Cost Efficiency Analysis of Design Variables for Energy-efficient Apartment Complexes

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Abstract
Energy-efficient buildings are essential to reduce greenhouse gas emissions. However, improved energy efficiency may also bring about a rise in construction costs. If design variables can be prioritized according to their cost efficiencies, energy-efficient buildings can be designed more cost-efficiently. The aim of this study is to analyze the cost efficiencies of design variables related to energy efficiency of the apartment complex. After making 78 alternatives for 29 target items, each alternative's increased amount of construction cost and decreased amount of energy cost against the baseline model were then estimated using actual price data and the assessment methods of the Building Energy Efficiency Rating System that has been implemented in Korea, respectively. The life cycle cost, net present value, internal rate of return, and payback period of each alternative were shown as cost efficiency indexes. The order of priority of each alternative was presented and very cost-efficient alternatives were suggested.

Keywords: energy efficiency; cost efficiency; Building Energy Efficiency Rating System; apartment complex

1. Introduction
With the implementation of the Kyoto Protocol, many countries have endeavored to reduce greenhouse gas emissions, which are mainly caused by energy consumption, in various fields of industry. In Korea, the building sector accounts for over 24% of the total national energy consumption, and about 68% of the energy consumption in the building sector comes from residential use1). This situation is not considered to be very different from those of other countries. Consequently, energy-efficient residential buildings can play a key role in reducing greenhouse gas emissions and further solving environmental problems caused by the use of fossil fuels.

The energy efficiency of residential buildings has been enhanced by various systems or projects, such as the Home Energy Rating System (HERS), the Energy Star-Home, and the LEED for Homes of the USA, the R-2000 of Canada, the Standard Assessment Procedure (SAP) and the Code for Sustainable Homes of the UK, the Nationwide House Energy Rating Scheme (NatHERS) of Australia, the Passive House of European countries, and so on. In Korea, the Building Energy Efficiency Rating System (hereafter referred to as the BEERS) has been in force since 2001 as an attempt to improve the energy efficiency of apartment complexes, which are the most common type of residence.

Improved energy efficiency may also bring about a rise in construction costs. If design variables can be prioritized according to their cost efficiencies, energy-efficient apartment complex can be designed more cost-efficiently. Thus, the aim of this study is to analyze the cost efficiencies of design variables related to energy efficiency of the apartment complex by using the assessment method of the BEERS.

The baseline model was made, based on a recently completed apartment complex that is regarded as a common type. Among all the assessment items in the BEERS, the items suitable for cost efficiency analysis were selected as target items. The overall performance range of each target item was determined, and the lowest limit value was set at the value of the baseline model. The highest limit value was set at the values that reflect the BEERS Management Regulations or the envelope insulation level of the Passive House. Alternatives were then prepared whose performance values varied stepwise between the lowest and highest limit values for each target item. After selecting actual systems that could meet the performance values of alternatives, an estimate was made of each alternative's increased amount of construction cost and decreased amount of energy cost against the baseline model using actual price data and the assessment methods of the BEERS. The life cycle cost, net present value, internal rate of return, and payback period of each alternative were obtained as cost efficiency indexes, and then orders of priority were given to all the alternatives.

2. BEERS and Passive House
2.1 BEERS
The BEERS has been implemented by the Ministry of Knowledge Economy (MKE) and is managed by the Korea Energy Management Corporation. The codes related to the BEERS are: the Building Energy Efficiency Rating Regulations (MKE, Notification No. 2008-14); the Guidelines on the Funding of Energy Use Rationalization Work (MKE, Announcement No. 2008-14); and the
BEERS Management Regulations.

An apartment complex with more than 18 units is eligible to voluntarily apply for certification. Energy efficiency of the assessed apartment complex is determined by its energy demand reduction rate relative to the standard apartment complex, and it is graded from one to three as presented in Table 1. If the assessed apartment complex receives the first or second grades, financial incentives are given to builders, such as loans at a very low interest rate, etc. The standard apartment complex acts as a criterion for determining the energy efficiency grade of the assessed apartment complex, and it represents a hypothetical apartment complex with the typical level of energy efficiency. It is almost identical to the assessed apartment complex (e.g., shape, size, structure, floor height, ceiling height, energy source, heating plant type, and so on) except that assessment items have values mandated by the current building codes.

The energy demand reduction rate relative to the standard apartment complex is calculated by using Eqs. (1) through (7). In Eqs. (1) and (2), the heating load of each unit in both assessed and standard apartment complexes \( (HLC_{\text{unit}} \text{ and } HLC_{\text{unit, std}} \text{ in Eqs. (1) and (2)}) \) by using the heat losses of heated and unheated spaces from envelopes and ventilations and the heat loss of heated space from regions facing the unheated space.

Step 2: Calculate the heating degree-day of a unit \( (HDD_{\text{unit}} \text{ and } HDD_{\text{unit, std}} \text{ in Eqs. (1) and (2)}) \) in accordance with the balance point temperature that is obtained by using the heat loss coefficient and the internal and solar heat gains of heated and unheated spaces.

Step 3: Calculate the heating load of a unit \( (HL_{\text{unit}} \text{ and } HL_{\text{unit, std}} \text{ in Eqs. (1) and (2)}) \) using the heat loss coefficient and the heating degree-day. Then, calculate the heating energy demand of a unit \( (HED_{\text{unit}} \text{ and } HED_{\text{unit, std}} \text{ in Eqs. (3) and (4)}) \) by using the heating load, the boiler efficiency, the pipe loss coefficient, and the boiler load loss coefficient.

Step 4: Repeat steps one through three for all the units in both assessed and standard apartment complexes.

Step 5: Calculate the energy demand reduction rate of a unit in the assessed apartment complex \( (RED_{\text{unit}}) \) by using the heating energy demand of each unit in both assessed and standard apartment complexes. Also, include the sum of energy demand reduction rates of extra items for a unit \( (RED_{\text{unit, extra}}) \) in the calculation methods used to determine the energy demand reduction rate of the assessed apartment complex relative to the standard apartment complex, which is described in the BEERS Management Regulations.

Step 6: Calculate the energy demand reduction rate of a building in the assessed apartment complex \( (RED_{\text{bldg}}) \) by using the sum of each unit’s energy demand reduction rate and the sum of energy demand reduction rates of extra items for a building \( (RED_{\text{bldg, extra}}) \) applied to the assessed apartment complex, as shown in Eq. (5).

Step 7: Calculate the energy demand reduction rate of the assessed apartment complex \( (RED_{\text{cplx}}) \) by using the sum of each building’s energy demand reduction rate, as shown in Eq. (7).

Extra items for a unit and a building and their energy demand reduction rates are prescribed in the BEERS Management Regulations. If extra items are applied to the assessed apartment complex, their corresponding energy demand reduction rates are added, as shown in Eqs. (5) and (6).

The energy demand and the energy cost of the assessed apartment complex can be obtained by extending the calculation methods used in the BEERS. The heating energy demand of the standard apartment complex \( (HED_{\text{cplx, std}}) \) is the sum of the heating energy demands of all the units in the standard apartment complex \( (HED_{\text{unit, std}}) \), as shown in Eq. (8). The heating energy cost of the standard apartment complex \( (HEC_{\text{cplx, std}}) \) can be obtained by multiplying the heating energy demand of the standard apartment complex \( (HED_{\text{cplx, std}}) \) by the heating energy rate \( (HER) \), as shown in Eq. (9). The energy demand and the energy cost of the assessed apartment complex \( (ED_{\text{cplx}} \text{ and } EC_{\text{cplx}}) \) can be obtained by using the heating energy demand and the heating energy cost of the standard apartment complex \( (HED_{\text{cplx, std}} \text{ and } HEC_{\text{cplx, std}}) \) and the energy demand reduction rate of the assessed apartment complex \( (RED_{\text{cplx}}) \), as shown in Eqs. (10) and (11), respectively. Then, calculate the energy demand reduction rate of the assessed apartment complex \( (RED_{\text{cplx}}) \) includes

\[
HLC_{\text{unit}} = 8.64 \times 10^{-5} \times HLC_{\text{net}} \times HDD_{\text{net}}
\]

\[
HLD_{\text{unit, std}} = 8.64 \times 10^{-5} \times HLC_{\text{net, std}} \times HDD_{\text{net, std}}
\]

\[
HED_{\text{unit}} = \frac{HL_{\text{unit}}}{E_{\text{boiler}}} \times L_{\text{pipe}} \times L_{\text{boiler}}
\]

\[
HED_{\text{unit, std}} = \frac{HL_{\text{unit, std}}}{E_{\text{boiler}}} \times L_{\text{pipe}} \times L_{\text{boiler}}
\]

\[
RED_{\text{unit}} = \frac{HED_{\text{unit}}}{HED_{\text{unit, std}}} - \frac{HED_{\text{unit, std}}}{HED_{\text{unit, std}}} \times 100 + \sum RED_{\text{unit, extra}}
\]

\[
RED_{\text{bldg}} = \frac{\sum (RED_{\text{unit}} \times A_{\text{bldg}})}{A_{\text{bldg}}} + \sum RED_{\text{bldg, extra}}
\]

\[
RED_{\text{cplx}} = \frac{\sum (RED_{\text{bldg}} \times A_{\text{cplx}})}{A_{\text{cplx}}}
\]

\[
HED_{\text{cplx, std}} = \sum HED_{\text{unit, std}}
\]

\[
HEC_{\text{cplx, std}} = HED_{\text{cplx, std}} \times HER
\]

\[
ED_{\text{cplx}} = HED_{\text{cplx, std}} \times \frac{100 - RED_{\text{cplx}}}{100}
\]

\[
EC_{\text{cplx}} = HEC_{\text{cplx, std}} \times \frac{100 - RED_{\text{cplx}}}{100}
\]

Table 1. Certification Grades of the BEERS

| Grade | Energy demand reduction rate relative to the standard apartment complex (%) |
|-------|---------------------------------------------------------------|
| 1     | 33.5 or higher                                               |
| 2     | 23.5–33.5                                                   |
| 3     | 13.5–23.5                                                   |
the energy demand reduction rates of extra items, covering not only heating but also domestic hot water, electric power, lighting, control, and others. The BEERS uses the terms of heating energy and energy separately for this reason.

2.2 Passive House

The Passive House refers to construction projects for very energy-efficient residential buildings, such as those initiated in European countries including Germany, Sweden, Austria, Switzerland, France, and so on. The Passive House minimizes the heating load by using passive means such as super insulation, heat recovery, passive gain, and so on. It has a limited heating load of 15 kWh/m²/year, and this value is reported to be less than one fifth of the heating load mandated by the building codes currently in force in the participating countries. In addition, energy demand is limited at 120 kWh/m²/year for heating, domestic hot water, and electric appliances. The Promotion of European Passive Houses project team provides technical solutions and performance value range of each solution to achieve the Passive House level.

3. Baseline Model, Target Items, and Alternatives for Cost Efficiency Analysis

3.1 Outlines of the studied apartment complex and the baseline model

The apartment complex "A", recently completed in Seoul, was selected for this study. This complex consists of fourteen buildings where each unit’s floor area for private use varies from 85 m² to 273 m². In Korea, national housing, which originates from the policy to relieve the housing shortage, is defined in the Housing Act and its construction is encouraged. It can be regarded as the most common and normal housing for ordinary people, and its floor area for private use should be 85 m² or below. Considering that it may be appropriate to give precedence to the national housing size, it is assumed that every unit’s floor area for private use is 85 m², while the gross floor area of the apartment complex is maintained.

The results of analyzing actual and modified apartment complexes are considered to show few differences because construction and energy costs of an apartment complex are mainly influenced by the gross floor area. Table 2. shows the outline of the studied apartment complex.

A building having only 85 m² units was selected among all the buildings in the studied apartment complex. This building has two stair halls, nineteen floors, and four units per floor. There is a pilot at the right corner of the ground floor, so this building has 75 units. The baseline model is assumed to be an apartment complex composed only of replicates of this building. Table 3. shows the outline of the building composing the baseline model.

3.2 Target items

The assessment items of the BEERS consist of basic and extra items. Basic items are used to calculate the heating energy demand of each unit in both assessed and standard apartment complexes (HEDunit and HEDunit_std in Eqs. (3) and (4)). Extra items are used to calculate the extra energy demand reduction rates (REDunit_extra and REDunit_extra in Eqs. (5) and (6)). Among all the assessment items, the items that are suitable for cost efficiency analysis and whose performance values are changeable in the baseline model were selected as target items. Ventilation rate was not included in target items because the BEERS allows only 0.7 ACH as a ventilation rate, based on the national code. The target items are presented in Table 4.

\[ \frac{1}{U_{eff}} = \frac{1}{U_1} + \frac{1}{U_2} \times \frac{1}{2} \] (12)

According to the BEERS Management Regulations, a balcony is regarded as outside space even if windows are installed. If windows are installed for the balcony, effective U-values are used for the U-values of heated space windows (Item 2 in Table 4.), doors, and other openings (Item 3 in Table 4.) in order to reflect the U-values of balcony windows, as presented in Eq. (12). In this study, balcony windows are assumed to be installed in all the units, and they are included as one of the target items (Item 1 in Table 4.).

3.3 Alternatives for target items and actual systems for alternatives

The overall performance range of each target item was determined. For basic items, the lowest limit values were

Table 2. Outline of the Studied Apartment Complex

| Item | Content |
|------|---------|
| Location | Seoul, Korea |
| Gross floor area | 192,452.0 m² (residence: 140,325.6 m², car park: 52,126.4 m²) |
| Number of units | Actual: 885 units, modified: 1,263 units |
| Gross floor area for private use | Actual: 113,081.1 m² |
| Heating plant | District heating |

Table 3. Outline of the Building Composing the Baseline Model

| Item | Content |
|------|---------|
| Gross floor area for private use | 8,329.6 m² |
| Gross floor area for the floor area for private use: 84.9 m²² |
| Floor height | Top and ground floors: 3.0 m, typical floors: 2.9 m |
| Insulation | Wall: 65 mm, side wall: 90 mm, roof: 110 mm, ground floor: 50 mm |
| Window glass | 16 mm double glazing (5CL+6Air+5CL) |
| Orientation | South |
| Inside temperature | 20°C for heated space |
| Internal heat gain* | Electricity : 307.5 W/unit, Occupant : 147.5 W/unit |

* This value is prescribed in the BEERS according to the unit’s floor area for private use.

Fig.1. Floor Plan of the Unit (85 m² Type)
Table 4. Target Items for Cost Efficiency Analysis

| Item no. | Type       | Items                                                                 |
|----------|------------|----------------------------------------------------------------------|
| 1        | Basic      | U-values of balcony windows (W/m²K)                                   |
| 2        | Basic      | U-values of heated space windows (W/m²K)                              |
| 3        | Basic      | U-values of heated space doors and other openings (W/m²K)             |
| 4-1      | Basic      | U-values of heated space walls in the front facing the outside (W/m²K) |
| 4-2      | Basic      | U-values of heated space walls in the back facing the outside (W/m²K)  |
| 4-3      | Basic      | U-values of heated space side walls in the front and back facing the outside (W/m²K) |
| 4-4      | Basic      | U-values of heated space walls in the side facing the outside (W/m²K)  |
| 5        | Basic      | U-values of heated space roofs (W/m²K)                               |
| 6-1      | Basic      | U-values of heated space ground floors facing the outside (W/m²K)      |
| 6-2      | Basic      | U-values of heated space ground floors facing the unheated space (W/m²K) |
| 7-1      | Basic      | U-values of heated space walls facing the unheated space (W/m²K)       |
| 7-2      | Basic      | U-values of heated space doors facing the unheated space (W/m²K)       |
| 8        | Extra      | Installation of thermostat per each room or zone Electric circuit configuration that enables the living room's main power outlet to be conveniently broken or installation of certified energy-efficient electric appliances |
| 9        | Extra      | Placement of windbreak space or structure at the building entrance Average efficiency of pumps for heating water, domestic hot water, service water, etc. (%) |
| 10       | Extra      | Equipment, pipes and ducts insulation                                |
| 11       | Extra      | Energy-efficient control systems of heating water pumps such as inverter control system, etc. Energy-efficient control systems of ventilation fans for underground car park |
| 12       | Extra      | Automatic control systems using computers, networking or internet     |
| 13       | Extra      | High efficiency induction motors (installation rate, %)               |
| 14       | Extra      | Voltage drop of main power line (%)                                   |
| 15       | Extra      | Bank configuration that enables to control the number of transformers in operation |
| 16       | Extra      | Peak demand control systems of electric power                         |
| 17       | Extra      | Automatic control systems of equipments for receiving and transforming electricity |
| 18       | Extra      | High intensity discharge lamps and automatic control systems of the outside lighting |
| 19       | Extra      | Energy-efficient control systems of service water pumps such as inverter control system, etc. |
| 20       | Extra      | Automatic power factor adjustment equipments of power condensers installed in a group Decentralized control systems with open protocol that enables data exchange and concentrated control for various equipments |
| 21       | Extra      | Extra items for a unit                                                |
| 22       | Extra      | Extra items for a building                                            |

* Allowed number of performance values is just two (baseline model and Alt. 1). A unit in the baseline model has three doors facing the outside. Two of them are PVC and one is steel.

* A building in the baseline model has three units and a pilot at the ground floor. These three units face the unheated space (underground car park), and one unit above the pilot faces the outside.

* Allowed number of performance values is just two (baseline model and Alt. 1).

* Performance values are prescribed in the BEERS Management Regulations. Performance values of the baseline model correspond to "not applied" because each $RED_{N_{i, t, x, x}}$ in Eq. (6) is zero.

** Cost Efficiency Analysis**

Every alternative's cost efficiency was analyzed using both the increased amount of construction cost and the decreased amount of energy cost against the baseline model. Maintenance costs (e.g., repair cost or replacement cost) of the baseline model and the alternatives for the same target item were assumed to be equal, and thus these costs were not considered. Each alternative's cost efficiency was analyzed by applying it to the baseline model one by one.


Table 6. Applied Systems for Alternatives of Basic Target Items

| Item no. | Alt. no. | Applied system |
|----------|----------|----------------|
| 1, 2     | Baseline | PVC frame, double glazing, air 6 mm |
| Alt. 1   | PVC frame, double glazing, air 6 mm |
| Alt. 2   | PVC frame, double glazing, argon 12 mm |
| Alt. 3   | PVC frame, low-e double glazing, argon 6 mm |
| Alt. 4   | PVC frame, low-e double glazing, air 12 mm |
| Alt. 5   | PVC frame, low-e double glazing, argon 12 mm |
| 3        | Baseline | PVC door: insulation thickness below 20 mm, Steel door with thermal breaker: insulation thickness below 20 mm |
| Alt. 1   | PVC door: insulation thickness 20 mm or higher, Steel door with thermal breaker: insulation thickness 20 mm or higher |
| 4-1      | Baseline | 65 mm thick polystyrene insulation (A type) |
| Alt. 1   | 85 mm thick polystyrene insulation (B type) |
| Alt. 2   | 105 mm thick polystyrene insulation (B type) |
| Alt. 3   | 135 mm thick polystyrene insulation (B type) |
| Alt. 4   | 185 mm thick polystyrene insulation (B type) |
| 4-3      | Baseline | 90 mm (wall1) and 65 mm (wall2) thick polystyrene insulation (A type) |
| Alt. 1   | 110 mm (wall1) and 85 mm (wall2) thick polystyrene insulation (B type) |
| Alt. 2   | 130 mm (wall1) and 105 mm (wall2) thick polystyrene insulation (B type) |
| Alt. 3   | 160 mm (wall1) and 135 mm (wall2) thick polystyrene insulation (B type) |
| Alt. 4   | 210 mm (wall1) and 185 mm (wall2) thick polystyrene insulation (B type) |
| 4-4      | Baseline | 90 mm thick polystyrene insulation (A type) |
| Alt. 1   | 90 mm thick polystyrene insulation (B type) |
| Alt. 2   | 100 mm thick polystyrene insulation (B type) |
| Alt. 3   | 120 mm thick polystyrene insulation (B type) |
| Alt. 4   | 150 mm thick polystyrene insulation (B type) |
| Alt. 5   | 190 mm thick polystyrene insulation (B type) |
| 5        | Baseline | 80 mm (inside) and 30 mm (outside) thick polystyrene insulation (B type) |
| Alt. 1   | 80 mm (inside) and 30 mm (outside) thick polystyrene insulation (B type) |
| Alt. 2   | 80 mm (inside) and 40 mm (outside) thick polystyrene insulation (B type) |
| Alt. 3   | 80 mm (inside) and 60 mm (outside) thick polystyrene insulation (B type) |
| Alt. 4   | 80 mm (inside) and 80 mm (outside) thick polystyrene insulation (B type) |
| Alt. 5   | 80 mm (inside) and 110 mm (outside) thick polystyrene insulation (B type) |
| 6-1      | Baseline | 50 mm (inside) and 50 mm (outside, B type) thick polystyrene insulation |
| Alt. 1   | 50 mm (inside) and 50 mm (outside) thick polystyrene insulation (B type) |
| Alt. 2   | 50 mm (inside) and 70 mm (outside) thick polystyrene insulation (B type) |
| Alt. 3   | 50 mm (inside) and 80 mm (outside) thick polystyrene insulation (B type) |
| Alt. 4   | 50 mm (inside) and 100 mm (outside) thick polystyrene insulation (B type) |
| Alt. 5   | 50 mm (inside) and 130 mm (outside) thick polystyrene insulation (B type) |
| 6-2      | Baseline | 50 mm thick polystyrene insulation (A type) |
| Alt. 1   | 50 mm thick polystyrene insulation (B type) |
| Alt. 2   | 70 mm thick polystyrene insulation (B type) |
| Alt. 3   | 90 mm thick polystyrene insulation (B type) |
| Alt. 4   | 120 mm thick polystyrene insulation (B type) |
| Alt. 5   | 180 mm thick polystyrene insulation (B type) |
| 7-1      | Baseline | 45 mm thick polystyrene insulation (A type) |
| Alt. 1   | 55 mm thick polystyrene insulation (B type) |
| Alt. 2   | 75 mm thick polystyrene insulation (B type) |
| Alt. 3   | 115 mm thick polystyrene insulation (B type) |
| Alt. 4   | 185 mm thick polystyrene insulation (B type) |
| 7-2      | Baseline | Steel door with thermal breaker, insulation thickness below 20 mm |
| Alt. 1   | Steel door with thermal breaker, insulation thickness 20 mm or higher |

A and B types refer to the insulation of which thermal conductivities are 0.035–0.040 W/mK and 0.034 W/mK or below, respectively.

Table 7. Applied Systems for Alternatives of Extra Target Items

| Item no. | Alt. no. | Applied system |
|----------|----------|----------------|
| 8        | Baseline | No thermostat, manual control of heating water distributor |
| Alt. 1   | Three thermostats, motorized valve system of heating water distributor |
| 9        | Baseline | No separated electric circuit for living room's main power outlet and the others |
| Alt. 1   | Separated independent electric circuit for living room's main power outlet |
| 10       | Baseline | No windbreak space or structure at the building entrance |
| Alt. 1   | Windbreak space with a double door system at the building entrance |
| 11       | Baseline | Basic motors for four heating water line-type pumps, four domestic hot water line-type pumps, and four service water booster pumps |
| Alt. 1   | High efficiency motor for one domestic hot water line-type pump of 1.5 kW |
| Alt. 2   | High efficiency motors for one domestic hot water line-type pump of 1.5 kW and one service water booster pump of 33 kW |
| Alt. 3   | High efficiency motors for one domestic hot water line-type pump of 1.5 kW and two service water booster pumps of 33 kW |
| Alt. 4   | High efficiency motors for two heating water line-type pumps of 5.5 kW and 7.5 kW, one domestic hot water line-type pump of 1.5 kW, and three service water booster pumps of 22.5 kW and 33 kW (2ea.) |
| 12       | Baseline | Insulation in accordance with the code |
| Alt. 1   | Insulation exceeding 20% of the code |
| 13       | Baseline | Local control panel |
| Alt. 1   | DDC panel |
| 14       | Baseline | Local control panel |
| Alt. 1   | Local control panel, CO sensor, and controller |
| 15       | Baseline | Local control panel |
| Alt. 1   | DDC panel using computer |
| 16       | Baseline | Basic motors for every fan, four heating water line-type pumps, four domestic hot water line-type pumps, and four service water booster pumps |
| Alt. 1   | High efficiency motors for every fan, one heating water line-type pump of 7.5 kW, and one service water booster pump of 33 kW |
| Alt. 2   | High efficiency motors for every fan, three heating water line-type pumps of 5.5 kW (2ea.) and 7.5 kW, and one service water booster pumps of 33 kW |
| Alt. 3   | High efficiency motors for every fan, four heating water line-type pumps of 5.5 kW (3ea.) and 7.5 kW, four domestic hot water line-type pumps of 1.5 kW and 2.2 kW (3ea.), and one service water booster pump of 33 kW |
| Alt. 4   | High efficiency motors for every fan, four heating water line-type pumps of 5.5 kW (3ea.) and 7.5 kW, four domestic hot water line-type pumps of 1.5 kW and 2.2 kW (3ea.), and two service water booster pumps of 22.5 kW and 33 kW |
| 17       | Baseline | After estimating the construction costs of baseline model and Alt. 4, the construction costs of Alt. 1–3 are estimated by the linear interpolation. Voltage drop rate is inversely proportional to the cross-sectional area of the cable. F-CV cable: 95 mm², 2,600 m (baseline and Alt. 4), 185 mm², 9,034 m (baseline) and 4,517 m (Alt. 4), 240 mm², 6,905 m (baseline) and 13,390 m (Alt. 4), 300 mm², 14,715 m (baseline) and 33,947 m (Alt. 4), and 400 mm², 460m (baseline and Alt. 4) |
| 18       | Baseline | FR-8 cable: 150 mm², 15,433 m (baseline and Alt. 4) |
| 19       | Baseline | Bank configuration in accordance with the load zone (total 4 banks) |
| Alt. 1   | Bank configuration that enables to control the number of transformers in operation (total 5 banks) |
| 19       | Baseline | Manual control system |
| Alt. 1   | Automatic peak demand control system |
| 20       | Baseline | Automatic control system including digital unit |
| 21       | Baseline | High intensity discharge lamps, single electric circuit, and manual on/off control system |
| Alt. 1   | High intensity discharge lamps, dual electric circuits, and timer control system |
| 22       | Baseline | System to control the number of service water booster pumps in operation |
| Alt. 1   | Inverter control system for the service water booster pumps |
| 23       | Baseline | Power condensers with the same capacity |
| Alt. 1   | Automatic power factor adjustment system of 4 banks size to control the power condenser's capacity in accordance with the load conditions |
| 24       | Baseline | Basic centralized control system with open protocol decentralized control system with open protocol that enables data exchange and concentrated control for mechanical and electrical equipments |
Table 8. Cost Efficiency Analysis Results for Alternatives

| Item | Baseline | Alt. 1 | Alt. 2 | Alt. 3 | Alt. 4 | Alt. 5 | Alt. 6 | Alt. 7 | Alt. 8 | Alt. 9 | Alt. 10 |
|------|----------|--------|--------|--------|--------|--------|--------|--------|--------|--------|---------|
| CC   | 100.0    | 100.0  | 100.0  | 100.0  | 100.0  | 100.0  | 100.0  | 100.0  | 100.0  | 100.0  | 100.0   |
| ΔCC  | 0.0      | 0.0    | 0.0    | 0.0    | 0.0    | 0.0    | 0.0    | 0.0    | 0.0    | 0.0    | 0.0     |
| RED  | 0.0      | 0.0    | 0.0    | 0.0    | 0.0    | 0.0    | 0.0    | 0.0    | 0.0    | 0.0    | 0.0     |
| ΔRED | 0.0      | 0.0    | 0.0    | 0.0    | 0.0    | 0.0    | 0.0    | 0.0    | 0.0    | 0.0    | 0.0     |
| EC   | 0.0      | 0.0    | 0.0    | 0.0    | 0.0    | 0.0    | 0.0    | 0.0    | 0.0    | 0.0    | 0.0     |
| ΔEC  | 0.0      | 0.0    | 0.0    | 0.0    | 0.0    | 0.0    | 0.0    | 0.0    | 0.0    | 0.0    | 0.0     |
| LCC  | 0.0      | 0.0    | 0.0    | 0.0    | 0.0    | 0.0    | 0.0    | 0.0    | 0.0    | 0.0    | 0.0     |
| ΔLCC | 0.0      | 0.0    | 0.0    | 0.0    | 0.0    | 0.0    | 0.0    | 0.0    | 0.0    | 0.0    | 0.0     |
| NPV  | 0.0      | 0.0    | 0.0    | 0.0    | 0.0    | 0.0    | 0.0    | 0.0    | 0.0    | 0.0    | 0.0     |
| IRR  | 0.0      | 0.0    | 0.0    | 0.0    | 0.0    | 0.0    | 0.0    | 0.0    | 0.0    | 0.0    | 0.0     |

Alternatives written in bold should be rejected (NPV < 0 and IRR < real interest rate of 4.44%).
4.1 Construction and energy costs

4.1.1 Construction cost

Based on governmental construction projects, the baseline model's construction cost and the increased amount of construction cost against the baseline model were estimated for each alternative by the professionals of "T" Architects and Engineers Company. Estimated construction costs consist of material and labor costs for only the systems presented in Tables 6. and 7. The cost of materials reflects the price in February 2008, and the labor cost reflects the Standard Labor Work Estimation prescribed by the government in January 2008. Aside from the systems presented in Tables 6. and 7., no other construction costs to complete the apartment complex (e.g., excavation work, structure construction, etc.) were included in the construction cost estimation. This is because, for each alternative, the increased amount of construction cost against the baseline model is not influenced by these costs. The baseline model's construction cost is 13,916.9 million won (1.3 thousand won is about 1 US dollar). Each alternative's increased amount of construction cost against the baseline model is presented in Table 8.

4.1.2 Energy demand reduction rate and energy cost

The heating energy demand of the standard apartment complex, calculated by using Eq. (8), is 55,905.5 GJ/year. The heating energy cost of the standard apartment complex, calculated by using Eq. (9) and the monthly energy rate for residential buildings of the Korea District Heating Corporation (basic charge: 42 won/m², usage charge: 13,589 won/GJ, March 2008), is 813.8 million won/year. The baseline model's energy demand reduction rate and each alternative's increased amount of energy demand reduction rate against the baseline model were calculated by using Eqs. (5) through (7). The baseline model's energy cost and each alternative's decreased amount of energy cost against the baseline model were calculated using Eq. (11). The baseline model's energy demand reduction rate is 23.7%, which comes under the second grade, and the baseline model's energy cost is 620.8 million won/year. Each alternative's increased amount of construction cost against the baseline model is presented in Table 8.

4.2 Cost efficiency indexes

4.2.1 Outlines of cost efficiency indexes

Various cost efficiency indexes, such as $\text{LCC}$, $\text{NPV}$, and $\text{IRR}$, consider the time value of money. $\text{LCC}$ is the sum of initial cost and operating cost during the lifetime, and operating cost during the lifetime is discounted to its present value. If initial cost and operating cost during the lifetime are defined as construction cost and every year's energy cost during the lifetime, respectively, and if the construction cost is paid at the beginning of the first year and the annual energy cost is paid at the end of every year during the lifetime, then the $\text{LCC}$s of the baseline model and each alternative can be obtained by using Eqs. (13) and (14)$^{5}$. $\text{NPV}$ is the total present value of investment (-) and return (+). If investment and return are defined as the alternative's increased amount of construction cost and decreased amount of energy cost during the lifetime against the baseline model, respectively, then the alternative's $\text{NPV}$ can be obtained by using Eq. (15). Here, $\text{NPV}$ represents the alternative's decreased amount of $\text{LCC}$ against the baseline model. The larger the alternative's $\text{NPV}$, the smaller its $\text{LCC}$, and if the alternative's $\text{NPV}$ has a negative value, it should be rejected because it increases the $\text{LCC}$.$^{6)}$

$\text{IRR}$ is the annualized effective return rate which can be earned on the investment. Put another way, $\text{IRR}$ is the discount rate that makes the present value of investment (-) the same as that of the return (+), i.e. it is the discount rate that makes the alternative's $\text{NPV}$ to be zero. If investment and return are defined in the same manner as for the $\text{NPV}$, then the alternative's $\text{IRR}$ can be obtained, for example, by using Microsoft Excel's $\text{IRR}$ function, which solves a polynomial equation iteratively. The higher the alternative's $\text{IRR}$, the better its return rate. If the alternative's $\text{IRR}$ is lower than the desired return rate, it should be rejected.$^{7,8)}$ In this study, the real interest rate ($r$ in Eq. (16)) was regarded as the desired return rate.

In addition, there is a payback period, which refers to the period of time required for the return to repay the investment. The payback period is widely used due to its ease of use despite limitations; it does not consider the time value of money and has no explicit criteria for decision-making. If investment and return are defined as the alternative's increased amount of construction cost and decreased amount of energy cost against the baseline model, respectively, then the alternative's payback period can be obtained by using Eq. (17)$^{9,10)}$. This study includes the payback period in the cost efficiency analysis in order for architects and engineers to easily understand the result.

\[
\text{LCC} = CC + PW \times EC 
\]

\[
PW = \frac{1 + i}{\left(1 + \frac{1 + i}{1 + R}\right)^n - 1} 
\]

\[
\text{NPV} = \Delta\text{LCC} = -\Delta CC + PW \times \Delta EC 
\]

\[
r = \frac{1 + R}{1 + i} - 1 
\]

\[
PP = \frac{\Delta CC}{\Delta EC} 
\]

4.2.2 Calculations of cost efficiency indexes

The baseline model's $\text{LCC}$ and each alternative's decreased amount of $\text{LCC}$ against the baseline model were calculated using Eqs. (13) through (15). In Eq. (14), the $i$ was set at 3.2%$^{9,10}$, which is the average consumer's price index over the last ten years from 1998 to 2007. The $R$ was set at 7.78%$^{9,10}$, which is the average interest rate on a loan by the Bank of Korea over the last ten years, and the $n$ was set at 30 years based on a previous study$^{9,10}$ that reports the lifetime of Korean apartment complexes. The baseline model's $\text{LCC}$ is 24,103.2 million won, and each alternative's decreased amount of $\text{LCC}$ against the baseline model is shown in Table 8. Each alternative's $\text{IRR}$ and payback period were calculated using the $\text{IRR}$ function of Microsoft Excel and Eq. (17), respectively, and the results are shown in Table 8.
4.3 Cost efficiency analysis results

Table 8. shows the cost efficiency analysis results for all the alternatives. The following alternatives not only have negative NPV but also have lower IRR than the desired return rate of 4.44% obtained by applying the i of 3.2% and the R of 7.78% in Eq. (16): all the alternatives of Item 1; Alt. 3 of Item 2; Alts. 4 and 5 of Item 4-4; Alts. 3 through 5 of Item 5; Alt. 5 of Item 6-1 (the above are basic items); all the alternatives of Items 8 through 10, 12, 17, 20, 21 and 24 (the above are extra items). Consequently, these alternatives should be rejected. In the case of Item 2, the construction cost is mainly influenced by the glazing cost, and it significantly increases with the use of low-e glazing. Among the alternatives with low-e glazing (Alts. 3 through 5), Alt. 3 with gas layer thickness of 6 mm has a negative NPV because the ΔEC cannot compensate for the ΔCC caused by the low-e glazing. Consequently, the U-values of Alts. 4 or 5 with gas layer thickness of 12 mm are required when applying the low-e glazing.

After excluding the alternatives with negative NPV, alternatives were selected for target items on the basis of NPV, IRR, and ΔEC, respectively, and they were then sorted in descending order. In the case of NPV, Alt. 5 of Item 7-1, of which NPV is 475.6 million won, shows the largest LCC decrease. Alt. 4 of Item 4-2, Alt. 5 of Item 2, Alt. 4 of Item 4-1, Alt. 1 of Item 3, and Alt. 4 of Item 4-3 also show large LCC decreases. In the case of IRR, Alt. 1 of Item 11 and Alt. 1 of Item 7-1, with IRRs over 400%, show a significantly high rate of energy cost decrease against the construction cost increase. Alt. 1 of Item 6-2, Alt. 1 of Item 13, Alt. 1 of Item 22, and Alt. 1 of Item 4-1 also show a high rate. In the case of ΔEC, Alt. 5 of Item 2, of which ΔEC is 72.4 million won/year, shows the largest energy cost decrease. Alt. 5 of Item 7-1, Alt. 5 of Item 4-2, Alt. 5 of Item 4-1, Alt. 5 of Item 4-3, and Alt. 1 of Item 3 also show a large energy cost decrease.

5. Summary and Conclusions

Energy-efficient buildings are essential to reduce greenhouse gas emissions and further solve environmental problems caused by the use of fossil fuels. However, improved energy efficiency may also bring about a rise in construction costs. If design variables can be prioritized according to their cost efficiencies, energy-efficient buildings can be designed more cost-efficiently. In this study, the aim is to analyze the cost efficiencies of design variables related to energy efficiency of the apartment complex by using the assessment method of the Building Energy Efficiency Rating System (BEERS) that has been implemented in Korea. The baseline model was made, based on a recently completed apartment complex. Among all the assessment items in the BEERS, the items suitable for cost efficiency analysis were selected as target items. After making alternatives for target items, each alternative's increased amount of construction cost and decreased amount of energy cost against the baseline model were then estimated using actual price data and the assessment methods of the BEERS, respectively. The life cycle cost, net present value (NPV), internal rate of return, and payback period of each alternative were shown as cost efficiency indexes. It was shown that 23 alternatives for 13 target items among 78 alternatives for 29 target items should be rejected because of their negative NPVs.

The order of priority of each alternative was presented and very cost-efficient alternatives were suggested.

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Nomenclature

| Symbol | Description |
|--------|-------------|
| HL     | heating load (GJ/year) |
| HLC    | heat loss coefficient |
| HDD    | heating degree day (‘Cday) |
| HED    | heating energy demand (GJ/year) |
| Ec     | energy cost (million won/year) |
| Ec_d   | effective U-values of heated space windows, doors and other openings facing the balcony (W/m²K) |
| U1     | U-values of heated space windows, doors and other openings facing the balcony (W/m²K) |
| U2     | U-values of balcony windows (W/m²K) |
| LCC    | life cycle cost (million won) |
| CC     | construction cost (million won) |
| PW     | present worth coefficient |
| i      | inflation rate |
| R      | interest rate |
| n      | lifetime (year) |
| NPV    | net present value (million won) |
| ∆LCC   | decreased amount of life cycle cost against the baseline model (million won) |
| ∆EC    | increased amount of construction cost against the baseline model (million won) |
| ∆CC    | decreased amount of energy cost against the baseline model (million won/year) |
| IRR    | internal rate of return (%) |

Subscript

- cplx_std extra item for a unit, applied to the assessed apartment complex
- bldg_extra extra item for a building, applied to the assessed apartment complex
- std standard apartment complex
- per unit area (m²)

References

1) Statistics Database of the Korea Energy Economics Institute (http://www. keei.re.kr). (2008)
2) Yu, K., Cho, D. and Song, K. (2006) A study on the energy efficiency rating and certification of apartment houses. Journal of Architectural Institute of Korea, 22 (12), pp.319-326
3) Feist, W. (2001) CEPHEUS-Project information no. 36 Final technical report. PASSIVHAUS INSTITUT.
4) The PEP (Promotion of European Passive Houses) project team. (2006) Passive house solutions. The PEP consortium.
5) Dell’Isola, A.J. and Kirk, S.J. (1981) Life cycle costing for design professionals. McGraw-Hill.
6) Lin, C.I. and Nagalingam, S.V. (2000) CIM justification and optimisation. Taylor & Francis.
7) Baker, S.L. (2006) Perils of the internal rate of return (http://hapm. sph.sc.edu/COURSES/ECON/invest/invest.html).
8) Economic Statistics System of the Bank of Korea (http://ecos.bok.or.kr). (2008).
9) Song, S. (1998) A study on the method for determining the optimal insulation details of thermal bridge at the joints of apartment building envelope. Ph.D. Thesis. Seoul: Seoul National University.