Development of a Decision Support Tool for nZEB (nearly Zero Emission Building) at the Early Design Stage

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Abstract

Financial problems are one of the major causes for sluggishness in realizing sustainable buildings. There is a pervasive perception among investors that an increase in the initial investment cost for building environmental improvement is financially denting. From the perspective of a building's life cycle, building environmental improvement and economic effect have an integrated composition. This is because the building operating period is long and this results in huge operating costs. When "green premium" (initial investment cost increases with the use of technology necessary for sustainable buildings such as energy saving or CO\textsubscript{2} emissions reduction) is invested, a considerable decrease in operating cost is expected at the operation stage. As the oil price is continuously increasing and a carbon tax is very likely to be imposed, the effect of "green premium" is anticipated to a greater extent. In contrast, if there is no information on life cycle cost analysis at the initial design stage when deciding "green premium", the investment of stakeholders can hardly be expected. This is considered as the leading cause for failure to realize sustainable buildings throughout the world. In particular in Korea, analysis techniques and experts are considerably insufficient. Therefore, this paper proposes the development of a Decision Support Tool for evaluating the reduction effect of CO\textsubscript{2} emissions against the cost, which is available at the early design stage. For this, a program has been developed with a database after implementing a CO\textsubscript{2} emission evaluation module, life cycle cost evaluation module, and output module for cost-effectiveness.

Keywords: nearly Zero Emission Building; nZEB design process; decision support tool; early design stage

1. Introduction

1.1 Research Background and Purpose

The nearly Zero Emission Building (nZEB) design process may involve several alternative design options attributed to multiple combinations of cost, energy-saving potential and environmental performance. Therefore, in nZEB projects, questions such as: "What options are applicable to reduce building emissions now and in the future? How cost effective are these measures? What will be the return on investment? How much CO\textsubscript{2} will each alternative save?" will be considered in a different way by investors and nZEB designers. The investors are usually interested in a high financial return, whereas the nZEB designer prioritizes low CO\textsubscript{2} emission.

To answer these questions effectively, a decision support tool is required, which will be able to analyze the intervention measures in a cost-effective and CO\textsubscript{2} emission reducing design approach. However, most decision support tools that are available in Korea usually target CO\textsubscript{2} emission reduction without considering the cost-minimization factors. Hence, this paper presents a decision support tool to identify the most financially and environmentally promising investment strategy, given an initial financial resource constraint; and the range of potential strategies that balance cost, return-on investment, and CO\textsubscript{2} emission reduction: where both embodied and operational emissions are considered.

1.2 Research Method

This study aims to develop a best-value approach to emissions saving in buildings, taking into account CO\textsubscript{2} emissions (including operational and embodied emission) as well as cost. The structure of the paper is as follows. At first, the nZEB Design Process, including economic analysis, has been established and an algorithm of the decision support tool has been presented. Second, a reference building has been established from a survey of residential buildings in Seoul. Third, the database for calculating environmental performance (CO\textsubscript{2} emission) and economic performance (life cycle cost) was constructed using a survey of buildings in Seoul. Finally, four cases

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have been analyzed with decision support tools and the results have been discussed.

2. The nZEB Design Process and Framework for a Decision Support Tool Including an Economic One

2.1 The nZEB Design Process

The first step of the nZEB design process (Fig.1.) is to formulate a set of nZEB goals. These goals should be explicit and measurable. Once the goals are set, the design process naturally leads to the analysis of strategies for achieving the goals. In this step, the analysis method is crucial. Current methods to quantify parameters are considered in isolation when making decisions about energy conservation in buildings. In order to effectively manage financial cost with the reduction of life cycle CO$_2$ emission, it is necessary to link financial cost with CO$_2$ emission.

2.2 Framework for a Decision Support Tool Including an Economic One

The Life Cycle Analysis (LCA) method and Life Cycle Cost analysis (LCC) are generally used to compare various alternatives, with the goal of selecting the alternatives with the best economic performance. This Decision Support Tool depends not only on the technical metrics of each alternative, but on the financial and economic value system of the owners/decision-makers. Such values include the payback period, and available capital for the project.

The framework for the decision support tool is based on five modules (Fig.2.) that include: (i) a module for the computation of the reference building performance, which is used as the reference for subsequent calculations and analysis. (ii) A module that includes technically feasible operational low CO$_2$ emission intervention measures and computes their potential CO$_2$ emission reduction; (iii) a module that computes the embodied emissions related to each low carbon intervention measure; (iv) an economic evaluation module based on an appropriate investment appraisal technique that evaluates investment and operating cost estimates (v) an output module, which integrates the measures of financial cost, operational and embodied emissions into a multi-criteria decision making method and sequencing nZEB alternatives.

3. Database Construction for a Decision Support Tool

In this study, research is narrowed down to multi-residential buildings. The variations in the design and construction of multi-residential buildings in Korea are very small and limited relative to other building types. Therefore, once evaluation methods are established, they can easily be disseminated which will result in effective reduction of CO$_2$ emission.

To perform computation for all modules, a huge volume of database is required. Survey data of 56 multi-residential buildings (about 3,360 units) in Seoul is collected to formulate the database.

3.1 Reference Building Evaluation Module

This is a module for the computation of the reference building performance. This is primarily important because all of the subsequent calculations and analysis consider the model as a reference. Most multi-residential buildings in Korea, as seen in the figure, are of a basic module type consisting of 4 units, and 2 households share one elevator. Fig.3. shows a simplified model drawing constructed for simulation. Generally, most buildings face south, and the balcony is found on the north side. What stands out is that the northward balcony is used like an interior space. A brief description of the reference building is given in Table 1.

| Category | Reference Building |
|----------|--------------------|
| Plan     | Basic module type consisting of 4 units, 2 households share one elevator. |

Fig.1. The nZEB Design Process

Fig.2. The Framework for the Decision Support Tool

Fig.3. Plan and Section of Reference Building
A survey of 56 multi-residential buildings is analyzed with respect to energy consumption (embodied and operational energy) and water operational consumption to ascertain the CO₂ emission of the reference building. By correlation analysis with a database of energy and water consumption, multi-regression equation for each unit type is developed. Especially in terms of water usage, hot water usage is analyzed separately due to its nature of seasonal variation. Embodied energy is calculated by an EPD database with 12 major materials: structural material (reinforcing bar, remicron, pile, form); finish material (room carpet, tile, cement, glass); equipment material (XL pipeline, wire, illuminator, copper pipe). Life Cycle Cost comprises investment cost, energy cost and CO₂ emission cost. The investment cost is calculated through performance-based regression equation incorporating inflation rate (Table 2.). When the user selects a type of unit in this module, comprehensive performance of the baseline model is automatically calculated through equations and the database which is mentioned above (Fig.4.).

Table 2. Multi-Regression Equation for Reference Building Performance Calculation

| Category          | Calculation Model |
|-------------------|-------------------|
| Energy Embodied Energy | y = 14592 × e (0.0124 x) |
| Operation Energy Heating Energy | y = 72.15 + 7.2 Ln (x) - 33.13 |
|                     Cooling Energy | y = 16.16-13.2 Ln (x) + 60.86 |
|                     Lighting Energy | y = 6.85 x |
| Water Usage Winter (Nov–Mar) | y = 431.1 Ln (x) - 1278 |
|                     Summer (Jun–Sep) | y = 352.79 Ln (x/3.3) - 422.39 |
|                     Apr, May, Oct | y = 551.95 Ln (x/3.3) - 593.51 |
| Cost Investment Cost | y = 431.1 Ln (x) - 1278 |
| Operation Cost Energy consumption × Energy price × PWF |
| CO₂ Emission Cost CO₂ Emission × CO₂ Emission price × PWF |

3.2 Operational Emission Evaluation Module

This module includes technically feasible low carbon intervention measures and computes their potential CO₂ reduction of proposed buildings (alternatives) at the operation stage. Regression equation which is able to evaluate cooling and heating energy consumption is included in this module. This regression equation was drawn with the EnergyPlus simulation program and statistical analysis. The major variables included in the regression equation were selected based on the priority of the design variable, which has a large influence on the energy in a multi-residential building. The variables are numbers of stories, orientation, unit area, type of balcony, number of units per story, window/wall ratio (façade, rear), insulation performance of walls, infiltration quantity (location of the insulation), and window performance. The p-values are $R^2 = 0.845$ for heating energy consumption and $R^2 = 0.735$ for cooling energy consumption.

The database for operational water consumption is constructed using the grey water/rain water system and water saving equipment. Grey water is evaluated based on the rate of water contamination and the amount of sludge in service water. Finally, calculated energy and water consumption is converted to CO₂ emission at the same time. (Tables 3., 4. and 5.), (Fig.5.).

Table 3. Multi-Regression Equation and Database for Operation (Heating and Cooling) Energy Calculation

| Category          | Multi-regression Equation |
|-------------------|---------------------------|
| Heating Energy Consumption (Y) | Y = 9.90 + 5.94 X₁ + 0.29 X₂ - 0.16 X₃ + 0.08 |
|                     X₄ + 0.49 X₅ + 0.05 X₆ + 0.10 X₇ + 4.51 X₈ + 0.20 X₉ + 2.86 X₁₀ + 2.70 X₁₁ + 0.10 X₁₁ |
|                     : a, Location of the Insulation (Interior: 1, |
|                     Middle: 0, Exterior: -1) |
|                     X₁ : WWR (Façade) |
|                     X₃ : a, Balcony (A Type: 1, B Type: 0, C |
|                     Type: -1)* WWR (Façade) |
|                     X₄ : a, Balcony (A Type: 0, B Type: 1, C |
|                     Type: -1)* WWR (Façade) |
|                     X₅ : Unit Area |
|                     X₆ : Thickness of the Insulation |
|                     X₇ : Orientation |
|                     X₈ : U-value of the Window (Façade) |
|                     X₉ : WWR (Rear) |
|                     X₁₀ : a, # of the Units (Two: 1, Four: 0, Six: -1) |
|                     X₁₁ : U-value of the Window (Rear) |
| Cooling Energy Consumption (Y) | Y = 20.82 - 0.43 X₁ + 0.10 X₂ - 0.02 X₃ + 0.03 |
|                     X₄ - 0.05 X₅ + 0.65 X₆ + 2.30 X₇ - 0.37 X₈ |
|                     : a, Unit Area |
|                     X₂ : WWR (Façade) |
|                     X₃ : a, Balcony (A Type: 0 B Type: 1 C Type: |
|                     -1)* WWR (Façade) |
|                     X₄ : Orientation |
|                     X₅ : a, Balcony (A Type: 0 B Type: 1 C Type: |
|                     -1)* WWR (Façade) |
|                     X₆ : U-value of the Window (Façade) |
|                     X₇ : a, Balcony (A Type: 1 B Type: 0 C Type: |
|                     -1) |
|                     X₈ : Location of the Insulation |

Fig.4. Dataflow of Reference Building Evaluation Module
Table 4. Equations and Database for Operational Water Consumption Calculation

| Category                      | Equations                                                                 |
|-------------------------------|---------------------------------------------------------------------------|
| Estimation of Water Savings   | Sink = Demand × 0.20** × (B**/*C*** × 0.5**** |
|                               | Shower = Demand × 0.17 × (B/C) × 0.4                                      |
|                               | Toiletries = Demand × 0.11 × (B/C) × 0.5                                  |
|                               | Toilet = Demand × 0.27 × (B/C) × 0.4                                      |
|                               | *Ratio of total usage                                                     |
|                               | **B = Number of Water Saving Devices                                      |
|                               | ***C = Number of Total Water Faucets                                      |
|                               | ****Saving Ratio                                                          |
|                               | Water Consumption for Laundry is excluded.                                 |

Table 5. Database for CO₂ Emission Factor

| Energy Type | Energy unit | TOE | Carbon Emission Factor | CO₂ Emissions Conversion Factor | TCO₂ | CO₂ Emission Right Price (Won/ton) | Unit CO₂ Emissions Charge (Won/Unit) |
|-------------|-------------|-----|------------------------|---------------------------------|------|-----------------------------------|---------------------------------|
| Gas         | tor         | 44  | 0.421                  | 0.00424                         | 35.577.33 | 38.577.33                           |

* TOE = caloric value/ton of crude oil = 10 Kcal
* In case of CO₂ emission calculation
  - Recommended standard of IPCC - Net caloric value applied
  - TOE = Energy Consumption × NetCaloric Value/10
  - TC = TOE × Carbon Emission Factors (IPCC Factors)
  - TCO₂ = TC × CO₂ Conversion Factors (44/12)
  - CO₂ Emission Trading Price (base date 2008.5.1)
  - EUA (European E (1,558.68 Won)
  - Environment pollution charge
  - Energy Consumption × Unit Environment pollution charge

Table 6. EPD Database (Partial)

| Cod  | Basic Flow | Contents       | Unit CO₂ Emission (kg-CO₂/Unit) |
|------|------------|----------------|---------------------------------|
| 0039 | ****       | Sand & Gravel  | -                               |
| 0039 | 0100       | Sand           | m³ 5.3322633                    |
| 0039 | 0200       | Gravel         | m³ 5.15683300                   |
| 0040 | ****       | Stone          | kg 0.19858101                   |
| 0041 | 0100       | Granite        | kg 0.41059888                   |
| 0041 | 0200       | Marble         | kg 0.97840753                   |
| 0041 | 8800       | Etc.           | kg 0.39611447                   |
| 0042 | ****       | Limestone      | kg 0.03582183                   |
| 0042 | 0100       | Limestone      | kg 0.04578367                   |
| 0042 | 8800       | Etc.           | kg 1.33169105                   |

Fig. 6. Dataflow of Embodied Emission Evaluation Module

3.3 Embodied Emission Evaluation Module

This module computes the embodied emissions related to each low carbon intervention measure. Embodied CO₂ emission was calculated by EPD (Environmental Product Declaration). The EPD Database consists of the most frequently used common material which is analyzed integrally among 3 materials on work type, and materials which represent a large part of the environmental load by 2003’s input-output table of the Bank of Korea[7]. Below, Table 6. is a typical EPD database which is used for evaluation (Fig.6.).

3.4 Economic Evaluation Module

The economic evaluation module evaluates investment and operating cost utilizing the appropriate investment appraisal technique. Investment cost is calculated by regression equation, which is made based on the construction cost database with inflation rate. The additional cost incurred by sustainable strategies is applied after calculating the reference building. The generated subsidy by installing a renewable energy system is also applied to the corresponding system. Operation cost is classified as energy cost, water cost and waste cost (Table 7.). To calculate the operation cost, the PWF (present worth factor) used in energy cost reflects the inflation rate (average rate of rise for 10 years) and the trend of energy cost fluctuation (indexation of production cost for the electricity, indexation of production cost for the city gas, and increase rate of the international oil price). Currently CO₂ emission cost is not applied in Korea but carbon taxation has already been considered in Europe and Australia recently. From this point of view, calculated CO₂ emission cost is included because it is assumed that it will be applied in Korea soon. In this calculation, the carbon emission value is used in the emission trading market of the EUA (Fig.7.).
The output module integrates the measures of financial cost, operational and embodied emissions into a multi-criteria decision-making method and sequencing nZEB alternatives. It is necessary to output the integrated result of the environment and economy for the Decision Support Tool to help the effective decision making process at the early design stage. However, as economics and the environment have different performance and units, the linear scale transformation method is used for this integration.

The linear scale transformation method was used to normalize different MADM methods. Of all linear transformation methods, complex-linear transformation was used to transform values to based maximum value and minimum attribute. A subset of the attributes transformed to values between 0 and 1. Therefore, the value with the best performance is transformed to 1 while that of the reference building has the minimum value of 0. The following shows an equation of the complex linear scale transformation that is changed to correspond to the evaluation instrument (Fig.6.).

For example, when $E_j$ denotes environmental load impact, the maximum value of $E_j$ means the greatest decrease in environmental footprints. $E_j$ is the environmental performance value for an alternative value $j$. $E_{min}$ is the minimum value of $E_j$ and $E_{max}$ is the maximum value of $E_j$ in a standard model. Normalization of environmental performance using complex-linear transformation is shown as the following Equation 1.

$$\text{Env} = \frac{E_{env} - E_{env_{min}}}{E_{env_{max}} - E_{env_{min}}} \quad \text{Equation 1.}$$

Through normalization, values between 0 and 1 were obtained as the outcome value of each performance criterion transformed to dimensionless scores. Where, 0 denotes the reference building and 1 denotes the target building with maximum performance. A normalized score drawn from each criterion can be presented as a specific point in multi-dimensional space, where each dimension (quadrant) represents performance criteria.

### 4. Development of Decision Support Tool

The Decision Support Tool has been developed by an excel based program. Thus, the program can be executed by a very simple process. Each module is divided into a separate excel sheet and consists of a Reference Building Module, Operational CO2 Emission Module, Embodied CO2 Emission Module, Life Cycle Cost Analysis Module and Output module.

The tool is delineated through the following Fig.8. The sheet consists of a user input column (white column), result column of the proposed building performance (green column), result column of the reference building performance (black column). If the user inputs the value, the results of the performances appear immediately. It is more advanced than conventional assessment tools that can only produce output after total evaluation and is useful to compare with the reference building and confirm the effect of selected strategies at the early design stage.

An overall comparison of the alternatives is available to confirm the output module after input is completed. The output module demonstrates the reduction effect of CO2 emission and cost increase in contrast with the reference building in a non-dimensional unit (Fig.9.). As the output is visual, it is very easy to compare the output.
alternatives. Also, the module provides the output of CO₂ emission reduction and the result of life cycle cost separately to ascertain the performance according to the user's interest.

5. Case Study

For verification, a multi-residential building with 100 households (85m² each) is selected as a reference (Table 8.). Four case buildings, to which less energy consuming sustainable technology was applied, were selected for the evaluation. The design goal assumed a 10% increase in initial investment cost and 30% reduction in CO₂ emission compared with the reference building.

According to the evaluation result, GH40 shows that CO₂ emissions can be reduced by 40% for a 10% increase in initial investment cost. Thus, it is considered that the design goal could be achieved when insulation windows and an insulation system are installed at the design stage and the volume of the renewable energy system is limited to 17% of energy consumption to save cost. Model 2 (GH60) can be applied if an alternative is necessary which has the lowest life cycle cost during the decision making process (Table 9.).

6. Conclusion

A lot of alternative design options having different environmental and economical implications are made during the early design stage of nZEB and comparing the alternatives requires a decision support tool that helps judge their respective performance clearly and suggests a design direction. In particular, designing without evaluating economic feasibility at the initial decision making process may lead to an unexpectedly huge increase in initial investment or it may be easy to give up on nZEB performance in the face of the owner's opposition. However, Korea does not have a tool that outputs a comprehensive result through the evaluation of economic feasibility.
Therefore, the study developed a Decision Support Tool that helps comprehensive evaluation and a comparison of environmental and economic implications for effective decision-making in the early design stage. It is considered that this tool can improve the realization and spread of nZEB, as using it helps draw evaluation results quickly and simply and compares comprehensive evaluation results regarding design alternatives.

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