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Development of an Nearly Zero Emission Building (nZEB) Life Cycle Cost Assessment Tool for Fast Decision Making in the Early Design Phase

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Abstract: An economic feasibility optimization method for the life cycle cost (LCC) has been developed to apply energy saving techniques in the early design stages of a building. The method was developed using default data (e.g., operation schedules), energy consumption prediction equations and cost prediction equations utilizing design variables considered in the early design phase. With certain equations developed, an LCC model was constructed using the computational program MATLAB, to create an automated optimization process. To verify the results from the newly developed assessment tool, a case study on an office building was performed to outline the results of the designer's proposed model and the cost optimal model.

Keywords: cost optimal model; designer's proposed model; LCC analysis; nearly Zero Emission Building; investment cost; operation cost

1. Introduction

1.1. Introduction

Korea is the world's fifth largest oil importer and it lacks fossil fuel reserves. Oil imports accounts for a large proportion of overall imports of Korea, and thus, fluctuating oil prices greatly affect the overall balance of payments [1]. The country's continued reliance on depleting fossil fuel energy sources may also undermine its energy security, and as a result the government plans to decrease fossil fuel dependence in the long run. The government encourages buildings to use less fossil fuel by setting energy policies, regulating the minimum U-value and advocating the use of renewable energy sources. The government is also offering incentives and tax benefits. However, building owners and builders manage only to meet the regulations and have no interest to exceed these minimum targets. This is attributed to green premium, the initial cost that rises with use of the technologies necessary to build a nearly Zero Emission Building (nZEB), which occur in the construction stage. Decision makers simply link the green premium and the subsequent rise of the initial cost to a reduced economic benefit.

In fact, energy performance of a building which has been improved by green premium and the economic benefit do not have a conflicting but a causal relationship This is due to the fact that the time and money needed to operate a building is quite substantial and investing in green premium can considerably reduce the operational costs in the operating stage. This is particularly true when the oil price is expected to increase, and with the additional cost of CO_2 emissions, the green premium effect is expected to further increase [2].

Decision makers have yet to fully recognize the life cycle concept incorporating the green premium and the operating costs comprehensively. Insufficient technologies and experts to evaluate their economic effect also limit the information that can be accessed. Though the outline of the initial investment is decided at the initial design stage, there is no system that supports decision making at that stage and this causes hesitation in people to invest in the green premium.

Therefore, providing information on the economic advantages coming from the green premium can be a solution in reducing the obstacles to realize a nZEB. As it is complicated to consider all of the energy consumed and the economic benefits generated by a building during its life cycle, an assessment tool must to be developed that would help general decision makers easily grasp the effects [3].

The current study attempted to develop an assessment model which can be used to calculate the LCC (initial investment cost and energy cost) and thereby assist in decision making during the early design phase. The assessment tool which was developed should operate together with a program that can draw an optimized design. The energy saving design for a building envelope typically takes into account different design variables, such as heat insulation, natural lighting and natural ventilation in the early design stage. The energy saving technologies trade off their heating and cooling load, and requires many cases to be designed and evaluated. This process takes time and repeated trials and is therefore omitted in the early design phase most of the time. A tool is required which can be connected to an auto–optimized design process that helps to generate the cost-optimal design without going through a large number of iterations. Therefore, a supportive decision making tool was developed in the present study.

1.2. Research Scope

A baseline building was selected for the present study to develop a cost optimization model and 153 office buildings in Seoul were surveyed to validate the model. The scope for applying each design variable was set, according to current legal requirements for minimum performance and the latest technology available in the market for the maximum performance.

The study developed a simple prediction equation that allowed calculation of energy consumption and LCC based on the baseline building. This was derived to be easily operated by any architect, as it comprised design variables considered in the early design stage. To develop the energy prediction equation, an orthogonal array was used to drastically reduce the number of experiments to 81 from 3^{24} (=282,429,536,481), the number required for energy simulation. EnergyPlus was used for the computer simulation and the relative importance of each design variable was identified using Analysis of Variance (ANOVA). The ANOVA result was used as multiple regression analysis data to develop the prediction equation.

To calculate initial investment in the LCC model, a prediction equation was also developed. To develop the prediction equation, several cases were established where technological elements designed to improve energy performance, were designed for the baseline model before entering quotation data. A regression formula was then generated through statistical analysis of the calculated data. The equation parameters were made to correspond to the energy prediction equation as far as possible and important factors were included to the LCC which would not affect the energy performance.

The LCC model was constructed by using the energy performance prediction equation and the initial investment cost equation developed above. Based on this LCC model, an optimization model was developed by applying a multi-objective optimization method. Finally, a program was constructed and verified.

2. Literature Research

2.1. Definition and Research of Nearly Zero Emission Building

The concept of "Zero Emission" was first proposed by Pauli (United Nations University) in 1994, and it was meant to describe the process where a minimum amount of waste would be generated, eventually creating zero waste. "Zero Emission Building" in architecture means a building with the objective of creating zero CO_2 emissions during the life cycle of the building. When it is explained that "Zero Emission Building" widened the scope of CO_2 emitted by the building into three that are operation energy, embodied energy and transportation energy [4], scope 1 or the operation energy used by the building accounts for 70% of all CO_2 emissions and has the greatest importance [5].

Buildings in South Korea emit more than 25% of all greenhouse gases. With the idea that there plenty of room to reduce the greenhouse gases by constructing green buildings, a great deal of effort has been made to reduce the greenhouse gas emissions from buildings. Besides, the Ministry of Land, Infrastructure and Transport and the Ministry of Trade, Industry and Energy have designated zero energy as a new industry and made joint efforts to realize the goal through cooperation as one of the key projects to create a future growth engine [6]. "Zero Energy Building" basically means a building where the sum of used energy and produced energy is 0 (Net Zero) [7]. Given the current technologies and economic feasibility, however, the policy defined it as a building that consumes the least energy (Nearly Zero, 90% reduction) [8], with maximized heat insulation performance, minimized building energy load (passive), use of renewables, such as photovoltaic (active) and minimum energy needs for proper functioning [9].

Therefore, studies carried out in the country mainly focus on realizing nearly zero emission by analyzing and combining individual elementary technologies. Song [10] analyzed the energy saving effect of air conditioning technology when applied using simulation while Gang [11] studied the effect of ventilation, eave and lighting control. Though the final goal of the above studies was to make a zero energy building, policy studies were also conducted to overcome the gap between the goal and reality. Policy wise, Shin [12] analyzed the energy demand and consumption depending on combination of technologies to bring the zero energy housing into reality. In the meantime, Jo studied the policies of South Korea and other countries to build zero energy buildings and examined the local policies [13].

2.2. Decision Making for Realization of Zero Emission Building

As the early design stage decides 80% of the initial investment and most of the design decided in this stage influences energy consumption during the operating stage [14], it can be said that the operating cost is decided here as well. Many decisions are made in the early design phase. A high-performance envelope designed with high performance insulation materials can help to reduce the heating costs as well as the operating costs. Building exterior shading can also decrease the cost of the cooling system and also the energy consumption for cooling. Exterior shading can however increase the heating cost as it is likely to block solar heat during winter, which raises the LCC. Accordingly, design variables should be analyzed comprehensively as they have varying impacts on the initial investment, cooling/heating costs and lighting costs.

Financial problem is one of the major obstacles in the realization of nearly Zero Emission Buildings (nZEBs). Some investors believe that increasing initial investment to enhance building performance results in an economic loss. However, it is reasonable to calculate the building cost with the life cycle cost (LCC) that includes both the initial investment cost and the operational cost, as investment to improve the energy performance should eventually lead to a lower energy cost during operation. Thus, the return on investment calculation should be related not only to the investment costs, but should also take into account the operational and maintenance costs of buildings [15]. Reaping the most benefit out of the least investment cost is important to consider. In this concept, the "lowest LCC" option, which pertains to the entire life cycle of a building is the most economical one [16]. Recently, the most economical condition is also called cost optimal, with investors wanting their investment to be cost optimal.

Calculating the optimal LCC at the early design phase requires calculation of the initial investment and operational costs and this also calls for a significant investment of time and money in a database. This suggests that the most early design phases end with only a small portion of the design space examined and a large number of design solutions left untouched. There is therefore no guarantee that the final design will be an optimal one. Besides, it is almost impossible in Korea to make the best decision based on such analysis in the early design phase as a quick decision is usually required. If the optimization includes an automatic process of design creation, simulation and evaluation, building design optimization will become beneficial as it will help to create a design quickly which can realize the performance that the building seeks for and provide an overall knowledge of the whole design space [17]. The optimal design created by an automatic process facilitates the designer's decision making that considers the reality of nZEB [18]. It also acts to relieve the designer of a very time-consuming and labor-intensive trial and error approach, which designs and evaluates a number of buildings to reach the same goal [19].

In the study of optimal life cycle cost, Wang [20] developed an LCC model, which considered cost effective design rather than only the energy performance in a single-objective function. The LCC here, which reflected a trade-off between the initial investment and the operating cost, was more advanced than other previous models. Znouda [21] developed a standard GA which included a tool (CHEOPS) that allowed load calculation for a simple building. This model produces both energy consumption and a LCC optimal model. Typically, the economic impact (LCC) and the environmental impact (energy consumption) were used as design goals in the multi-objective optimization model. Hasan et al. [22] combined the IDA ICE 3.0, energy simulation tool, and the GenOpt2.0, genetic algorithm program, to develop an LCC design process. In the multi-objective optimization model developed by Shi (2011) [23], EnergyPlus, a sophisticated and widely used BEPS software tool, was integrated into mode FRONTIER, an optimization suite which contains a series of pre-programmed optimization algorithms, to minimize the energy demand for space conditioning and insulation usage for office buildings in Southeast China. With only one insulation material, the insulation usage ishas essentially an equivalent term to the initial cost.

2.3. Tools for Fast Decision Making in the Early Design Phase

Most of the recently developed optimal LCC tools are calculated based on a very detailed database which includes the finishing paint coating and type of stone finishing [24,25]. It is quite difficult to use an optimal LCC tool that uses a detailed database at the early design stage. Therefore, data which cannot be determined and obtained at early design stage to calculate the LCC must be included in the tool [26]. This helps to minimize both time and effort needed to calculate the initial investment and operating cost to give results quickly, thereby resulting in quick decision making. Moreover, the fast automatic process of the optimized LCC analysis presents the optimal LCC or the lowest LCC that can be drawn using the given variables, providing a guideline for the designer.

3. The Framework of Decision Supporting Tools in the Early Design Phase

The basic framework of the decision supporting tools was established with an input module, an assessment module and an output module and core elements which were derived from the assessment tool comparative analysis [27].

3.1. Input Module

The items to calculate for the LCC analysis should be decided considering the analysis target. The initial investment can largely be divided into items which influence the building's operating stage, i.e., energy consumption and those not. Considering the goal of the study, the items that did not affect the energy performance had a relatively low influence. Hence, these were not included in the LCC analysis and the initial investment that was entered into the input module was set up. The initial investment cost usually comprises civil engineering, architecture, mechanical system, electric system, landscape and interior construction. Out of these, civil engineering, landscaping and interior construction were excluded because their impact on the energy performance is relatively insignificant. In the electric construction, only the lighting system needs to be considered and should be addressed in the early design phase.

3.1.1. Architecture

Extracting the variables that affect the energy consumption and cost is important. Architectural design factors at the early design phase include building shape, size, window/wall ratio, envelope and structure. Though the number of deciding factors is not large, they interact with one another, which in turn further affects the energy performance. Therefore, each factor needs to be systematically classified into two categories [28]. One is the factors which affect both the energy consumption and the architectural design, whilst the other has no relevance to the design but affects energy consumption. The factors affecting the design have to be further sorted first through literature review. After the sorting process, a sensitivity analysis should be performed to select the critical input parameters. The parameters selected through statistical analysis have relatively greater influence or sensitivity on the energy consumption than others. After sensitivity analysis, the parameters which had larger ratios were selected. A factor influencing the energy, though it is not one of the design factors, was also checked, as it had to be entered to predict the energy consumption. It is particularly important to pre-set the factors that affect energy consumption as a default database for prediction used at the early design phase even if they are not any design factor. The factors that do not include design factors but must be input are the internal loads, ventilation rate, indoor temperature set points and operating hours. If these inputs are set up as standard information, time and efforts to find and input them can be greatly reduced.

3.1.2. Mechanical and Electrical System

For mechanical systems, a Heating, Ventilating, Air-Conditioning, and Refrigeration (HVAC&R) system should be of primary interest as it is a complicated system with numerous variables and restrictions. According to past research, the HVAC&R system matrix has a combination of 16 AC sub-systems, 15 plant sub-systems and 4 transportation systems. The number of possible combinations that can be made is therefore 960 [29]. However, it was narrowed down to the realistic and universal systems which are used in Korea. Thus, a total of 56 sub-system combinations (4×14) can be produced. The present study used these 56 basic HVAC&R database sets to calculate the energy consumption of the HVAC&R system. In the electric system, only lighting system that can be decided in the early design phase needs to be considered and others should be set to a default value [30].

3.2. Assessment Module

A LCC process usually includes the following steps: definition of LCC analysis/identification of the goals, establishment of a basic assumption for the analysis, selection methodology for the LCC analysis (e.g., cost breakdown structure, identifying data sources and contingencies) and LCC modeling [31].

3.2.1. Definition of the LCC Analysis/Identification of Goals

Life cycle cost (LCC) is an approach that assess the total cost of an asset over its life cycle including initial investment, operating cost, maintenance costs. Nowadays, most builders are only concerned about the initial investment, working toward their minimization [32]. This leads to an emphasis on the initial cost, in detriment of other life cycle cost, and, for the same cases, to the supporting of solutions that require smaller investment but have higher operational costs (such as the application of less insulation resulting in higher need for heating and cooling energy) and also lower Zero Emission levels (like higher carbon emission).

Life cycle cost is an economic methodology for selecting the most cost-effective alternative over a particular time frame, taking into consideration its initial cost (construction), operational cost and maintenance cost. However, the material cost and installation cost of the initial investment as well as the energy operating cost are the most influential in reflecting the energy saving strategies into the building design. Therefore, only the costs of these two stages of the life cycle were calculated to analyze the LCC in this study (Figure 1).

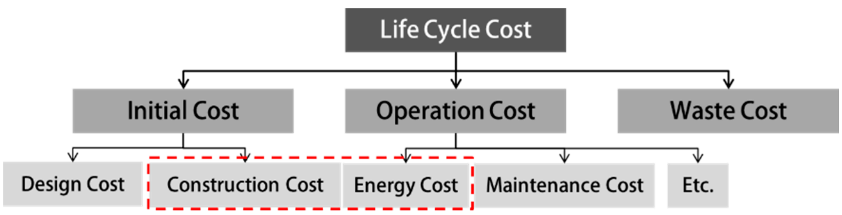


Figure 1. Scope of the Life Cycle Cost Analysis.

3.2.2. Establishment of the Basic Assumptions for Analysis

A discount rate should be established to calculate operating cost, with interest rate (10 years on average), oil, electricity and gas prices considered in the calculation [33]. South Korea is also expected to face carbon price soon which is not yet decided in the market. Therefore, this study employed a price from the CO_2 emissions trading market of the EUA (European Union Allowance) [34].

3.2.3. Selection of Methodology for the LCC analysis

The process of predicting the LCC requires calculation of the costs that occur throughout the period in question at a certain time. The global cost method [35] was used to calculate the LCC. This calculation method includes a system that affects the building's energy performance. In this study, the construction and facility costs that affect the energy performance were included in the calculation. All costs were deemed to occur when they are calculated. The global cost calculation method is as shown below:

$$\text{Life Cycle Cost } (X) = C_p\ (C_i + C_o) = C_p\ (C_m + C_E + C_{Em}) \tag{1}$$

where C_p = Conversion Factor of Present Value; C_i = Initial Cost; C_o = Operation Cost; C_m = Construction Cost; C_E = Energy Cost = $C_C \times (E_C + E_H + E_L + E_E + C_{EM})$; C_{EM} = CO_2 Emission Cost = $C_C \times E_{Emission}$, where E_C = Cooling Energy; E_H = Heating Energy; E_L = Lighting Energy; E_E = Electric Energy; $E_{Emission}$ = CO_2 Emission.

The discount rate coefficient R_d was used to refer to the replacement cost and the final value to the starting year. It is expressed as:

$$R_d = \frac{1}{(1+R_r)^i} \tag{2}$$

where R_r is the real interest rate in the year of calculation. When the annual costs occur for many years, such as the running costs, the present value factor, which is expressed as a function of the number of years n and the interest rate R_r can be calculated using Equation (3):

$$f_{pv}(n) = ((1+R_r)-1)/\left(R_r \times (1+R_r)^n\right) \tag{3}$$

This study used the present value method to calculate the value of all future costs at the current value:

$$P_F = F\frac{1}{(1+i_r)^n} P_A = A\frac{(1+i)^n - 1}{i_r(1+i_r)^n} P = P_F + P_A \tag{4}$$

P_F: Present value of a lump sum; A: Annual Value; F: Future Cost; P: Present Worth Factor; i_r: interest; n: Analysis Period.

3.2.4. LCC Modeling

Table 1 presents the LCC analysis procedure for a nZEB in which the CO_2 emission cost was considered.

Table 1. LCC Analysis procedure of nZEB.

Procedure		Contents
1. Identification of goals Investigation of LCC formation items /Establishment of analysis model	→	LCC Analysis of a nearly Zero Emission Building Selection of applicable technology, Establishment of analysis model Construction stage: Initial Investment cost Operation stage: Energy Cost, Environmental cost
2. Establishment of the basic assumptions for analysis	→	Analysis period, Time point of analysis, Analytical unit, Interest rate, Inflation rate, Discount rate, Energy price escalation rate, Market-linked energy cost, Present value factor, Trading cost of CO_2 emission

Table 1. *Cont*.

Procedure		Contents		
3. Selection methodology for LCC analysis	→	Initial Investment cost		
		Energy Consumption Conversion of energy consumption and CO_2 emission occurring during the operating stage	→	Energy cost: Energy consumption, Price of energy Environmental pollution charge: CO_2 emissions, Price of CO_2 emission trading
		DCFA (Conversion into present value) → LCC estimation Application of a discount rate and prime cost interlocking, Present value factor calculation of prices and energy sources		
4. Decision making based on LCC analysis	→	LCC estimation results → Making a decision for each analyzed goal		

3.3. Output Module

A linear scaling transformation was applied to normalize the performance assessment results. The method is suitable when different attributes are mixed. The attributes consist of decision making factors which are in different units and cases where a minimization standard (e.g., expense) and a maximization standard (e.g., profit) that should be applied are mixed. Under a complicated linear scaling transformation in particular, the value is transformed between the range of the maximum and minimum value of each attribute. This means that each attribute transforms precisely to a value between 0 and 1. Hence, a complicated linear scaling transformation was applied to this study. Under the assumption that E is economic feasibility. for example, the maximum value of E is obtained when the LCC is at its lowest. Ej is the performance value of E for the alternative j. $E_{\max}$ and $E_{\min}$ represent the LCC of the baseline model and the optimized model, respectively. This suggests that $E_{\min}$ is the lowest possible life cycle cost among the selected variables, which signifies the optimal cost. If $E_{\max}$ and $E_{\min}$ are normalized using complicated linear scaling transformation, Equation (5) is obtained. When each performance result is transformed to a dimensionless score through normalization, the output value lies between 0 and 1. In this case, 0 represents the standard model, whilst 1 represents the target building with maximum performance.

- *Establishing the minimum performance*: Minimum performance means the lowest performance realized by the suggested model. Therefore, the LCC is the largest model and the value of the universal standard model that complies with the minimum legal requirements in general has the minimum performance.
- *Establishing the optimal performance*: The optimal performance implies the best performance of the suggested model conditions, meaning that the building is cost-optimal with the lowest LCC under the given condition. Therefore, an optimization design method was applied and the economic performance resulting from its best solution was set as the optimal performance. The optimization design is determined by the objective function for many decision variables:

$$Env = \frac{Env_{\mathrm{j}} - Env_{\min}}{Env_{\max} - Env_{\min}} \quad (5)$$

3.4. Framework for the Decision Tool for Use at the Early Design Stage

The basic framework is established with an input module, an assessment module and an output module and core elements (Figure 2). An assessment software program for nZEB is developed based upon this framework derived from a logical calculation flowchart.

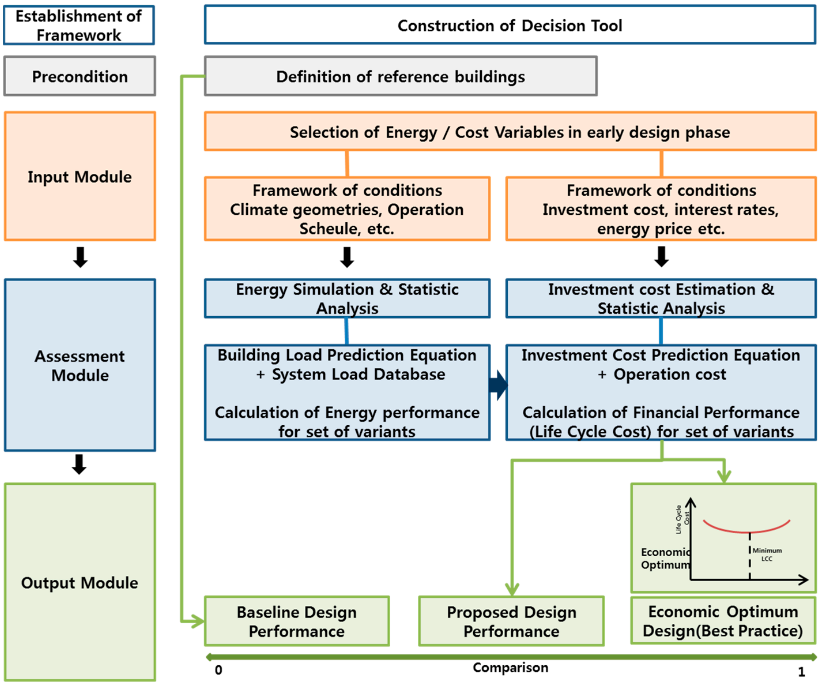


Figure 2. Framework of the Decision Tool.

4. Development of the Decision Support Tool

4.1. Input Module

4.1.1. Description of the Baseline Building

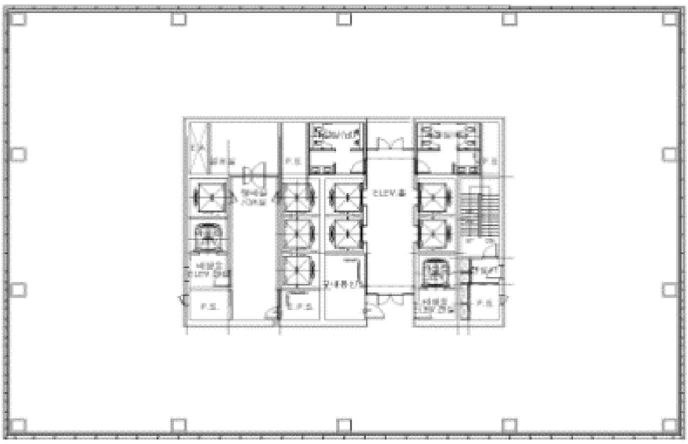
In Korea, it is mandatory to submit an "energy conservation plan" when applying for a construction permit to build an office building larger than 5000 m^2. In this study, the building data of 158 typical office buildings with their design drawings and energy conservation plans were thoroughly examined among these data, the contents of 30,000–50,000 m^2 of floor area are mentioned in this text. At this time, the Baseline is the building which is the Mean Average within the database.

The baseline buildings served as the basis for calculations applying the methodology. The baseline building was defined to reflect the typical buildings of the building stock of Seoul, Korea [36]. The characteristics of the baseline building were determined by careful examination of a typical design. Survey results showed that most of the office buildings in Korea are of basic module type consisting of a central building core. Figure in the Table 2 is a simplified model for simulation and Table 2 shows a description of the baseline model and operating features.

Table 2. Brief Description of the Baseline Model.

Category	Factors		Value
Climate Site	Climate Data		Seoul (TMY2)
	Heating/Cooling period	Heating Cooling	1/1~3/15, 10/31~12/3 3/15~10/31
Building	Floor area Ceiling height Plenum height Width/Depth Ratio (%) Window/Wall Ratio (%) Wall		40,000 m^2 2700 mm 1400 mm 1:1 40% 2.48 W/m^2·K
	Windows	U-Value Visual Light Transmittance Solar Heat Gain Coefficient	2.1 W/m^2·K 70% 0.2

Table 2. *Cont.*

Category	Factors	Value		
System	Heating Cooling Ventilation	Heating Ventilation Air Conditioning Unit, Fan Coil Unit		
Operation Occupancy	Temperature control	Heating Cooling		24 °C 26 °C
	Ventilation quantity	0.3 Air Change Rate/Hour		
	Number of occupants	5 m^2/person		
	Internal heat (W)	Person	Latent Sensible	70 45
		Equipment Lighting	10.4 W/m^2 15.1 W/m^2	
Plan of Typical Office				

4.1.2. Design Variables

In this study, the building data of 153 typical office buildings with their design drawings and energy conservation plans were thoroughly examined, and all the variables which contribute to building energy consumption were identified. Among them, 24 factors are selected as energy related design parameters based on sensitivity analysis. These variables are related to architects' early design decision and, at the same time, are able to be defined in quantifiable objective values. A number of precedent researches were also examined to verify the validity of the findings [37–39] (Table 3). Also, the practically applicable ranges of each design variable in the building were set based upon investigated data, which encompassed performance from the minimum level regulated by the building code to cutting edge commercialized technologies.

Table 3. Applicable ranges of the design variables.

Category	Energy Strategies		Ranges
Volume, Shape, Plan	gross floor area (m^2)		30,000–50,000 (Mean 41,000)
	# of stories		20–30 (Mean 22)
	floor height (m)		3.7–4.4 (Mean 4.0)
	width/depth ratio (%)		1:1–1:2
	Window/wall ratio (%)		30–60
Arrangement	Orientation		0~90 (0: South)
Others	Insulation performance ($W/m^2{\cdot}K$)	Roof	0.56–0.15
		Wall	0.27–0.09
		Ground Floor	0.69–0.19
	Window performance	U-value	1.00–1.72
		Solar Heat Gain Coefficient	0.2–0.4
		Visual Light Transmittance	15%–70%
	Ventilation rate		0.4–0.8

4.1.3. Sensitivity Analysis

The parameters which have significant contribution at the 5% significant level (p-value) in ANOVA were selected as the contributing energy factors, and the non-significant terms (p-value greater than 0.05) were eliminated. Only nine parameters were selected as significant factors for heating energy consumption. For cooling energy consumption, 13 parameters were found to be significant. They are; Floor to Floor Height, Window Wall Ratio (Façade), Orientation, Window Wall Ratio (South), Window Wall Ratio R (North), Ventilation, U-value of the Wall, U-Value of Window (North), Solar Heat Gain Coefficient-South for heating energy. For cooling energy, Gross Floor Area, Surface Floor Ratio, Floor to Floor Height, Width Depth Ratio, Window Wall Ratio (East), Window Wall Ratio (West), Daylighting, U-Value of Wall, Window U-factor (South), Solar Heat Gain Coefficient (West), Solar Heat Gain Coefficient (South), Visual Light Transmittance (West), Visual Light Transmittance (South) will be selected (Tables 4 and 5).

Table 4. Coefficient (a) for Heating Load.

Factors	Unstandardized Coefficients B	Standard Error	ß	*t*	*p*
(Invariable)	30.6	1.99		15.392	0.000
Floor Height	1.75	0.64	0.152	2.734	0.008
Window Wall Ratio (Façade)	1.78	0.64	0.155	2.788	0.007
Orientation	1.65	0.64	0.143	2.574	0.012
Window Wall Ratio (South)	−1.92	0.64	−0.167	−3.003	0.004
Window Wall Ratio (North)	−1.47	0.64	−0.128	−2.294	0.025
Ventilation	1.51	0.64	0.131	2.361	0.021
Wall	−8.72	0.64	−0.756	−13.589	0.000
U-value (North)	−1.59	0.64	−0.138	−2.480	0.016
Solar Heat Gain Coefficient (South)	2.86	0.64	0.248	4.456	0.000

Table 5. Coefficient (a) for Cooling Load.

Factors	Unstandardized Coefficients B	Standard Error	ß	*t*	*p*
(Invariable)	46.93	1.675		28.020	0.000
Gross Floor Area	−1.62	0.45	−0.252	−3.573	0.001
SFR	−0.80	0.45	−0.125	−1.765	0.082
Floor Height	1.41	0.45	0.219	3.110	0.003
Width Depth Ratio	1.48	0.45	0.232	3.284	0.002
Window Wall Ratio (East)	1.10	0.45	0.172	2.438	0.017
Window Wall Ratio (West)	1.12	0.45	0.174	2.465	0.016
Daylighting	−1.62	0.45	−0.253	−3.580	0.001
U-value (Wall)	−1.49	0.45	−0.232	−3.295	0.002
U-value (Win-S)	0.94	0.45	0.147	2.077	0.042
Solar Heat Gain Coefficient (West)	−2.60	0.45	−0.406	−5.748	0.000
Solar Heat Gain Coefficient (South)	−2.10	0.45	−0.327	−4.631	0.000
Visual Light Transmittance (West)	0.62	0.45	0.010	0.137	0.049
Visual Light Transmittance (South)	−0.78	0.45	−0.122	−1.733	0.049

4.2. Assessment Module

4.2.1. Initial Cost

Costs related to building elements with no influence on the energy performance, such as e floor covering and wall painting, while the costs that remain the same for all measures/packages/variants, e.g., earthworks and foundations, staircases, and demolition costs can be excluded. The costs must be market-based and coherent regarding the location and time of the investment costs, running costs, energy costs, and CO_2 cost. Data sources can be an evaluation of recent construction projects, an analysis of standard offers of construction companies, or existing cost databases which have been derived from market-based data gathering.

(1) Architecture Cost Prediction Equation

It is not easy to estimate the construction cost. In particular, in the early stage of design, the cost is calculated excluding the design cost. This is because many undetermined design factors are generally present which affect the construction cost. Therefore, it becomes difficult to generate reliable cost estimates. In the current study, a construction cost prediction equation was developed for the early design stage using statistical methods and actual construction cost estimated data. The reliability of the prediction equation was increased by producing data through interpolation. Variables used in the construction cost prediction equation are the factors from the early design stage which affect energy consumption during the operating stage. The predicting equation was developed through the following four steps:

- Estimation of a first-order model based on actual data volatility
- Generation of model development data and step by step data interpolation
- Development of an initial investment cost estimation model and equation
- Correction of the model based on estimation results

- *Estimation of the first-order model based on actual data volatility*

The first-order model based on actual data volatility was estimated in the first step of the analytical process, namely validating the relationship between the construction cost and the various independent variables for the data enrichment or interpolation. Interpolation is essential for the estimation of the initial investment as data extraction for each condition is limited [40]. The construction variability based on the baseline floor area (1500, 2000 or 2500 m^2) was the most fundamental and significant part and was set as a reference point for data interpolation done later. This variability arose due to a lack of measured values when changes in the independent variables occurred along with the changes in the baseline floor area. First, an estimation equation between the construction cost and the changes in the independent variable was derived. No data were available to represent the changes in the baseline floor area and the floor height. Therefore, a regression equation for changes in the construction cost according to changes in the floor height, and the relation between the change in the floor height and the floor area was applied at 1500 m^2, 2000 m^2 and 2500 m^2. Figure 3 shows a graphical representation of the derivation of the first-order model for changes in the construction cost with changes in certain independent variables (Figure 3).

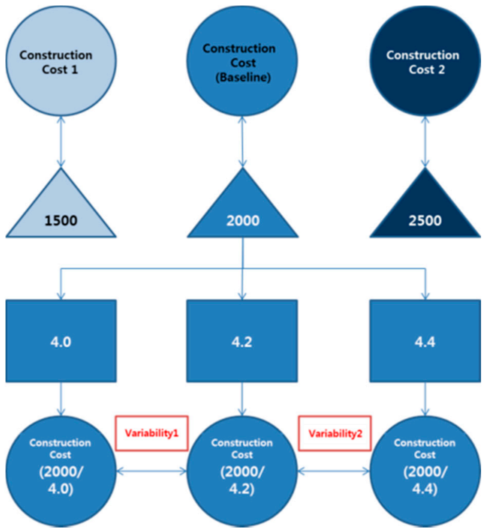


Figure 3. First-order model estimation process based on volatility.

- *Generation of model development data and step-by-step data interpolation*

This step refers to the process of filling the areas which lacked data for specific conditions through a what-if analysis, using the model created in the previous step. A what-if analysis is a process of finding an outcome when values are altered with respect to the actual values. This kind of analysis is often applied in time-series forecasting models. However, since this model does not have time-series data, a linear model was applied [41]. The result from the previous first-order model estimation process was applied to perform data interpolation based on a construction cost relations estimation equation to populate the area for which data did not exist. The results obtained from the regression estimation equation were applied and data interpolation was performed in the following order: the baseline floor area, floor height, width depth ratio, window wall ratio, U-value of wall and wall insulation. This series of steps was applied sequentially and repeatedly (Figure 4).

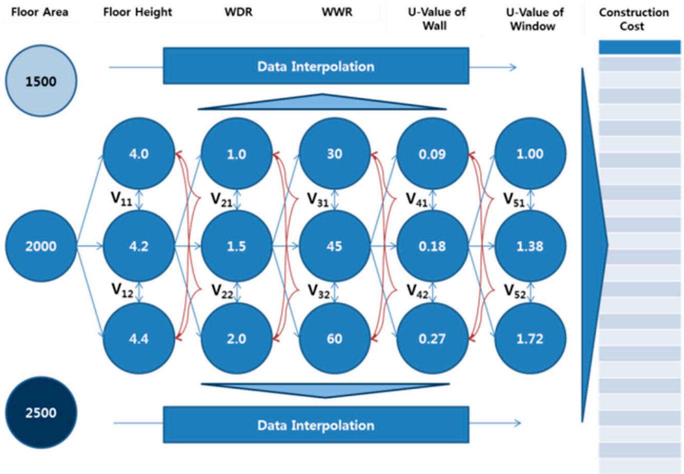


Figure 4. Model development data and step-by-step data interpolation.

- *Development of an estimation model for the initial investment cost*

Based on the integrated data extracted from the analysis process in phases 1 and 2, a linear model was established. Since time series factors were absent, the ARIMA model was not applied. Instead, a linear model, which has a high potential for expansion, was estimated [42]. The regression model was used as a basis for derivation of the Best Linear Unbiased Estimator (BLUE) from several linear models [43].

- *Correction of the model based on estimation results*

In this final step, the derived initial investment cost estimation model was examined and validated for any model adjustment. By hypothesizing a particular condition, discrepancies between the estimates derived from the model and the real values provided at the early design phase were calculated and examined. The average error rate was 3%–5%, and to improve this, the model was adjusted through random simulations of the estimated values by changing the intercept term and the beta coefficient. Thus, the model created from step 3 was adjusted to a final form to derive the initial investment cost model estimation equation (Figure 5).

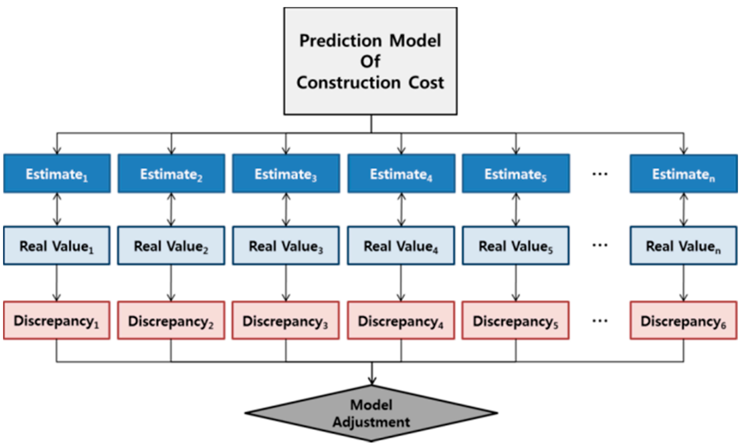


Figure 5. Final correction of the model based on estimation results.

- *Prediction Equation*

A mathematical model was developed through a multiple regression analysis (Table 6). Multiple regression analyses were conducted using the data set, and the load prediction equations were derived.

The coefficient of determination (R^2) between the regression models was 0.845 for the heating load prediction and 0.998 for initial cost prediction. As a result, the regression equations were found to have a considerable predictive power.

Table 6. Coefficient of Equations of the Initial Cost Prediction.

Factors	Unstandardized Coefficients	Standardized Coefficients	ß	t	p
	B	Standard Error			
(Invariable)	−467,611,530.097	10,486,340.385		−44.592 **	0.000
Gross Floor Area	599,921.127	950.139	0.982	631.404 **	0.000
Floor Height	142,207,711.837	2,352,457.595	0.107	60.451 **	0.000
Width Depth Ratio	25,200,179.482	943,528.129	0.053	26.708 **	0.000
Window Wall Ratio (South)	−73,285.833	11,449.391	−0.012	−6.401 **	0.000
Window Wall Ratio (North)	−85,622.281	14,210.349	−0.011	−6.025 **	0.000
Window Wall Ratio (South)	−119,988.105	13,482.439	−0.015	−8.900 **	0.000
Window Wall Ratio (North)	−113,804.377	18,499.495	−0.011	−6.152 **	0.000
U-value of Wall	−112,897,138.380	5,241,935.320	−0.028	−21.537 **	0.000
U-value of Window	−30,919,301.401	1,309,811.482	−0.036	−23.606 **	0.000

F = 68,492.228, R^2 = 0.998, adj. R^2 = 0.998; ** p < 0.01.

The equation is y = (−467,611,530.097) + 599,921.127 × Gross Floor Area + 142,207,711.837 × Floor Height + 25,200,179.482 × Width Depth Ratio + (−73,285.833) × Window Wall Ratio (East) + (−85,622.281) × Window Wall Ratio (West) + (−119,988.105) × Window Wall Ratio (South) + (−113,804.377) × Window Wall Ratio (North) + (−112,897,138.380) × U-value of Wall + (−30,919,301.401) × U-value of Window.

(2) Mechanical System Cost Prediction Equation

This study used 56 basic HVAC&R database sets, as mentioned above. For the facility system construction cost for each set, the capital cost is calculated for baseline and basic HVAC&R system, which consists of typical floor, mechanical room, and riser construction cost. The construction cost is then used to predict 56 combinations of HVAC&R system initial construction cost (Figure 6) [44].

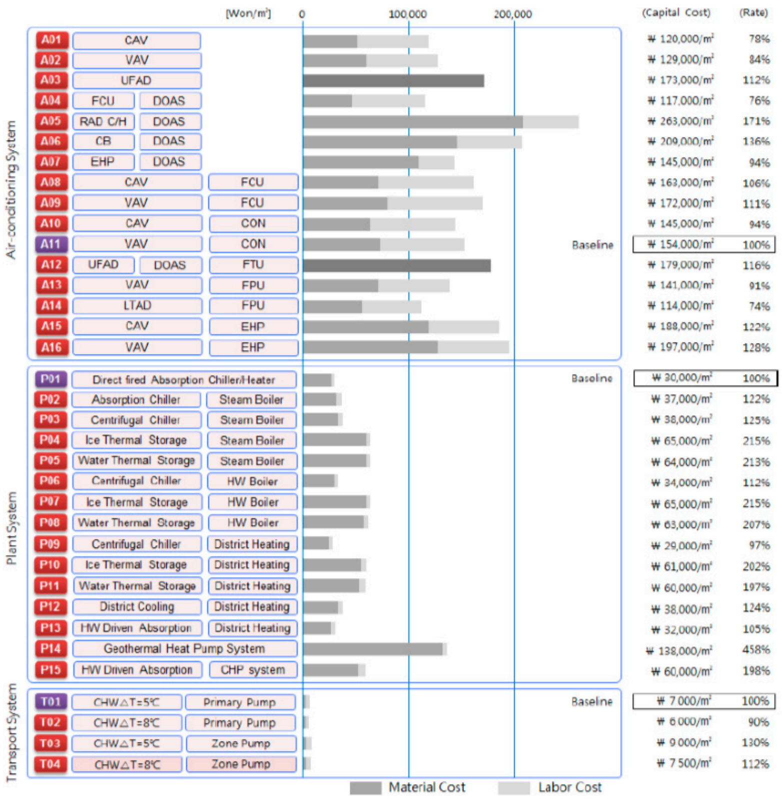


Figure 6. Analysis of construction cost of HVAC system boundary.

(3) Electrical system

Assuming that electrical construction cost is rarely an influencing factor to be decided in the early design stage, the electrical construction cost was taken as a constant, except for the lighting system and the cost of the lighting system. The constant was 178,251 won/m^2. The value for the lighting system and the cost of the lighting system was automatically selected from 48,413 won/m^2, 33,889 won/m^2 and 17,659 won/m^2, depending upon the selected lighting density [45].

4.2.2. Operating Cost

The energy cost of operating was calculated considering the expected energy consumption, the energy price inflation rate, inflation rate and the discount rate that reflected the interest rate and operational period. The building load prediction equation was developed with the variables mentioned above and the energy consumption was calculated through a connection with the disclosed equipment system database.

(1) Building Load Prediction Equation

The energy load prediction equations developed in the present study can be easily utilized to estimate heating and cooling load of office buildings in the central climatic zone of Korea during the early design stage. The number of tests needed to analyze the sensitivity was 3^{24} (=282,429,536,481), which was reduced to 81 using an orthogonal array. The tests applied an EnergyPlus simulation. The prediction equation was developed using ANOVA and multiple regression analysis (Table 7) [46]. The criterion used for the improvement of the prediction was the coefficient of determination (R^2). R^2 represents the square of the correlation between the predicted value and actual value. It is expressed as a decimal number between 0.00 and 1.00. 1.00 means perfect prediction in the model. The p-values were R^2 = 0.753 for heating energy consumption and R^2 = 0.602 for cooling energy consumption.

Table 7. Equations for Energy Consumption Prediction.

Partial R-Square	**R-Square**	**Modification of R-Square**	**Standard Error**
0.883	0.780	0.753	4.712
Heating Energy Consumption (Y) = 30.692 + 1.75 X_1 + 1.78 X_2 − 1.65 X_3 − 1.93 X_4 + 1.47 X_5 + 1.514 X_6 − 8.17 X_7 − 1.59 X_8 + 2.86 X_9			
	X_1	Floor to Floor Height	
	X_2	Window Wall Ratio (Façade)	
	X_3	Orientation	
	X_4	Window Wall Ratio (South)	
	X_5	Window Wall Ratio R (North)	
	X_6	Ventilation	
	X_7	U-value of the Wall	
	X_8	U-Value of Window (North)	
	X_9	Solar Heat Gain Coefficient-South	
Partial R-square	R-square	Modification of R-square	Standard Error
0.861	0.666	0.602	3.3329
Cooling Energy Consumption (Y) = 46.94 − 1.62 X_1 − 0.80 X_2 + 1.41 X_3 + 1.49 X_4 − 1.10 X_5 + 1.12 X_6 − 1.62 X_7 − 1.53 X_8 + 0.94 X_9 − 2.60 X_{10} − 2.10 X_{11} + 0.06 X_{12} − 0.79 X_{13}			
	X_1	Gross Floor Area	
	X_2	Surface Floor Ratio	
	X_3	Floor Height	
	X_4	Width Depth Ratio	
	X_5	Window Wall Ratio (East)	
	X_6	Window Wall Ratio (West)	
	X_7	Daylighting	
	X_8	U-value of Wall	
	X_9	U-value of Window (South)	
	X_{10}	Solar Heat Gain Coefficient-West	
	X_{11}	Solar Heat Gain Coefficient-East	
	X_{12}	Visual Light Transmittance-West	
	X_{13}	Visual Light Transmittance-East	

(2) System Load Prediction Equation

Energy simulation is a considerably accurate tool, but in order to use this, a professional knowledge and detailed input variables are needed. Therefore, an easily and conveniently available tool is highly desirable at the early design phase for practical purposes.

To compensate for the drawbacks of energy simulation, a database was developed based on the comparison analysis of different combinations of Heating Ventilation Air Conditioning & Refrigeration (HVAC&R) systems. This database was opened to public. As shown in Table 8, 56 possible combinations (4 Air conditioning × 14 Plant system) were chosen as the most widely used systems in Korea [44].

The energy consumed by operating the water heating and lighting systems, and the electrical distribution for the equipment use in the building was calculated by using data from an energy-consumption survey of 40 office buildings [47] (Table 9).

Table 8. Basic HVAC&R database set.

Air Conditioning System		Plant System	
		P01	Directed Fire Absorption Chiller/Heater
		P02	Absorption Chiller + Steam Boiler
		P03	Centrifugal Chiller + Steam Boiler
		P04	Ice Thermal Storage + Steam Boiler
		P05	Water Thermal Storage + Steam Boiler
A03	UFAD	P06	Centrifugal Chiller + Hot Water Boiler
A06	CB + DOAS	P07	Ice Thermal Storage + Hot Water Boiler
A08	CAV + FCU	P08	Water Thermal Storage + Hot Water Boiler
A11	VAV + CON	P09	Centrifugal Chiller + District Heating
		P10	Ice Thermal Storage + District Heating
		P11	Water Thermal Storage + District Heating
		P12	District Cooling + District Heating
		P13	Hot Water Driven Absorption + District Heating
		P14	Geothermal Heat Pump System

UFAD: Underfloor air distribution, CB: Chilled Beam; DOAS: Dedicated Outdoor Air System; DOAS: Dedicated Outdoor Air System; CAV: Constant Air Volume; FCU: Fan Coil Unit; VAV: Variable Air Volume; CON: Controller.

Table 9. Lighting and Electrical Energy Consumed.

Category	Calculation Model
Electricity Energy	$y = 10.4\ x^*$
Lighting Energy	$y = 15.1\ x^*$

x^*: Area (m^2).

4.3. Output Module

Finding an optimal model with the given variables requires calculation with application of the LCC evaluation equation to the optimization methodology. To undertake this optimization methodology, objective function and constraints which are appropriate for the given question are required.

4.3.1. Optimization Methodology

A multi-objective optimization function should be applied that uses multiple local minima solutions to produce an optimal value of the building energy cost and initial investment. Solution Space incorporates the features for discrete variables [48–50]. In this context, a genetic algorithm (GA) was believed to be the most appropriate among the many optimization models for calculating the optimal value of the discrete variables [51]. The overall process of the GA has been shown below (Figure 7).

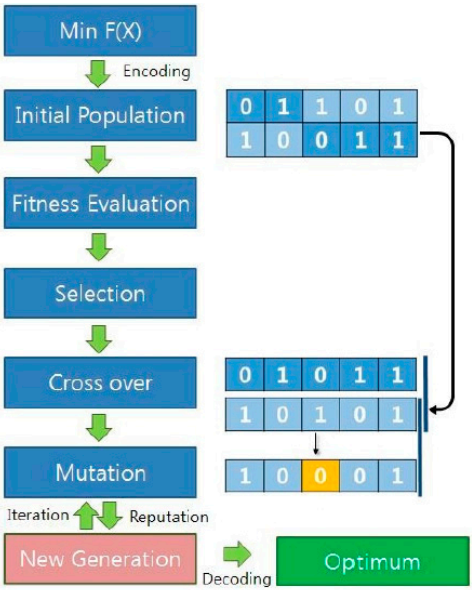


Figure 7. Process of GA algorithm.

4.3.2. Objective Function of the LCC and Constraints

As indicated earlier, an objective function was considered in the model, namely minimization of cost and energy consumption. The objective function can be expressed as shown in Equation (6):

$$\text{Objective function is } f(x) = \min\,(X_1) \quad (6)$$

where, X_1 = Life Cycle Cost = $C_p(C_i + C_o) = C_p(C_i + C_E + C_{Em})$; C_p = Conversion Factor of Present Value; C_i = Initial Cost; C_o = Operation Cost; C_E = Energy Cost; C_{Em} = CO_2 Emission Cost.

4.3.3. Constraints

The constraints on the design variables essentially delineate the bounds of the feasible range for each variable, which is influenced by market availability of the relevant products and the applicable codes and regulations. Constraints on the selected design variables are shown in Table 10.

Table 10. Constraints for the selected design variables.

Variables			Constraints		
Gross floor area (m^2)		X_1		$30{,}000 \le X_1 \le 50{,}000$	
Floor area (m^2)		X_2		$1500 \le X_2 \le 2500$	
Floor height (ceiling 1.3 m)		X_3		$4.0 \le X_3 \le 4.4$	
Width depth ratio		X_4		$1 \le X_4 \le 2$	
Orientation		X_5	0		1
		X_6	1		0
Window wall ratio (%)	East	X_7		$30 \le X_7 \le 60$	
	West	X_8		$30 \le X_8 \le 60$	
	South	X_9		$30 \le X_9 \le 60$	
	North	X_{10}		$30 \le X_{10} \le 60$	
U-value of wall ($W/m^2{\cdot}K$)		X_{11}		$0.09 \le X_{11} \le 0.27$	
U-value of window ($W/m^2{\cdot}K$)		X_{12}		$1.0 \le X_{12} \le 1.72$	
		X_{13}		$1.0 \le X_{13} \le 1.72$	
		X_{14}		$1.0 \le X_{14} \le 1.72$	
		X_{15}		$1.0 \le X_{15} \le 1.72$	
Solar Heat Gain Coefficient		X_{16}		$0.3 \le X_{16} \le 0.6$	
		X_{17}		$0.3 \le X_{17} \le 0.6$	
		X_{18}		$0.3 \le X_{18} \le 0.6$	
Visual Light Transmittance (%)		X_{19}		$30 \le X_{19} \le 60$	
		X_{20}		$30 \le X_{20} \le 60$	
		X_{21}		$30 \le X_{21} \le 60$	
Lighting density (W/m^2)		X_{22}	7	9.7	15

5. Development of a Fast Decision Support Tool and Validation

5.1. Fast Decision Support Tool

The LCC Model was developed using an Excel-based program. Thus, the program can be executed in a very simple manner. Each module was divided into separate Excel sheets which consisted of an Input Module, an Assessment Module and an Output module. This tool was developed for use at the early design phase. The input module comprised only the variables considered at the early design stage to reduce the time of analysis. For the assessment module, a cost/energy prediction equation was developed that does not affect the energy but allows the users to calculate the output by simply adjusting the variables. A computational optimization model calculation program (MatLab) was linked with the output module (Excel sheet) to provide an automated optimization process.

In most cases, the proposed designs, which should meet actual land conditions, designer's intentions and legal obligations, do not fit the optimization model condition. This optimization model will be used for designing and recognizing how far a proposed design lies from the optimized model. The baseline result which is shown in the output module will be used as starting point to measure how far the proposed design was improved over the baseline building. The LCC of the design proposed by the designer will probably be positioned between the LCC of the baseline building and that of the optimal building. The LCC that is the closest to the optimal building is the optimal design, that is, the lowest LCC. This can then serve as a yardstick to show what performance the proposed design can attain and also offer a guideline to the designer. As shown in Figure 8, the tool developed in the current study was output graphically when a design was compared with the optimized building and the baseline building (Figure 8).

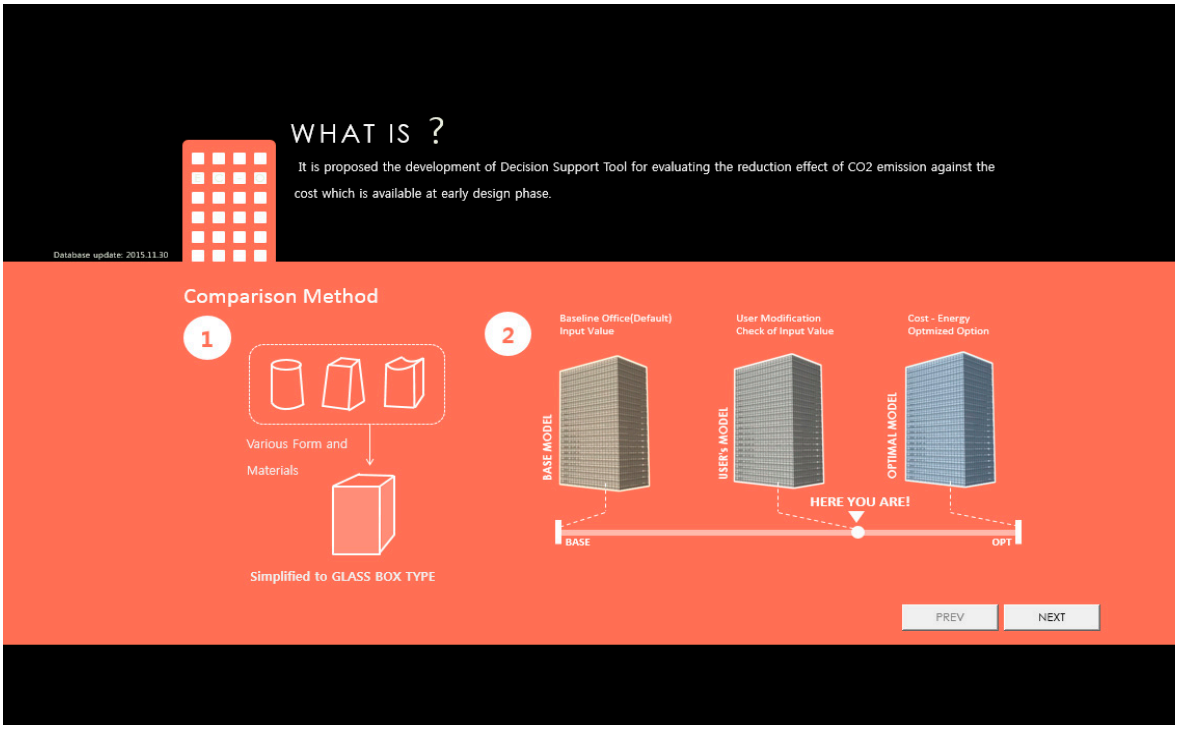


Figure 8. Fast Decision Support Tool developed using excel-based program (output module).

5.2. Case Study

The present study also verified the optimization model by running the model with a MatLab program. Case A was designed with the actual preference of the client (or designer), whereas case B was the model that allowed a significant LCC saving, which was obtained from the optimization model.

Case B, despite its high initial investment cost, provided a higher economic efficiency in terms of life cycle with a lower energy cost than that of case A. When case B increased the efficiency by selecting a chilled beam to enhance the envelope performance (a better U-value of the wall and enhanced window and air tightness), the initial investment grew by 300,000 won/m^2. The lighting facility cost, when LED lightings replaced the general ones, also rose by 300,000 won/m^2. The initial investment was finally increased by 300,000 won/m^2, and the energy consumption decreased by 300,000 won/m^2 with the enhanced envelope performance and 300,000 won/m^2 with the improved facility efficiency. This meant that with 40 years of the building's operation there will be a drop in the total operating cost by 60%. For case B, the total LCC was reduced by 35% compared to case A (Table 11). A continuous comparison between case A (proposed model) and case B (optimized model) enabled the decision makers to find an alternative which is closer to a nZEB. A comparison with the basic model is not described here.

Table 11. Evaluation Results.

Category		Case A (Proposed Model)	Case B (Optimized Model)
Architecture	Gross Area	40,000 m^2	
	Floor Area	2200 m^2	
	Floor Height	4.3 m	
	Width Depth Ratio	1:2	
	Orientation	South	
	Window Wall Ratio	40%	40%
	U-Value of Wall	0.27 W/m^2·K	0.09 W/m^2·K
	U-Value of Window	1.72 W/m^2·K	1.0 W/m^2·K
	Solar Heat Gain Coefficient	60%	30%
	Air Tightness	2.0	0.5
Mechanical	Air Distribution System	CAV + FCU	Chilled Beam + Dedicated Outdoor Air System
	Plant System	Direct Fired Absorption Chiller/Heater	
Electrical	Lighting Density	15 W/m^2	7 W/m^2
Energy Use	Mechanical	210.61 kWh/m^2·year	78.66 kWh/m^2·y
	Electric	45.27 kWh/m^2·year	13.51 kWh/m^2·y
	Process	106.05 kWh/m^2·year	106.05 kWh/m^2·y
	Total	361.97 kWh/m^2·year	294.24 kWh/m^2·y
CO_2 Emission		208.29 TCO_2/m^2·year	129.07 TCO_2/m^2·y
Cost	Investment Cost	1,780,150 won/m^2	1,809,103 won/m^2
	Energy Cost (40 years)	79,001,783 won/m^2	50,749,169 won/m^2
	Total	80,781,933 won/m^2	52,558,272 won/m^2

6. Conclusions

Multi-objective optimizations have been applied with multiple optimization targets (objective functions) through use of genetic algorithm [6], the Taguchi-ANOVA method [9] and the PSO algorithm [10] as optimization techniques. Recent studies on life cycle cost buildings published in other countries [11–15] estimated all costs, including building energy and reduction of CO_2 emissions. However, Korean studies have limited their scope to optimal construction cost, focusing on structure, materials and construction. Especially, past studies rarely used a generic algorithm (GA), which is known to be a good method to identify the cost optimization model based on discrete variable data.

Therefore, LCC evaluation and a cost optimal design tool with GA algorithm (MATLAB program) were developed in the present study which can be used in the early design phase. With this tool the client can recognize the financial benefit of nZEB rapidly in the early design phase and invest to achieve a higher performance from the nZEB. This newly developed tool can also provide the necessary guidance to a designer on the building design of a nZEB and enable them to take effective decisions without spending much time and effort.

It has been found in this study that more design variables must be considered in the early design phase to be able to easily use the tool for fast decision making. Programs for different purposes should be developed that can facilitate decision making for the design of other buildings as well as office buildings. It is essential to continue to update the database of the developed programs as the performance of the technology applied to the baseline building will improve and the unit cost will fall as the technology develops. Therefore, an up-to-date database needs to be maintained through market surveys.

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