an Envelope Structure

2.1 Analysis of Trend in Low-Energy Building Design

An analysis of the architectural design process based on the results obtained from reference literature (Jean et al., 1997; Park, 1995) and working-level interviews revealed a great deal of variety according to the experience and perspective of each architectural designer and researcher. However, as mentioned in an advanced study (Woo, 2004), the architectural design process can be generally divided into the stages of investigation and analysis, planning, schematic design, master design and execution design, in that order. The schematic design stage, where the overall framework of the design is established, is based on the direction of and policy on design that corresponds to the core of the entire design process, which ultimately determines the quality of design outcomes.

Fig.1 shows the relationship between the architectural design process and low-energy building design (LEBD). At the schematic stage, where design plans are established, the plans must ensure LEBD by incorporating energy-saving technologies and complying with the legal requirements of each related field such as architecture, facility installation, and electricity. The requirements need to be satisfied during the process of defining design conditions and concepts as well as design plans. This process determines critical design factors and values that affect the building's energy performance. As for the master design stage, where design plans established at the schematic stage are made more concrete, the energy-saving technologies and legal requirements incorporated into the schematic design are revised and supplemented. The primary goal of the revising and supplementation is to scrutinize the legal requirements in greater detail and ensure that they are fully incorporated into the design, although in some cases new energy-saving techniques and technologies are also taken into consideration at this stage.

In recent years, there has been a growing interest in, as well as a more acute awareness of, the impacts of human activity on the environment and the need for eco-friendliness and green growth. That concern has translated into an industry-wide trend of incorporating environment-friendly building design methods and techniques from the earlier stages of the design process. This goes beyond conventional energy-saving design practices, and specific examples of this trend in Korea include the Green Building Certification System (The Ministry of Land Transportation and Maritime Affairs, 2011), the Housing Performance Grade Indication System (The Ministry of Land Transportation and Maritime Affairs, 2005) and the Building Energy Rating System (The Ministry of Land Transportation and Maritime Affairs, 2009).

In sum, a shift is taking place in LEBD practices— from those based on decades-long, commonly-accepted laws and regulations to those incorporating the growing importance of green architecture and construction into LEBD technologies and related laws, rules, regulations, and systems.

2.2 Analysis and Establishment of a Building Envelope Design Process

The design process of the envelope is part of the LEBD described in the preceding section of this paper and is implemented via the same flow shown in Fig.1. The schematic stage indicates that the envelope design outline is created by incorporating relevant laws and regulations and low-energy design techniques and deciding design orientation and factors for each part of the envelope. Based on the outline, the master design stage involves reviewing technical matters in design applicability and methods (e.g., design concept,
economic feasibility, and dimensions) and specifying the envelope design (Woo, 2009).

The general envelope design process is not a proactive approach to improving the energy efficiency of buildings. Rather, it is a way to satisfy minimum requirements (related laws and regulations) or current architecture and construction standards. But today, the envelope design process is shifting towards a more proactive energy efficiency improvement initiative just as the latest LEBD is transitioning in the same direction.

Given the industry environment, the building-envelope design process (BEDP) has been defined as the process shown in Fig.2. — a tool for adopting the latest trend and improving the energy performance of buildings. The proposed process was based on the findings of previous research as well as interviews with industry experts and a review of the literature. In Fig.2., the goal of improving energy efficiency is achieved by varying the materials that make up each component of the envelope.

Design processes are classified into 5 stages (see Fig.2.), which can be assessed theoretically rather than the existing architectural design process (Woo, 2004; Park, 1995). The design process (see Fig.2.) that advances the framework in which the building energy performance goal can be attained using objective methods and data, in consideration of the interrelationships between related design factors, can be considered as more systematic than the existing building envelope design process that sets the design values for building envelope based on the experiences and intuitions of architectural designers, through a simple comparison between related regulations and related design factors.

Furthermore, the design process shown in Fig.2. establishes reasonable design skills that can be directly applied to architectural design in order to attain the target building energy performance, unlike the existing building envelope design process, which calculates the building energy performance after the architectural design is fixed and only its results can be known.

2.3 Creating a Design Model

BIM technology, which manages the information generated during the whole life of buildings in an integrated manner, both changes the architectural design work process and enables the consistent use of the architectural information generated in the architectural design process in various fields such as architectural environment, structure, M&I, etc. For this reason, BIM technologies are being introduced more and more to the field of architectural design and are being generalized. Based on the BEDP in Fig.2., a model was created using BIM-based design software programs as platforms (see Fig.3.). The modeling helps the designer improve the energy efficiency of buildings while implementing the BIM-based design process.

The outline of the model was based on the process presented in Fig.2., and modules were created in four areas: input, database, decision-making system, and output. The input module involves the input of information and data on qualitative and quantitative factors that are needed in the BEDP. The information/data input is conducted mostly by the design team directly associated with the building under analysis, or by other staff members involved in the task. The database module stores information/data on buildings that were designed via BIM platforms as well as the results of decision-making systems. The module also can continually revise and accumulate the information/data. The decision-making system is the core of this model, and is capable of utilizing the information/data that has been entered and other databases to use inferences in decision-making. The module prioritizes: the parts of the envelope that need to be modified and the materials that make up the parts that were identified. Lastly, the output module visualizes the results of decision-making in a form that can be understood by the user.

The design model concept as presented in Fig.3. can be processed as the framework that uses the architectural data generated in the design process by accommodating BIM based architectural design work that leads the variation of architectural design work. In other words, the design model in Fig.3. presents a plan in which architectural designers themselves can perform and apply the building energy performance analysis and performance improvement plan from the basic planning stage, while these have generally been made by related external experts in the building envelope structural design process.
3. Establishment of Decision Making System for Design
3.1 Analysis of Decision Making for Design During BEDP

Fig. 3. shows a BEDP model, with a three-stage envelope modification process to increase the energy performance of the building. At each stage, the design is determined by related factors. All stages were analyzed to help explain the characteristics of the design-deciding process dubbed the decision-making system module. The results are summarized below.

Deciding the level of energy performance of the building involves setting a goal for its energy efficiency improvement. The key is to select which of the energy performance standards currently in use are to be the criteria for the goal. External factors, such as the intention of the client and other related staff/engineers and the direction of government policy, have significant effects on the goal. For this reason, this goal-setting process is more externally oriented.

Deciding which of the envelope parts is to be modified corresponds to a process of prioritizing the candidate parts to help satisfy the type and values of the energy performance goal that was set. Critical factors at this point include significant qualitative and quantitative design factors and design values that are related to established priorities. Part modification is heuristic in that the judgment by and experience of the design team and associated experts significantly affect the prioritization.

Deciding materials for the part to be modified involves changing the materials comprising the parts of the envelope that require modification. Just as in the modification part selection, this process is significantly affected by the qualitative and quantitative values of the relevant design factors. Also affecting the decision is the judgment by and experience of the design team and associated experts and (to a greater extent) the objective information and data that is available, including relevant theories and analytical results. Thus, deciding optimal materials for the modified parts requires multi-faceted decision-making that includes both empirical and logical rendering.

3.2 Survey and Analysis of Decision Making Techniques

The preceding section of this paper summarizes the characteristics of the envelope modification processes. Although each process has its own unique features, there is common ground among the methods employed to achieve the energy efficiency goal. That is, the externality, empiricism and multi-facetedness create combinations of related design values; and based on the values, the architect and other experts involved decide (or make decisions) to achieve the efficiency goal.

So far, logical decision-making based on interaction between related design factors has been considered a unique human ability — a kind of black box. However, multiple studies have been done on the systematization of logical thinking that resembles that of humans (Park, 1998). Among the related research findings, decision-making methods and AI techniques were selected and analyzed if they were deemed applicable to the envelope structural modification process that was established in the previous section of this paper.

Analytical results indicated that two candidates — FLSs (Fuzzy Logic System), an AI technique; and AHP (Analytic Hierarchy Process), a decision-making method — were most likely to accommodate the characteristics and content of the modification process.

Rule-based FLSs are used as a tool for expressing subjective knowledge and solving problems (Wang, 1994). FLSs consist of four components: rules, fuzzifier, inference engine, and output processor. The inference engine performs by utilizing the values of linguistic variables and fuzzy functions and is capable of delivering a single logical solution even when multiple variables, at odds with or similar to, are involved simultaneously. This architecture resembles the process implemented by the design team and associated experts while working on envelope modification where mutually-conflicting or similar quantitative and qualitative design factors interact. Developed first by Thomas L. Saaty, AHP is characterized by its abilities to take into account both qualitative and quantitative factors using the evaluator's intuitive and rational vs. irrational judgments and offer a comprehensive framework for problem-solving (Thomas, 1995). The process calculates the degree of importance by using a pair-wise comparison matrix when prioritizing factors that compete for design criteria. The method is deemed applicable to deciding the degree of importance for quantitative and qualitative design factors that are related to the...
modification parts and materials to be used.

3.3 Architecture and Content of the Decision Making System for Design

Fig. 3 presents an analysis of the characteristics of the decision-making system for design, dubbed Envelope Module. Optimal decision-making techniques capable of expressing the characteristics were also analyzed in the previous section of this paper. By combining the analytical results with interviews with industry experts, and the author’s experience, an architecture of the decision-making system for design was defined using the four areas shown in Fig. 4: input data, output data, inference, and database.

1) Structure and content of input data

Input data is where the input of design factor data determined during the process of deciding the design takes place. It is composed of two data types. The first one (Type I Data) relates to deciding realistic design values by incorporating the building’s status (Architectural design element, Economic element, Construction element, etc.) into the design-deciding process. The second one (Type II Data) involves calculating the degree of importance that indicates the correlation between related design factors. The goal is to ensure generality of the design values/data. To summarize the conversion of Type I Data into the input data needed for inference, values of the relevant design factors that indicate the status of the building were converted into values with linguistic characteristics. The aim of this was to re-create the same effects as those of human thinking ability. Knowledge and judgment of the design team staff were fuzzified, and the mean fuzzy value was calculated to determine the design values agreed upon by the staff. The calculation was based on the staff’s fuzzy numbers using Eq. (1) below (Woo, 2006).

\[ A_{ij} = \frac{\sum_{i=1}^{n}(a_{ij},b_{ij},c_{ij})}{n} = \left( \frac{a_{ij}+b_{ij}+c_{ij}}{3} \right) \]  

where, 

- \( A_{ij} \): the mean fuzzy number of n fuzzy numbers for the i\textsuperscript{th} design factor
- \( (a_{ij}, b_{ij}, c_{ij}) \): fuzzy number
- \( \left( a_{ij}, b_{ij}, c_{ij} \right) \): mean fuzzy number

\[ x_{ij} = \left( \frac{a_{ij} + 2b_{ij} + c_{ij}}{4} \right) \]  

where, 

- \( x_{ij} \): non-fuzzy number (normal number)

2) Structure and content of inference

Here, inference refers to the area for which inference was conducted to help decide on a design and was based on the hierarchical structure of AHP. The hierarchical structure was defined with four tiers, because it was deemed capable of securing the actual status of the building as well as the generality. The four tiers were based on the four components associated with the decision-making system for design.

Referencing to the model in Fig. 3, the building-envelope design requires goals that need to be decided, such as the parts for modification, and alternatives that are the consequences of the goals. Selecting optimal alternatives requires related design factors. Using the components needed, the hierarchy can be standardized with Tier I (design goal), Tiers II and III (design factors), and Tier IV (alternatives).

Eq. (3) below shows the process of inferring optimal alternatives that are based on the hierarchical structure and capable of satisfying the design goal. Using the equation, a combined non-fuzzy number was calculated, and a value was proposed with which the design team can prioritize.

\[ \sum_{i=1}^{n}(a_{ij},b_{ij},c_{ij})x_{i} + \sum_{i=m+1}^{n}(a_{ij},b_{ij},c_{ij})x_{i} + \sum_{i=t+1}^{n}(a_{ij},b_{ij},c_{ij})x_{i} + \sum_{i=k+1}^{n}(a_{ij},b_{ij},c_{ij})x_{i} \]  

3) Structure and content of database and output data

A database stores results and cases resulting from the decision-making process for design. The area also allows the continued accumulation of the degree of importance, which indicates the correlation among related design factors. Output data is the area where optimal alternatives are selected. Priorities were set based on the size of a combined non-fuzzy number for each alternative. The alternative with the largest value was selected as the optimal alternative.

4. Model of Modification System

4.1 Deciding Components of the Modification System

The BEDP model shown in Fig. 3 improves the energy efficiency of a building by ensuring logical decisions are made on the optimal envelope structure of the building during the schematic design stage. The core of the design stage is the BESMS. Fig. 3 indicates that the components of the BESMS can be defined as...
the same concepts as the four components of the BEDP model — input, decision-making system, output, and database. Fig.5. shows the BESMS, i.e., the results of combining the information in Figs.3. and 4.

![Architecture of the BESMS](image)

**Fig.5. Architecture of the BESMS**

The decision-making system, the core of the BESMS, is geared to implement decision-making items that are identified during the BESMS by the decision-making system for design, which was established in Section 3 of this paper. Examples of the items include: energy performance goals of a building, parts for modification, and materials making up the envelope that need to be changed. To implement these items, decision-making items were calculated as required by the framework that was proposed in Section 3 and via Eq. (3). In addition, it was necessary to establish an inference structure for each item. The data needed for establishing the structure were obtained using the framework for input data (see Fig.4.) as well as Eq. (1) and (2). Design values also needed to establish the structure were handled by the design team and associated experts via input (one of the BESMS components). To implement input, relevant design factors were defined for each decision-making item and the degree of importance was calculated.

Output, a BESMS component, involves finalizing the envelope structure as decided by the output data and the design team's judgment, producing drawings, and storing the outcomes in the database so that the information can be used for new projects.

### 4.2 Surveying and Analysis of Related Design Factors

To define the relevant design factors for each decision-making item that are needed in the input component of the BESMS, decision-making items were divided into three processes: Process I, a process for deciding efficiency improvement goals for a building; Process II, a process of deciding parts of the envelope that need to be modified; and Process III, a process for selecting materials that will make up the envelope. For each of these processes, design factors deemed to be influential were selected based on a literature review (Park et al., 2005; Nick et al., 2000) and the author's experience. Factors were defined through interviews with the participating experts. Table 1. summarizes the factors re-established. The table lists 37 influential design factors in the BESMS. These are further divided into seven groups according to their characteristics.

### 4.3 Establishment of Design Deciding Structure and Degree of Importance

To define the structure that decides the inference used in decision-making for each item, design factors listed in Table 1. were applied to obtain results (see Table 2.).

A pair-wise comparison matrix was used to calculate the degree of importance between design factors that make up each tier of the decision-making structure (Cho, 2000). The comparison started from the highest tier of the hierarchy in a top-down fashion to select the criteria or properties to be used in the comparison. Next, elements were selected for comparison from the tier immediately below the one from which the criteria/properties were selected. The author calculated the degree of importance between design factors for each tier in the decision-making structure of Process II (deciding parts of the envelope that need to be...
modified). Using the same method, the author obtained the degree of importance between design factors for each tier in the decision-making structure of Processes I (deciding efficiency improvement goals for a building) and III (selecting materials that will make up the envelope).

A pair-wise comparison matrix was used to calculate the degree of importance between design factors that make up each tier of the decision-making structure. The comparison started from the highest tier of the hierarchy in a top-down fashion to select the criteria or properties to be used in the comparison. Next, elements were selected for comparison from the tier immediately below the one from which the criteria/properties were selected. The degree of importance calculation described above was based on the assumption that the pair-wise comparison satisfies perfect compatibility (the consistency ratio must be no greater than 10%). Ensure a 5% CR with 3×3 matrices, 9% with 4×4 matrices, and 10% with matrixes beyond). The review revealed that the consistency ratios were less than 10%.

### 4.4 Establishment of the BESMS Algorithm

The previous sections described and analyzed components and details constituting the core of the BESMS, which assists the design team and participating experts in their decision-making practices while establishing the optimal building-envelope structure and achieving the efficiency goal for the building. Using the BESMS components (the results of the review and analysis) shown in Fig.5, as the basic elements and combining Fig.3 and 4., an algorithm for the BESMS was created (see Fig.6).

#### Table 2. Hierarchical Components of Decision-Making Process

| Tier I | Tier II | Tier III | Tier IV |
|--------|---------|----------|--------|
| The goals of building energy performance improvement | The building envelope parts to be changed | The constituent materials of the changed building envelope parts | |
| Architectural design element | Economic element | Social element | Environmental element |
| X1, X2, X3, X4 | X11, X12, X13, X14, X15 | X23, X24, X25 | X30, X31, X32 |
| X5, X6, X7 | X11, X12, X13, X16 | X18, X19, X20 | X26, X27, X28, X29 |
| X8, X9, X10 | X11, X12, X13, X16, X17 | X18, X21, X22 | |

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Fig.6. Algorithm of the BESMS
In Fig.6., the design team utilizes the opinions of the client and related experts in deciding the goal of improving energy efficiency of the building by modifying its envelope structure. Next, the team decides which parts of the envelope need to be modified to achieve the goal, then selects the materials to be used for the parts. After this, analytical results from precision energy analysis programs such as EnergyPlus are used to review whether the goal was achieved. This is followed by decisions made on whether the materials comprising the immediately-lower priority need to be modified; and if so, whether to proceed with the modification of the parts identified in the envelope. The BESMS is confirmed when this verification reveals the goal was either achieved or abandoned.

The Decision System algorithm was utilized in prioritizing for each process during the BESMS. That is, linguistic variable values and functions of the design factors that were input by the design team staff were defined as the five-stage linguistic variable values and trigonometrical functions. Linguistic variables (fuzzy numbers) of the design factors that were entered by each member of the design team were subjected to non-fuzzification and then converted into a single value for each design factor. Normal numbers were calculated based on the degree of importance between the single value for each design factor and the design factors that were turned into a database.

The numbers were then used as the basis for prioritization. The design team finalizes the prioritization and judges the satisfaction status.

5. Conclusion

The model of BESMS (Building-Envelope Structural Modification System) was developed to support the design team in achieving energy performance improvement at the schematic design stage. The results can be summarized as follows.

First, a five-step design process was established that allows the team to achieve the energy consumption reduction goal by varying the materials comprising each part of the envelope. This process was defined as the BEDP (Building-Envelope Design Process), which became the basis for creating the BESMS. Next, a four-module model was proposed using BIM-based design software programs as platforms. To decide the structure of the 'decision-making system' (the core area of the model), FLSs (AI technique) and AHP (decision-making method) were combined to create a decision-making system for design with four components. Based on these outcomes, the BESMS was then defined as having four components: input, decision-making system, output, and database. Next, an inference-deciding structure was established, related design factors were selected, and degree of importance was calculated for each decision-making item as requested by the BESMS. The results were used to create an algorithm for the BESMS.

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