MODEL STUDY OF DESIGN COMPONENTS FOR ENERGY-PERFORMANCE-BASED ARCHITECTURAL DESIGN USING BIM LOD 100

KweonHyoung Lee[1], InHan Kim[2], SeungYeon Choo[3]

ABSTRACT

One of the biggest global issues at present involves the search for measures to conserve energy and to combat climate change. Because of an increase in natural disasters and energy use, architects and engineers have been focusing more on creating green buildings with low-carbon designs. Building information modeling (BIM) is used to record all of the data related to buildings from the early design stage. This information can be used to respond to energy simulation feedback and to accommodate changes that may be necessary during the design developments. To mitigate greenhouse gas emissions and to conserve energy in the buildings, the application of a BIM-based low-carbon design technique is required from the early design stage. However, the existing research is limited to sub-segmented topics; therefore, it is difficult for designers to establish a rank grade for a low-carbon design technique that is required for application in design planning.

In this study, we attempt to analyze the rank grade and the correlation among design components that affect a building's energy performance. We selected tower buildings for the experiment, as they consume a massive amount of energy and have a large impact on the surrounding environment. We analyzed the values that resulted from different shapes, scales, slenderness ratios, window-to-wall ratios, and solar orientations of the tower buildings. Then, we identified a correlation and rank grade among different design components. Architects can maximize energy performance efficiency by considering and applying the rank grade of a low-carbon design technique during design planning. In addition, the development of guidelines for green BIM would reduce confusion in the decision-making process and design modification during the stages of design development, which would then minimize the cost. Furthermore, it is expected that this study can be used to create a database for the realization of green buildings.

KEYWORDS

Green BIM, Energy-performance-based Architecture, Design Components, Tower Office

1. Kyungpook National University, Daegu, Republic of Korea.
2. Kyunghee University Global Campus, Yongin, Republic of Korea.
3. Kyungpook National University, Daegu, Republic of Korea, corresponding author: choo@knu.ac.kr.

1. INTRODUCTION

One of the biggest global issues at present involves the search for measures to conserve energy and to combat climate change. The Fukushima nuclear disaster of May 2011 brought renewed attention to the need for new and renewable energy sources, efficient energy management, and energy saving. In Korea, there was a sudden escalation of electricity demand in September 2011 due to a heat wave, and the overload of electricity led to a massive nationwide power failure and consequently to enormous damage. This problem occurred because the Korea Electric Power Corporation (KEPCO) underestimated the demand for electricity. With disasters such as these coupled with skyrocketing energy use, attention on green buildings and low-carbon design has been increasing. At the 17th Conference of the United Nations Framework Convention on Climate Change (UNFCCC), which was held in Durban, South Africa in December 2011, the second commitment period of the Kyoto Protocol was agreed upon, and it was decided to establish a single protocol or legally binding deal applicable to all parties after 2020. It is expected that each of the world's countries will accelerate the preparation of policies to mitigate greenhouse gas emissions. For instance, the Korean government is making efforts to strengthen the guidelines for reducing the primary energy consumption of buildings.

It is advantageous to use building information modeling (BIM) for the integrated operation of design, construction, and maintenance. Therefore, there is a need to establish a simulation-based performance assessment system that can utilize BIM data. However, at present, members of the architectural field are focused mainly on pursuing energy-saving construction materials or energy-saving measures using new and renewable energies. The preparation of an energy-performance assessment system that utilizes BIM-based simulation, which can be used to address building maintenance through life-cycle management, is still unsatisfactory. In particular, to mitigate greenhouse gas emissions and conserve energy in the architectural sector, a continuous study on a low-carbon design technique using BIM for energy saving in buildings is required.

With regard to architectural planning components, in this study we will analyze the impact of each component of a building's energy performance in order to elucidate low-carbon design techniques and to establish a rank grade among design components. We will also make a correlation among design techniques based on the rank grade setting. The purpose of this study is to build a database for the realization of low-carbon green buildings by presenting measures for the development of energy-saving design techniques.

In this study, we analyze architectural design components that affect the energy performance of buildings in the early design stage. The window-to-wall ratio has a big impact on energy saving when applied to the early design stage due to the characteristics of architectural planning. The direct architectural design components necessary to ensure energy saving are as follows: solar orientation of buildings, ratio of lateral-to-longitudinal length, shape of buildings, elevation type, opening ratio, insolation, and heat insulation. We selected tower buildings for the experiments, as they are increasingly used as large-scale business facilities, they consume a massive amount of energy, and they have a large impact on the surrounding environment. In this article, we will analyze the correlation between architectural design technique and energy performance using the results of simulations with different window-to-wall ratios, design types, slenderness ratios, and solar orientations (slenderness ratio refers to the ratio of "width:length" based on a southern oriented building, while the ratio of lateral-to-longitudinal length means "lateral/longitudinal length" without distinction of width or length). We will also suggest ways to apply low-carbon design techniques in tower office buildings.

In the first stage, the current state of the BIM-based energy-performance assessment was analyzed. In the second stage, we analyzed the parameter set values used for energy-performance assessment. Next, representative types and a control group were selected. Based on the process, the modeling level and simulation scale were selected, and a BIM model based on LOD (level of development: AIA Document E202TM-2008, 2008) 100 was prepared. In the third stage, parameters based on the American Society of Heating, Refrigeration, and Air-conditioning Engineers (ASHRAE) were introduced, and the resulting values were compared and analyzed through simulation. In the final stage, a correlation was made between architectural design technique and energy performance.

2. CURRENT STATE OF ENERGY-PERFORMANCE ASSESSMENT

2.1 BIM Guidelines and Eco-friendly Building Certification Systems

BIM guidelines and eco-friendly building certification guidelines are being actively implemented in the United States and Europe. Eco-friendly guidelines for BIM-based energy-performance assessment have been developed in many countries as part of a major energy-saving agenda. The United States, the UK, and Australia are making efforts to introduce a simulation-based energy-performance assessment system (Lee Shi-Nae, 2009).

In the past, the general focus was on concept and type in the early design stage of a building, and there was insufficient consideration for energy performance. In those cases, as the design process proceeded, additional installation and improvement in insulation performance were required in order to improve energy performance. Consequently, without solving some of the problems that could be overcome in the early design stage, impartial assessments were implemented that focused on performance components such as heating, ventilation, and air conditioning (HVAC) systems, without much consideration of eco-friendly architectural plans. In addition, to overcome such architectural limitations for energy performance, people have to put up with excessive installation, overlapping resources, and investment of expenses.

2.1.1 Methods of Assessing Building Energy Performance in Korea

The energy-performance assessment system in Korea conforms to the Green Building Construction Support Act. According to the law, for buildings with a total floor area larger than 500 m2, an energy-saving plan must be submitted for construction permission, permission request, report of usage change, or change of details in the building register. Sub-guidelines under the Green Building Creation Support Act include G-SEED (Ministry of Land, Infrastructure and Transport, 2013), Energy Efficiency Certification Grade, and Energy-saving Design Standard of Buildings.

G-SEED was amended in 2013. It establishes nine sectors of categories and assessment items in seven construction areas. Grades are calculated by adding up the scores according to the checklists. Among the scores, the energy sector of commercial buildings accounts for 21.2% (green standard for energy and environmental design, 2014), which is the highest proportion along with the interior environment sector. G-SEED includes details on how to reduce the lighting load. However, at present, heating and cooling loads (HCL) by natural lighting and the window-to-wall ratio are not considered. In addition, the energy efficiency improvement items are only assessed using the Energy Performance Index (EPI) scores in the energy-saving design standard or building energy efficiency certification grades. Simulation-based energy performance assessment is not being considered yet.

According to the Energy Saving Design Standard, amended in 2012, EPI assessment items account for 36.12% of all assessment items. However, assessment items are based on a checklist assessment method for the heat transmission coefficient and the insulation performance of construction materials.

Therefore, in the early design stage, it is difficult to apply energy-saving plans by scale, type, or design. In addition, eco-friendly and energy-saving plans can focus mainly on insulation and installation.

According to the Energy Efficiency Grade Assessment Standard in "Regulation on Building Energy Efficiency Grade Certification," which has been applied since 2010, energy efficiency for the certification of office buildings should conform to international standards such as ISO 13790. However, this method can also be applied to the assessment of construction installation and insulation performance rather than assessment of architectural planning.

2.1.2 Methods of Assessing Building Energy Performance in Other Countries

Eco-friendly building certification standards in other countries include BREEAM (Building Research Establishment Environment Method) developed by Britain's Building Research Establishment, Australia's Green Star, Japan's CASBEE (Comprehensive Assessment System for Building Environmental Efficiency), Canada's BEPAC (Building and Environmental Performance Assessment Criteria), and the United States' LEED (Leadership in Energy and Environmental Design). LEED is widely used across North America, and it has recently emerged as the international standard with the most powerful authority.

LEED was developed by the U.S. Green Building Council. It evaluates seven sectors, including sustainable site development, water saving, energy efficiency, materials selection, indoor environmental quality, innovation and design process, and regional purity. One of the items specified in LEED is "Optimize Energy Performance, OPTION 1. Whole Building Energy Simulation." According to this, new buildings should prove their energy savings through simulation based on ASHRAE Standard 90.1. By proving energy-performance improvement through simulation, scores can be obtained according to the energy-saving rate. Through this process, LEED reflects the differences in energy performance based on design changes to buildings.

2.2 ASHRAE Standard and ISO 13790

The representative simulation engine using the energy-performance analysis method of ASHRAE Standard is the DOE (Department of Energy). ASHRAE created the ASHRAE Handbook to establish and implement about 150 standards, including test methods for refrigeration devices, air-conditioners, water-cooling systems, purifiers, filters, and solar heat use. Of these, ASHRAE Standard 90.1-2013 is Preliminary Determination: Quantitative Analysis. As shown in Table 1, the required data for simulation can be broadly divided into seven categories. The advantage of this is the possibility to assess architectural planning components.

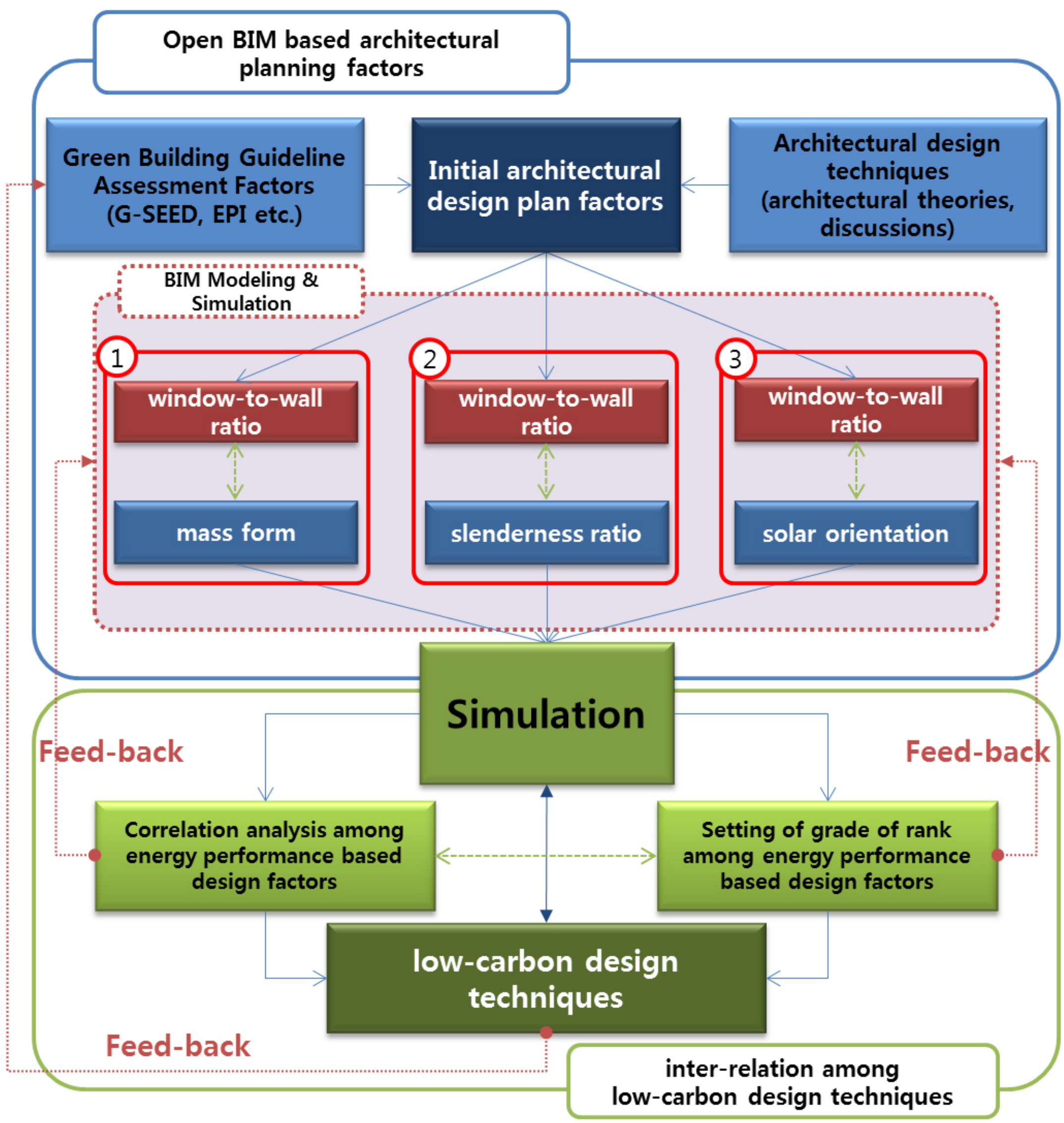
Meanwhile, the EU has issued an energy-performance certificate (EPC) through an energy performance of buildings directive (EPBD) that requires the documents to be attached

TABLE 1: General Required Data for Energy-performance Analysis.

Required data	Sub-items
1. Building location data	climate setting (weather data)
	regional condition (locational data)
2. Architectural component data	solar orientation / alignment (direction)
	type of building
	flat surface slenderness ratio
	opening shape
	shade
3. Building 3D geometric data	floor area
	roof area
	story height / volume
	window area
	wall area
4. Material data	heat transmission coefficient of walls
	heat transmission coefficient of roof
	heat transmission coefficient of windows
	heat transmission coefficient of floor
5. Zone/thermal area data	zone
	space
	void
6. Installation / system data	ventilation system
	heating system
	cooling system
	water heating system
	lighting system electric appliances
7. Operation & building usage data	activity type
	ventilation rate / infiltration rate
	set temperature condition
	number of occupants
	building operation schedule

for new construction, sale, or lease. Based on this system, EU countries are developing programs that can interpret the total energy requirements of a building, such as heating, cooling, water heating, ventilation, and lighting. The programs are based on the international standard of ISO 13790. The ISO 13790–based energy requirement calculation programs for residential buildings typically include SAP 2009 (The Government's Standard Assessment Procedure for Energy Rating of Dwellings) of the British national standard, and PHPP 2007 (Passive House Planning Package) by German's Passive House Institute. All these programs use a monthly calculation method that is among the calculation methods presented by ISO 13790. ISO 13790 stipulates calculation methods of energy requirements for the heating and cooling of a building, and this monthly calculation method includes calculation of the envelope, ventilation heat transmission, and internal heat, as well as obtaining solar heat gain. Among these, the energy requirement for heating and cooling refers to the value of energy required to maintain a set temperature of heating and cooling against the temperature of the outer atmosphere. For ISO 13790–based energy performance assessment, three property data, rather than all design components, are entered to analyze energy performance. The first are shape data, such as the area of the wall and material properties. Second, installation components and the thermal area's property data are input. Third, location data, weather data, and schedule data are input. This method has the advantage of identifying energy consumption promptly by inputting building data and calculating the results. However, it also has a disadvantage in that it is difficult to consider design properties.

Figure 1: Experiment Planning Chart.



3. BIM-BASED ENERGY MODELING

3.1 Simulation Requirement and Tools

Because of urban overcrowding, recent architectural trends have been focused on solving the horizontal placement problem through vertical structures. Tower office buildings have been preferred. However, as with the landmark nature of towers, there has been more attention on structures and envelopes rather than energy performance. Considering the scale of the buildings, the impact on the surrounding environment, and the massive energy consumption, it is necessary to assess the architectural planning components of green BIM-based design of tower office buildings.

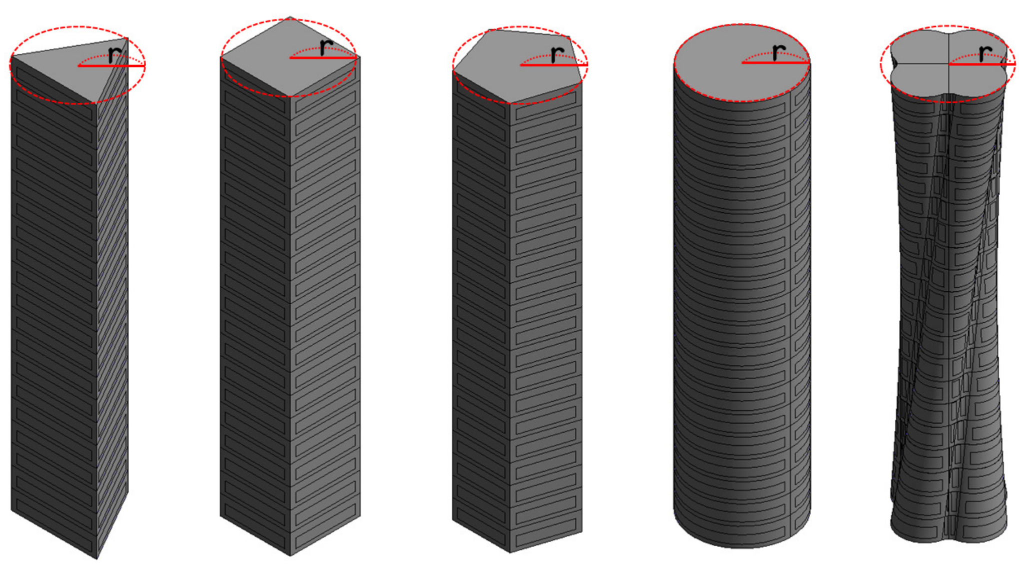
A recent popular architectural trend is a square-shaped lot. Presently, the ratio of the lateral-to-longitudinal length of a standard lot in Korea is 0.75–1.9 with an average of 1.2 and a maximum under 2.0. The individual lot scale is under 600 m2, with a lower than 1:2 ratio of lateral and longitudinal lengths (Jeong Jae-Hoon, 2008). In this study, a test was performed with a standard of 400 m2 considering the building-to-land ratio for a construction area in all experiments except for Experiment II.

The premise hypotheses for simulation are as follows:

- Window-to-wall ratio for solar orientation is always the same.
- There is no 0% window-to-wall ratio due to the area of the ventilation window.
- There is no 100% window-to-wall ratio due to structures such as floors and pillars.

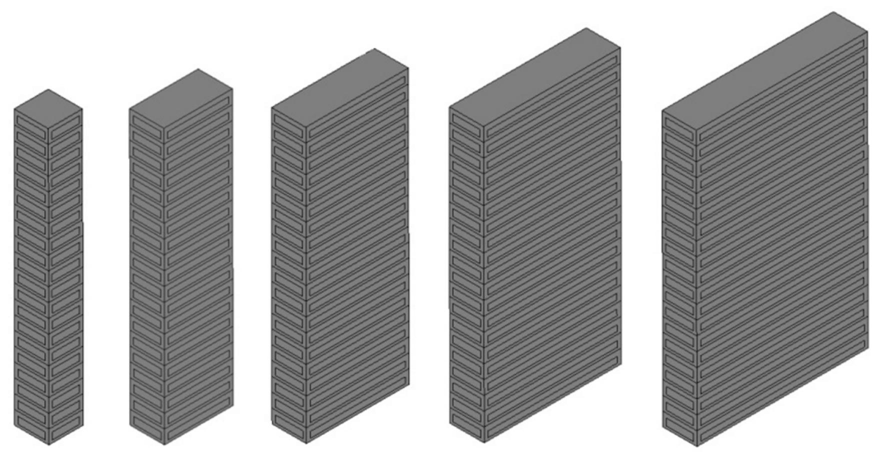
I: In the early design stage of tower office buildings, typical types of triangles, quadrangles, pentagons, and circles were selected as a mass form of design options. The masses in the early design stage were maintained with the same slenderness ratio. To keep the same distance from the center of a building to the outermost wall, each building is modeled to inscribe a circle with a radius (r) of 10, 15, and 20 m, respectively, as shown in Figure 2. The experiment was conducted by altering the window-to-wall ratios from 10% to 90% according to changes in the tower office building's shape and scale.

Figure 2: BIM-based Energy Simulation Model 1 (Design Type).



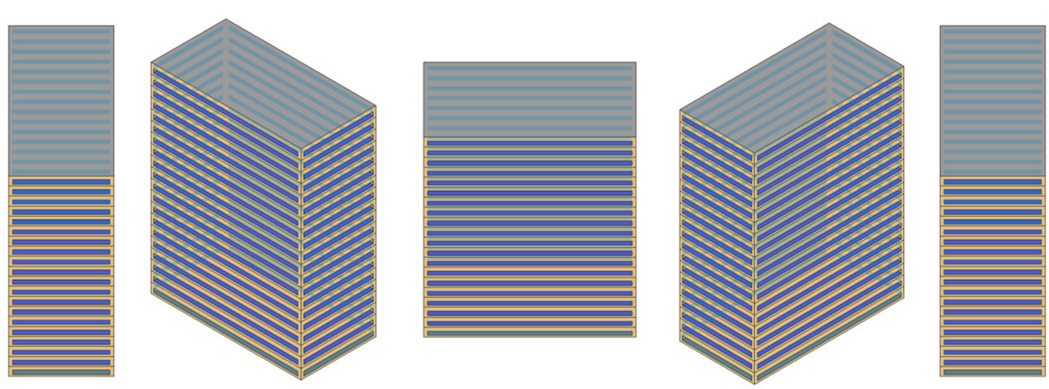
II: In this experiment, a basic quadrangle tower is placed facing south. The tower's slenderness ratios are not generally over 3.0. However, as large buildings are generally constructed in a lot combining multiple lots, the slenderness ratio of longitudinal and lateral lengths is modeled in integer proportion from 5:1 to 1:5, as shown in Figure 3. Through this process, we attempted to draw a clear proportional relation of the slenderness ratio influencing energy performance. In addition, the study hypothesized that the window-to-wall ratio for each solar orientation is consistent, and the experiment was conducted by altering the window-to-wall ratios from 10% to 90% according to the tower office building's change of slenderness ratio and scale.

Figure 3: BIM-based Energy Simulation Model 2 (Slenderness Ratio).



III: Considering that the slenderness ratios of office towers are not generally over 3.0, the slenderness ratios were set within the range of 1.0–3.0. The change of solar orientation was set with the baseline on the south, and the experiment was conducted every 10° from –90° to +90°, as shown in Figure 4. The window-to-wall ratio for each solar orientation was hypothesized to be the same. The experiment was conducted by altering the window-to-wall ratio from 10% to 90% according to a change in the slenderness ratio and solar orientation.

Figure 4: BIM-based Energy Simulation Model 3 (Solar Orientation).



For a simulation tool, we selected Autodesk's Project Vasari, which is compatible with Revit Architecture and Revit MEP. Project Vasari (project vasari beta 3, 2013) is a program that enables a mass-type BIM model energy-performance analysis in the early design stage. In addition, as it uses a DOE-2-based engine, it is relatively reliable. At present, it is possible to execute without conversion of extension or use of a convertor in Revit Architecture and Revit MEP. Therefore, the advantage is that architects can implement an assessment of the options instantly without data loss or separate operation, and the program is suitable for assessment of mass type options.

3.2 BIM Modeling Levels and Parameters

As there is no satisfactory Korean guideline for modeling levels, we used AIA Document E202TM-2008 defined by the American Institute of Architects to conduct modeling in accordance with LOD (level of development, level of detail) 100. Table 2 illustrates the requirements for the BIM modeling level at each LOD. Considering the modeling level in the early planning design, this study conducted modeling based on LOD 100, which can assess the scale of buildings at the level of concept design in Korea.

The summary of BIM modeling is prepared based on LOD 100 as in Table 3. Tables 4 and 5 illustrate the parameters for energy-performance assessment. These were input using basic setting values provided by Project Vasari based on ASHRAE standard 2007.

TABLE 2: BIM Modeling Level Requirements of LOD 100.

LOD	Object Physical Property	Energy Performance Analysis Requirements
LOD 100	Mass Length Mass Width Mass Height Mass Area Mass Volume	Location Weather Data HVAC Performance Basis Humidity Requirement Schedule Type

TABLE 3: Building Summary.

Items	Description
Building Type	Office
Location Data (Latitude/Longitude/Above Sea Level)	Seoul (37.57/126.98/82 m)
Weather Data	Seoul (Vasari)
Height (Story/Floor Height)	80 m (20 F / 4 m)
Space Type	Office – Open Plan
Condition Type	Heated and Cooled
HVAC System	Central VAV, HW Heat, Chiller 5.96 COP, Boilers 84.5 eff

TABLE 4: Setting Values of Space Property Parameter. (Space-Building Properties ASHRAE 2007)

Space Definitions	Office Open Plan
People Per 100 Sq Meter	3.5
People Sensible Heat Gain (W/person)	73
People Latent Gain (W/person)	59
People Sensible Heat Gain IP (Btuh/person)	250
People Latent Heat Gain IP (Btuh/person)	200
Lighting Load Density (W/sqMeter)	11.84
Power Load Density (W/sqMeter)	16.1
Electrical Equipment Radiant Percentage	0.3

TABLE 5: Energy Model, Predeterminded Values.

Mass Model	R-value, $W/m^2 \cdot °K$	Unit density, kg/m^2	Heat capacity, $J/m^2 \cdot °K$
Exterior Wall	3.05	155.97	0.214
Interior Wall	0.49	455.55	0.193
Exterior Wall Underground	11	110	22
Roof	22.7	9	2
Floor	4.9	2	1
Slab	34.5	170	34
	U-valueBtu/(ft2·oF·h)	SHGC	Tvis
Glazing	0.56	0.69	0.78
Skylight	0.56	0.69	0.78

4. CORRELATION ANALYSIS OF ENERGY PERFORMANCE AMONG BIM-BASED DESIGN COMPONENTS OF ARCHITECTURE

4.1 Correlation Analysis of Energy Performance Depending on Mass Type and Window-to-wall Ratio

The result of calculating heating and cooling loads (HCL) by altering the window-to-wall ratio (WWR) per tower type from 10% to 90% showed that HCL increased at a certain proportion as WWR increased. Table 6 shows that as WWR increased from 10% to 90%, the heating and cooling load of each tower increased from a minimum of 1.8-fold (10–90%, 20 m circular tower) to a maximum of 2.9-fold (10–90%, 10 m triangular tower).

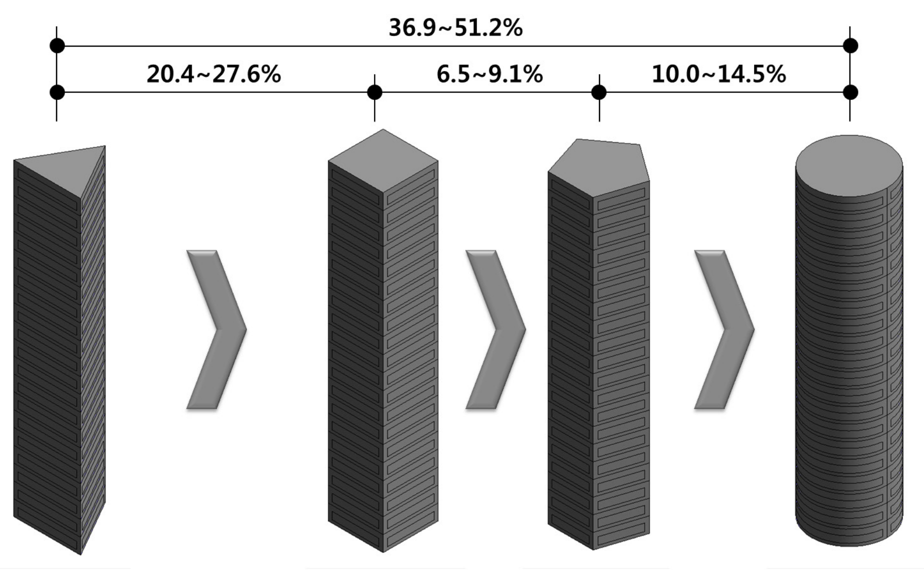
The results of the experiments showed that the impact of WWR on energy performance was high. To measure the change of HCL in detail by the type and scale of each tower, we identified an envelope area, a volume, and a floor area of each tower model, and we measured the HCL. The findings showed that the heating and cooling load per envelope area is proportional to the envelope area regardless of tower type. This indicates that the envelope area can be the scale when calculating the scale of the tower in the early design stage. The floor area show that they are more advantageous if the shape is closer to circular. Figure 5 shows the grade of rank of HCL by type.

TABLE 6: HCL as per WWR of Tower Type and Scale.

[Unit: 1,000 MJ (=1GJ)]

radius / WWR	Triangle			Quadrangle		
	10 m	15 m	20 m	10 m	15 m	20 m
10%	1,693	3,100	4,967	2,194	4,247	7,038
20%	2,190	3,829	5,918	2,729	5,023	8,031
30%	2,658	4,538	6,851	3,244	5,786	9,031
40%	3,097	5,216	7,759	3,737	6,531	10,016
50%	3,507	5,863	8,642	4,205	7,257	10,985
60%	3,891	6,477	9,492	4,649	7,958	11,935
70%	4,253	7,063	10,310	5,072	8,635	12,863
80%	4,592	7,623	11,095	5,474	9,286	13,769
90%	4,911	8,153	11,848	5,856	9,912	14,648
radius / WWR	Pentagon			Circle		
	10 m	15 m	20 m	10 m	15 m	20 m
10%	2,473	4,878	8,190	3,035	6,138	10,569
20%	3,024	5,674	9,188	3,583	6,938	11,516
30%	3,559	6,462	10,214	4,140	7,752	12,534
40%	4,076	7,236	11,234	4,683	8,564	13,590
50%	4,570	7,993	12,242	5,215	9,359	14,646
60%	5,042	8,730	13,231	5,730	8,934	15,692
70%	5,491	9,447	14,205	6,291	10,901	16,727
80%	5,922	10,141	15,159	6,902	11,642	17,747
90%	6,333	10,810	16,092	7,133	12,381	18,752

Figure 5: Grade of Rank of HCL of Unit Area by Type.



4.2 Correlation Analysis of Energy Performance Depending on Slenderness Ratio and Window-to-wall Ratio

The study classified the slenderness ratios of towers from 5:1 to 1:5, and the window-to-wall ratios from 10% to 90% to yield HCL. When the slenderness ratio was 1.0, the HCL increased at a certain rate. As the window-to-wall ratio increased, the increase rate of HCL decreased. (The increase rate had a negative correlation with the square of the slenderness ratio.) In the same total floor areas and the same volumes, slenderness ratios closer to 1.0 were 9–20% (on average 16.6%) more advantageous compared to a slenderness ratio of 5.0. Especially, in the same envelope areas, the HCL per unit area could save 12–25% (on average 21.2%) compared to 5.0. This indicates that designing a small envelope area is more advantageous for energy performance than a small slenderness ratio.

When the total floor area and volume increased, HCL decreased. However, when the envelope area increased, the HCL per unit envelope area increased gradually, showing a positive correlation with HCL. This supports the findings from Experiment I that when the slenderness ratios are the same, the envelope area has the highest impact on HCL.

As office towers generally do not have a slenderness ratio beyond 3.0, the study set the slenderness ratio of buildings within the range of 1.0–3.0. As can be seen from Table 7, the HCL did not increase but rather decreased as the WWR increased. This indicates that buildings with a bigger WWR have a higher impact on HCL per WWR.

TABLE 7: Change of HCL per Unit Envelope Area Depending on Scale and Slenderness Ratio (SR)

Scale	30×10	20×10	30×20	20×20	20×30	10×20	10×30	Mean
SR	3:1	2:1	1.5:1	1:1	1:1.5	1:2	1:3	
10~20%	28.0	29.4	20.6	23.3	20.6	29.4	28.0	25.6
20~30%	21.0	21.6	16.8	18.5	16.8	21.6	21.0	19.6
30~40%	16.5	16.8	14.0	15.1	14.0	16.8	16.5	15.7
40~50%	13.4	13.6	11.9	12.6	11.9	13.6	13.4	12.9
50~60%	11.2	11.3	10.3	10.7	10.3	11.3	11.2	10.9
60~70%	9.6	9.6	9.0	9.3	9.0	9.6	9.6	9.4
70~80%	8.3	8.3	8.0	8.1	8.0	8.3	8.3	8.2
80~90%	7.3	7.2	7.1	7.2	7.1	7.2	7.3	7.2
10~90%	189.0	195.5	149.8	165.5	149.8	195.5	189.0	176.3

4.3 Correlation Analysis of Energy Performance as per Solar Orientation Setting and WWR

As was mentioned in Chapter 3, most office towers do not have a slenderness ratio beyond 1:3 because of the limitations of the lot scale. Therefore, the study set the slenderness ratio as 1:1, 1:1.5, 1:2, and 1:3, and HCL was analyzed by changing solar orientation, with the baseline of the South direction (0°) from the East direction (+90°) to the West direction (–90°) at each span of 10°.

As can be seen in Figure 6, in a 30 m × 10 m tower with a baseline of 0°, the HLC was the lowest within the range of ±10° and the highest in the range of ±50° to ±70°. As in Experiment II, an increase of WWR leads to a gradual decrease of HCL (W/m2). Higher WWR leads to a bigger change of HCL. The difference for the solar orientation is smallest when the

Figure 6: HCL by Change of Solar Orientation and WWR in 30×10 Tower (MJ).

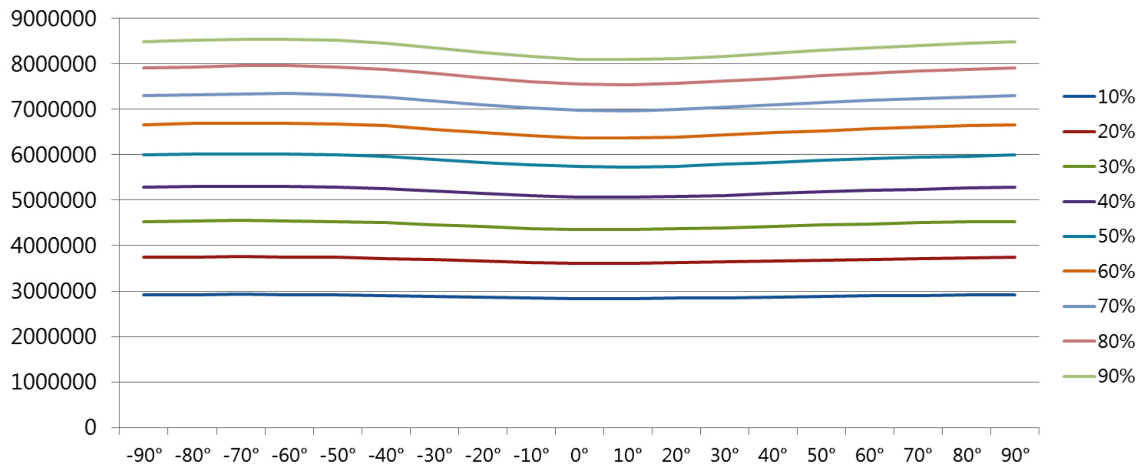


TABLE 8: HCL Deviation Ratio per Unit Area Depending on the Change of Solar Orientation and WWR

Scale		30×10	20×10	30×20	20×20	20×30	10×20	10×30
Slenderness R		3:1	2:1	1.5:1	1:1	1:1.5	1:2	1:3
10%	Mean	480.9	514.1	397.3	424.6	397.3	514.1	480.9
	DR	3.21%	2.31%	1.12%	0.35%	1.12%	2.31%	3.21%
20%	Mean	615.3	665.2	479.1	523.7	479.1	665.2	615.3
	DR	4.08%	2.86%	1.54%	0.58%	1.54%	2.86%	4.08%
30%	Mean	744.3	809.0	559.5	620.5	559.5	809.0	744.3
	DR	4.56%	3.20%	1.81%	0.67%	1.81%	3.20%	4.56%
40%	Mean	866.8	944.9	638.0	714.0	638.0	944.9	866.8
	DR	4.87%	3.42%	1.98%	0.73%	1.98%	3.42%	4.87%
50%	Mean	982.9	1073.1	714.2	803.9	714.2	1073.1	982.9
	DR	5.09%	3.57%	2.10%	0.73%	2.10%	3.57%	5.09%
60%	Mean	1093.0	1194.1	787.8	890.0	787.8	1194.1	1093.0
	DR	5.25%	3.68%	2.18%	0.76%	2.18%	3.68%	5.25%
70%	Mean	1197.4	1308.5	858.7	972.4	858.7	1308.5	1197.4
	DR	5.38%	3.76%	2.25%	0.83%	2.25%	3.76%	5.38%
80%	Mean	1296.6	1416.7	927.1	1051.5	927.1	1416.7	1296.6
	DR	5.48%	3.82%	2.31%	0.85%	2.31%	3.82%	5.48%
90%	Mean	1390.7	1519.3	992.9	1127.2	992.9	1519.3	1390.7
	DR	5.55%	3.87%	2.36%	0.87%	2.36%	3.87%	5.55%

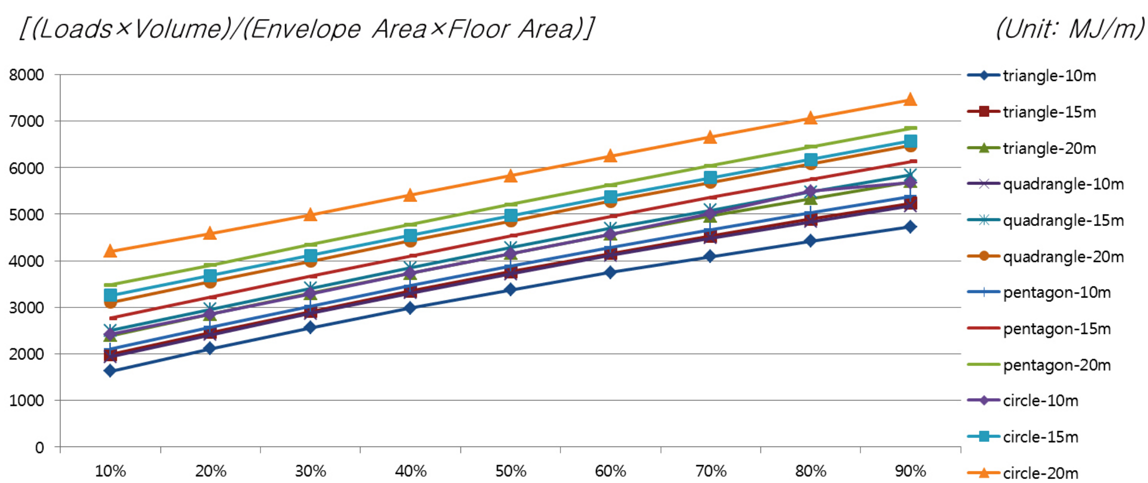
slenderness ratio is 1:1 and largest when the slenderness ratio is 1:3, as shown in Table 8. The deviation ratio (DR) gradually increased as per WWR and also increased when the slenderness ratio increased. When the slenderness ratio was 1:1, the difference in the HCL for the solar orientation was insignificant from a minimum of 0.35% to a maximum of 0.87%. However, when the slenderness ratio was 1:3, it increased to the range of 3.21%–5.55%.

4.4 Summary of Correlation and Energy Efficiency

The results of analyzing the correlation of HCL with the scale and WWR of the tower based on the analyzed HCL per floor area, HCL per envelope area, and HCL per volume are shown in Figure 7 and Table 9.

To establish a correlation of HCL with the scale and WWR of the building, the study set three conditions on the tower type. Using the resulting value that HCL is proportional to WWR per envelope area, Equation (1) is obtained.

Figure 7: Correlation Graph of Type, Scale, and WWR of Towers.



1. *Volume (m^3) = Area of Baseline Floor (m^2) × Height (80 m)*
2. *Floor Area (m^2) = Area of Baseline Floor (m^2) × Number of Floors (20 floors)*
3. *Volume (m^3)/Floor Area (m^2) = Height (80 m)/Number of Floors (20 floors)*
   = Floor Height (4 m)

• Loads/(Envelope × Floor Area/Volume)
= (Load × Volume)/(Envelope × Floor Area)
= (Load × Height)/(Envelope × Number of Floors)
= Load/(Envelope × Height) ⇒ K (MJ/m)
[(Load/Envelope) is proportional to WWR.]

∴Proportionate to Load=K{(Envelope × Floor Area)/Volume} .... *(1)*
i) K is a proportional factor depending on WWR and Floor Height

Section 4.1 identified that HCL can vary up to two- to three-fold depending on the change of WWR. The result of analyzing the impact on HCL by tower type and WWR

TABLE 9: Correlation Table of Type, Scale, and WWR of Towers.
Loads × Volume / Envelope Area × Floor Area

(Unit: MJ/m)]

WWR \ radius	Triangle 10 m	Triangle 15 m	Triangle 20 m	Quadrangle 10 m	Quadrangle 15 m	Quadrangle 20 m
10%	1,629	1,989	2,390	1,940	2,503	3,110
20%	2,107	2,457	2,847	2,412	2,960	3,549
30%	2,557	2,911	3,296	2,868	3,410	3,991
40%	2,979	3,346	3,733	3,303	3,849	4,426
50%	3,375	3,761	4,158	3,717	4,276	4,855
60%	3,744	4,156	4,567	4,109	4,690	5,274
70%	4,092	4,532	4,960	4,483	5,088	5,685
80%	4,418	4,890	5,338	4,838	5,472	6,085
90%	4,725	5,230	5,700	5,176	5,841	6,474
WWR \ radius	**Pentagon 10 m**	**Pentagon 15 m**	**Pentagon 20 m**	**Circle 10 m**	**Circle 15 m**	**Circle 20 m**
10%	2,104	2,766	3,483	2,415	3,256	4,205
20%	2,573	3,218	3,908	2,851	3,681	4,582
30%	3,028	3,665	4,344	3,294	4,113	4,987
40%	3,467	4,104	4,778	3,726	4,543	5,407
50%	3,888	4,533	5,206	4,150	4,965	5,828
60%	4,289	4,951	5,628	4,560	5,377	6,244
70%	4,671	5,358	6,041	5,006	5,783	6,656
80%	5,038	5,751	6,447	5,491	6,177	7,061
90%	5,388	6,131	6,844	5,675	6,568	7,462

change showed that if the building scale is larger, the building HCL increases but HCL per unit decreases. This is because the envelope area is proportionate to HCL and the increase rate of the floor area and the volume is relatively bigger than the increase rate of the envelope area. This can be evidenced by Equation (1), where Load=K{(Envelope × Floor Area)/Volume}. In addition, HCL can be controlled depending on the floor height. This can also help to predict the relative and broad HCL by tower types.

From the results of Section 4.2, it can be concluded that if the slenderness ratio is closer to 1.0, it is more advantageous for HCL, and the increase rate is inversely proportional to the square of the slenderness ratio. Even with a change of slenderness ratio, if the lateral-to-longitudinal length ratio is the same (for instance, if the lateral-to-longitudinal length ratio is the same at 5.0, even though the slenderness ratios are different at 1:5 and 5:1), there is a similar HCL per unit area, and the error was shown to be a maximum of 6.4%. The proportion relation of Equation (1) can be applicable to HCL depending on the change of slenderness ratio. However, the larger scale showed a decrease in the HCL increase rate and led to a larger error range.

Section 4.3 also identified the proportional relation for Equation (1), and depending on the changing solar orientation, the deviation was shown to be up to 5.55%. However, the correlation depending on the alteration of the solar orientation could not be identified. Generally, southeast (+30° – +60°) and southwest (–30° – –60°) are known to be favorable for HCL; however, the experiment showed that these were disadvantageous. The reason for this difference may be that this experiment hypothesized that the four WWRs of the tower are the same, and previous experiments used the model with windows on longitudinal sides and no windows on lateral sides.

5. CONCLUSIONS

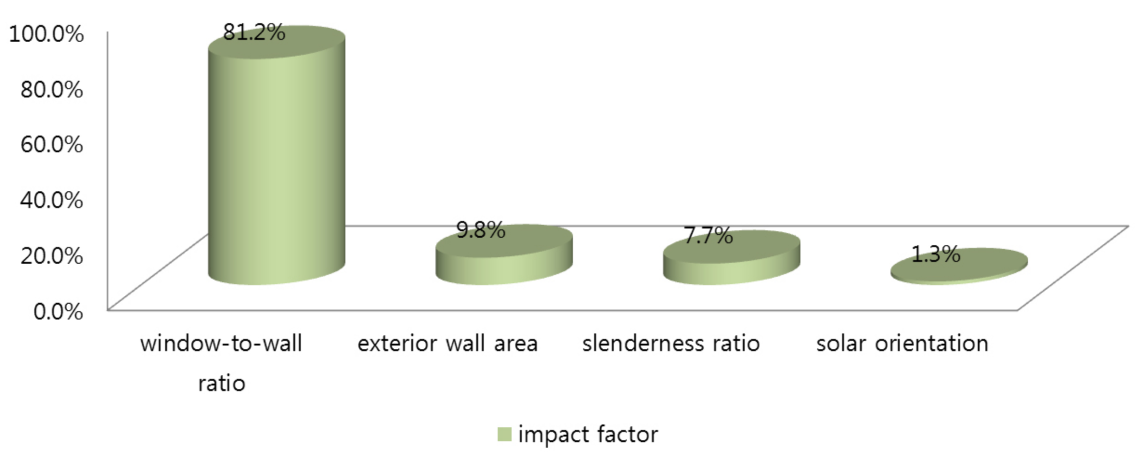
In this study, a correlation was established between a change of HCL and a change of mass type, slenderness ratio, and solar orientation depending on WWR in the building scale at the early design stage. Through this process, we attempted to find energy-saving measures from the early architectural planning.

Through the experiments, we found that the component that has the biggest impact on building energy performance is the WWR, followed by the slenderness ratio, envelope area, and solar orientation. Table 10 shows the change rate of the average HCL when each design component is changed. The WWR is an important design component determining the outer shape of the building, and it has the highest influential power index compared to other design components accounting for HCL. Mass type does have a high impact on HCL, but it is difficult to infer any correlation. However, as HCL shows a proportional relation with envelope area, which comprises the building shape, it is possible to predict HCL depending on building type.

TABLE 10: Influence on HCL by Design Components.

	WWR	Envelope Area	Slenderness Ratio	Solar Orientation
Change Rate	175.0%	21.2%	16.6%	2.7%
Influence	81.2%	9.86%	7.7%	1.3%

Figure 8: Influence on HCL by Design Components.



For instance, a comparison of four towers with the same total floor area is shown in Table 11. Even though the four towers have the same total floor area and volume, each has a different envelope area. As Table 11 shows, the HCL per unit area is more advantageous if the slenderness ratio is closer to 1:1. This is because while the total floor area and volume are the same, the envelope area increases as the slenderness ratio increases. This is evidenced by Equation (1), i.e., "(Envelope × Floor Area) / Volume," which shows that the envelope area is proportionate to HCL.

TABLE 11: Comparison of Towers with the Same Total Floor Area.

Slenderness ratio	1 : 1	1 : 1.5	1 : 2	1 : 3
Total floor area	8,000m^2	8,000m^2	8,000m^2	8,000m^2
Volume	32,000m^3	32,000m^3	32,000m^3	32,000m^3
Envelope Area	6,400m^2	6,531m^2	6,788m^2	7,390m^2
WWR	HCL per Unit Area (MJ/sm/yr)			
10%	644	647	652	669
20%	751	754	766	803
30%	883	886	900	950
40%	1,011	1,012	1,031	1,090
50%	1,132	1,133	1,155	1,224
60%	1,248	1,243	1,273	1,351
70%	1,359	1,358	1,387	1,474
80%	1,466	1,465	1,495	1,591
90%	1,568	1,565	1,601	1,703

Therefore, when considering the HCL of buildings with the same {(Envelope × Floor Area)/Volume}, in the first place WWR should be smaller. (Smaller WWR increases efficiency.) Next, when the floor areas are the same, the envelope area should be as small as possible. When designing mass types, this is applicable by avoiding a triangle-type tower and by designing a slenderness ratio closer to 1.0. In addition, a larger total floor area is more advantageous for HCL per unit area. This is because an increase in the total floor area is relatively larger than an increase in the envelope area as the fixed floor height is used. The total floor area here includes the ratio of width × length, and this refers to the slenderness ratio. (Towers of 10 m × 40 m and 20 m × 20 m have the same total floor area; however, a tower of 20 m × 20 m with a smaller slenderness ratio is more advantageous with respect to HCL.) Lastly, in the case of solar orientation, as can be seen from Experiment III, it is advantageous for HCL to avoid the range of ±50° – ±70° and construct within the range of ±10°.

When summarizing the findings in the research, performance-based rank grade can be given as follows:

- In the design stage, it is more advantageous to design WWR as small as possible. The influence of WWR is the largest among the design components, with 81.2%. Smaller WWR leads to a bigger change range in HCL. Therefore, even a small change can have a significant effect on energy performance.

- It is more advantageous to design a smaller envelope area, particularly if the type is close to circular. However, as {(Envelope × Floor Area)/Volume} is proportionate to HCL, it is desirable to consider these comprehensively.
- For the same total floor area, a slenderness ratio closer to 1:1 is more advantageous for HCL. In addition, even with the same ratio of lateral-to-longitudinal length, relatively long mass in the East and West directions can increase energy performance up to 6.4%.
- Solar orientation has the lowest rank grade. It had the lowest change rate of HCL, and it had the lowest rank grade in this experiment because the same WWR was set for four sides of the tower. Nevertheless, it is found that a larger WWR led to an increase in HCL range. In addition, as it has an average deviation of 2.7% and as Korea has four distinct seasons and is highly influenced by seasonal winds, designing an optimal WWR for solar orientation would maximize efficiency.

This study helps to overcome difficulties for architects in analyzing the values of energy-performance results and in reflecting alternative design using correlation analysis. The architects can infer relative energy performance for alternative designs, and at the same time, they can design types considering WWR in the concept planning stage. Even if the calculation of HCL through simulation is not conducted, they can predict the change in energy performance with a change of type (including WWR) in certain parts and can provide feedback. As such, construction quality can be improved and realization of performance-based architectural design can be possible. Furthermore, it is expected that Green BIM design techniques can be used as component technologies applicable in the early design stage of architecture.

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REFERENCED WORK

1. AIA, AIA Document E202TM-2008, 2008
2. ASHRAE. 2009 ASHRAE Handbook Fundamentals, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., 2009
3. Cho Jong-Soo. “Design Methodology for tall office buildings: Design measurement and integration with regional character”, Ph.D. Dissertation, Chicago University, 2002
4. Choo Seung-Yeon, Lee Kweon-Hyoung & Park Sun-Kyung. “A Study on LOD Modeling level for Development of Green BIM Guideline - Focusing on Energy Performance Assessment” Journal of Architectural Institute of Korea (Planning & Design) 28, no. 6 (2012)
5. Cresswell, Mark G.L. Energy use and economic assessment of a multistory office building with daylighting of the interior core, ASHRAE Transactions, 1995
6. Ha Dae-Woong, Song Jin-Yong, Park Kyung-Soon, & Sohn Won-Deuk. “A Study on Energy Consumption depending on Alteration of Window Area on Building Envelope” Presentation, Spring Conference of Korean Society of Industrials Application, 2008
7. Jeong Gwang-Seob, Kim Su-Bin, Lee Yeon-Saeng, & Kim Young-IL. Green Building System and Installation System, Seongandang, 2009
8. Jeong Jae-Hoon & Kim Ki-Ho. “A Study on Urban Architectural Properties by Slenderness Ratio of Lot - Focusing on Pedestrian Roads in Jungdong Pyeongchon” Presentation, Fall Conference of Urban Design Institute of Korea, November 2008

9. Kim Eun-Hee & Suh Seung-Jik. "Correlation Analysis of Heating and Cooling Loads and Lighting Energy depending on the Daylight", Presentation, Fall Conference of The Korean Solar Energy Society, 2006
10. Korea Energy Management Corporation. 2012 Energy Saving Statistics Handbook, 2012
11. Lee Kweon-Hyoung, Kim In-Han & Choo Seung-Yeon. "A Study on Improvement Measures of Energy Performance Index of BIM based Eco-friendly Building Grade Certification Standard" Journal of Architectural Institute of Korea (Planning & Design) 27, no. 9 (2011)
12. Lee Kweon-Hyoung, Ryu Jeong-Lim & Choo Seung-Yeon. "A Simulation based Study on Correlation Analysis between Window-to-wall Ratio and Heating and Cooling Loads of Tower-type Business Facilities", Journal of Architectural Institute of Korea (Planning & Design) 29, no. 9 (2013)
13. Lee Shi-Nae, Kang Hye-Jin, & Lee On-Gu. "A Study on Improvement of Energy Performance Index through Comparison Analysis of Domestic and Overseas Eco-friendly Building Certification Assessment Standards" Journal of Architectural Institute of Korea (Planning & Design) 29 no. 1 (2009)
14. Ministry of Land, Transport and Maritime Affairs, Energy Saving Design Standard of Buildings, MoLTM Standard 2012-69, 2012
15. Ministry of Land, Transport and Maritime Affairs, Certification Standard of Eco-friendly Buildings, MoLTM Standard 2009-1294, 2009
16. Park Sang-Dong, Architectural planning of Green Buildings and Guideline of Design, Construction, Assessment for Eco-friendly Buildings, 2009
17. Park Seung-Gil & Yoo Ho-Cheon "A Study on Optimal Window-to-Wall Ratio of Commercial Buildings for Energy Efficiency" Journal of Architectural Institute of Korea 25, no. 1 (2005)
18. Song Seung-Yong, Koo Bo-Kyung & Lim Jae-Han, "Analysis of Heating and Cooling Energy Saving Effect by Eliminating Heat Bridge and Increase of Heat Capacity in Multi-unit Dwelling Building using Monthly Calculation Method of ISO 13790" Journal of Architectural Institute of Korea (Planning & Design) 26, no. 7 (2010)
19. United States Department of Energy, EnergyPlus Manual Engineering Reference, Version 2.1, 2007
20. USGBC, 'LEED 2009 for New Construction and Major Renovations Rating System With Alternative Compliance Paths For Projects Outside the U.S.', 2008.11
21. Weiland, Richard P. (FRW), 2009 International Energy Conservation Code and ANSI / ASHRAE / IESNA Standard 90.1-2007 Energy Stan, CengageLearning, 2009