Development of a Sustainable Design Guideline for a School Building in the Early Design Stage

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Abstract

This study was designed to develop a design guideline that is to be used in the early stages of the design process of a school building. Although increased demand for sustainable buildings has driven many architects into sustainable design, non-conventional and sophisticated design steps associated with sustainable buildings preclude proper implementation of such design concept in practice. Appreciating the critical need of a systematic approach, this study is intended to document a design guideline for sustainable buildings. Based on a careful evaluation of available literature, energy strategies and performance levels that affect heating and cooling energy consumption were established for a reference baseline building. Computer simulations were performed using EnergyPlus to analyze the sensitivity of each of the energy strategies to overall performance. Analysis of variance (ANOVA) was also conducted to estimate the relative importance of each energy factor. The priority of each energy factor was then determined in relation to the design guideline.

Keywords: sustainable building; design process; analysis of variance; orthogonal array; energy sensitivity; design guideline

1. Introduction

1.1 Background and Purpose of the Study

In traditional design processes, the early design phase is mostly in the hands of architects allowing very limited participation by engineers. After this early design phase, drawings are handed to engineers, who then perform the required calculations and simulations. However, many architects have recently observed that the early design phase of sustainable buildings requires more calculations and simulations than conventional building design. Most architects have identified sustainable building design as a more iterative and dynamic approach. That said, most of them also found their technical competence to be inadequate for computer simulation.

Despite such incompetence, architects hardly try to attain the technical knowledge that is essential for building performance simulation and calculation. Instead, they use simple rules of thumb, which they have developed in collaboration with engineers. Moreover, some architects have clearly stated that they did not want to gain extensive knowledge of these simulations because it would be too "costly". Consequently, traditional and graphic design guidelines that include simple rules of thumb are still being used by many architects; primarily because they are easy to use.

However the need for a comprehensive design guideline is long overdue and it is imperative to develop it to make decision making even easier in order to attain the targeted performance level.

1.2 Method and Scope of Study

The study intends to develop a design guideline that can be easily used in the initial design stages of sustainable primary schools to be built in the central climatic zone in Korea. Although a number of earlier studies have developed design guidelines for primary schools and other building types, no attempt has yet been made to set a priority index and energy sensitivity concerning the design variables for primary schools in Korea. In this study, extensive literature scouring was carried out to establish the energy-related design variables and performance levels for a baseline building. To analyze the sensitivity of each energy-related design variable to overall performance, computer simulations were performed using EnergyPlus. It is to be noted here that the table of Orthogonal Array was used to calculate the number of simulations required, which decreased the number of experiments to 81 from the original value of $3^{20}$ (= 3,486,784,401). At the same time, the Analysis of Variance (ANOVA) was conducted to estimate the
relative importance of each energy parameter. The results of the ANOVA were used as the data resource to develop the design guideline.

2. Sustainable Design Process and Design Guideline

2.1 Sustainable Building Design Process

For sustainable design, the first task is to establish the performance requirements. The explicit definition of the quantifiable performance requirements is the backbone of the sustainable design paradigm. The design proposal, performance prediction, and performance evaluation constitute a loop of actions that ends at the instant when desirable performance is reached. The "design iteration" describes the process of going through the loop of achieving the desired performance. The presence of design iterations is not unusual in design processes. A building designer initiates a design iteration by generating a design proposal: usually in the form of sketches and drawings of building plans, sections, elevations, etc., focused on aesthetic and spatial performance requirements. The performance of the proposal is then predicted using various modeling and simulation techniques depending on the type and number of the performances to be predicted. Whether a proposal satisfies the pre-established performance requirements depends on the outcome of the performance evaluation process. If the evaluation shows that the proposed design does not fulfill the requirements, the designer has two options left: either reject the idea or adjust it to fit the specifications. (Fig.1.)

2.2 A New Sub-task of Sustainable Design Process

The sustainable design process is a well-known but challenging task. There is always a risk that designers, especially inexperienced ones, will attempt adjustments to satisfy one violated performance requirement that then results in the violation of another requirement that was satisfied in the original design. In this case, the designer is forced to make another design iteration, which could in turn force yet another, and so on. The workflow in Fig.1. can thus lead to a large number of design iterations until a satisfactory solution is found. Each of these new design iterations is time-consuming. Therefore, keeping the general time constraint in building design process in mind, it is desirable to keep the number of design iterations to a minimum. This could be achieved if designers have some knowledge of the consequences of their design decisions prior to making adjustments in the design proposal. In an attempt to include this kind of information in the design iterations, a new subtask called "use of design guidelines" is added. (Fig.2.)

2.3 Framework of a Sustainable Design Guideline

In the new sub-task stage, a design guideline can help architects discover variables that would achieve a sustainable building and inform them about the sensitivity of each variable. Therefore, the design guideline of sustainable buildings during the early design processes should include the features described below.

1) Identification of Key Design Variables

Energy consumption depends on the simultaneous combination of the thermal and bulk properties of many components, e.g., dimensions of the building spaces and glazed areas, ventilation rates, system efficiencies, the climatic conditions, and usage patterns. Therefore, key variables are identified that are relevant to conceptual design decisions. The choice of variables and the associated ranges of their values define the design space to be explored.

2) Sensitivity Analysis

A sensitivity analysis focuses particularly on the changes to energy consumption, which can vary significantly due to the variations in these parameters. Changing one design variable at a time may give insight into the relative effects and sensitivity of the variables to the energy use.

3) Consequences of Different Design Variables for the Energy Use of a Building

As of yet, only a few architects have demonstrated a clear and visual overview of the impact of energy-related decisions on architecture. This guideline is
proposed as a roadmap of example design decisions and its impact on the energy used. It also elucidates which steps are necessary to reach the desired energy use.

3. Energy-Related Design Variables and the Applicable Performance Range Affecting Energy Consumption

3.1 Energy-Related Design Variables Affecting Energy Consumption

There are many design variables that affect the energy consumption of primary school buildings at every stage. Based on an intensive literature research, the number of variables were narrowed down to 20 that have significant effects on the energy consumption of primary schools. These variables include the width of classrooms, height of classrooms, number of classrooms per story, ceiling height, width of corridor, orientation, location of the core, insulation performance (exterior wall, interior wall, windows), window/wall ratio (façade, interior wall, rear), shading, infiltration quantity, SHGC (Solar Heat Gain Coefficient). (Table 1.)

Table 1. Design Parameters Affecting Energy Performance

| Category                  | Energy Strategies                                      |
|---------------------------|--------------------------------------------------------|
| Volume, Shape, Plan       | No. of Classrooms per Story, Width/Depth of Classroom, Ceiling Height, Width of Corridor, Location of Core |
| Arrangement               | Orientation                                            |
| Others                    | Insulation Performance Façade                          |
|                           | Interior Rear                                          |
|                           | Window Performance Façade                              |
|                           | Interior Rear                                          |
|                           | Window/Wall ratio Façade                               |
|                           | Interior Rear                                          |
|                           | Solar Heat Gain Coefficient Façade                     |
|                           | Shading                                                |
|                           | Infiltration Quantity Classrooms                       |
|                           | Etc.                                                   |

3.2 Applicable Ranges of Each Variable

In order to analyze the relative importance of the chosen variables, the practical range for each design variable is set. These ranges are based on the investigated data which encompass performances from the minimum level regulated by the building code to commercialized cutting-edge technologies. Table 2. describes the ranges set for each parameter.

3.3 Description of the Baseline Building

The selection of the baseline building is the crux of the analysis. This is primarily because all of the subsequent calculations and analyses consider the baseline building as a reference. The baseline building has been established from a survey of primary schools in Seoul. The characteristics of this building were determined through careful examination of a typical design. As shown in Fig.3., most of the primary schools in Korea are of a basic module type consisting of 3-5 classrooms that share one core space (rest-rooms, elevators, stairs, etc.). Fig.3. shows a space diagram and a simplified drawing of the model constructed for simulation. Generally, most buildings face south, and the corridor is found on the north side. A brief description of the baseline reference building and characteristics of operation are given in Table 3.

Table 2. The Ranges Set for Each Parameter

| Design Parameters         | Ranges               |
|---------------------------|----------------------|
| Classroom Width           | 7.5-8.4 (m)          |
| Classroom Depth           | 8.1-9.0 (m)          |
| No. of Classrooms per Story | 2-4                 |
| Ceiling Height            | 3.6-4.0 (m)          |
| Width of Corridor         | 1.8-3.3 (m)          |
| Orientation (degree)      | 0 ~ 90 (0: South)    |
| Location of Core*         | Side Rear Center     |
| Insulation Performance    | Exterior (W/m²K) 0.15-0.36 |
| Window Performance        | Façade (W/m²K) 0.96-2.40 Interior (W/m²K) 0.96-2.40 |
| Window/Wall Ratio         | Interior Façade (%) 30 ~ 50 Rear (%) 30 ~ 50 |
| SHGC                      | Façade 0.35-0.85     |
| Shading                   | 0, 65 (m), 85 (m)    |
| Infiltration Quantity     | Classroom 0.3-0.7     |
|                           | Etc. 0.9-1.5         |

Fig.3. Space Diagram (above) and Baseline Model (below)

4. Energy Simulation

4.1 Experimental Design

In order to determine the relative importance of a variable on energy consumption, all other variables should be fixed and that variable should be manipulated diversely to investigate the effect of such change. However, even if the 20 variables presented in Table 4 are changed on only three levels, as many as \(3^{20} = 3,486,784,401\) simulations will be required, making
the analysis almost impossible. As mentioned earlier, utilization of Orthogonal Arrays has the potential to reduce the number of simulations to a manageable value, i.e., 81. (L$_{81}$[340]). Hence, the total number of experiments conducted with the combination of variables in this study was 81. Table 5. depicts the conditions of every combination.

4.2 Simulation Results

The simulations for cooling and heating load calculations were performed by the EnergyPlus program and a database for the analysis of variance was established based on the simulation results (Table 6.). Seoul weather data documented by KMA (Korea
Meteorological Administration) was converted to TMY2 (Typical Meteorological Year version 2) format, which is one of the supported weather data types of EnergyPlus. There are three distinct climatic zones in Korea, and the analysis was carried out for Seoul, the representative location for "central climatic zone". The results of simulations show that the average annual heating and cooling load are 817.0 kWh/class.yr and 303.6 kWh/class.yr, respectively.

### Table 5. Orthogonal Array Table L81 (3^4)

| No. | Heating Load | Cooling Load | No. | Heating Load | Cooling Load |
|-----|--------------|--------------|-----|--------------|--------------|
| 1   | 924.6        | 157.6        | 42  | 868.1        | 276.4        |
| 2   | 820.8        | 235.3        | 43  | 881.8        | 271.6        |
| 3   | 270.1        | 550.8        | 44  | 653.2        | 272.1        |
| 4   | 768.8        | 413.1        | 45  | 490.0        | 359.7        |
| 5   | 787.5        | 255.5        | 46  | 211.8        | 374.6        |
| 6   | 649.3        | 218.0        | 47  | 977.8        | 242.0        |
| 7   | 682.8        | 240.6        | 48  | 938.2        | 211.1        |
| 8   | 288.3        | 315.2        | 49  | 909.8        | 243.7        |
| 9   | 961.0        | 235.7        | 50  | 437.6        | 306.8        |
| 10  | 767.7        | 627.4        | 51  | 660.7        | 290.2        |
| 11  | 965.4        | 175.9        | 52  | 759.5        | 297.4        |
| 12  | 735.2        | 272.5        | 53  | 717.4        | 193.4        |
| 13  | 740.5        | 398.6        | 54  | 876.9        | 430.3        |
| 14  | 384.4        | 273.8        | 55  | 827.8        | 296.5        |
| 15  | 1,041.3      | 185.6        | 56  | 882.4        | 278.2        |
| 16  | 983.1        | 161.5        | 57  | 1,229.7      | 432.4        |
| 17  | 809.5        | 339.8        | 58  | 556.9        | 335.4        |
| 18  | 362.0        | 416.4        | 59  | 695.3        | 276.5        |
| 19  | 666.2        | 286.6        | 60  | 1,031.8      | 348.3        |
| 20  | 245.4        | 463.4        | 61  | 1,197.4      | 553.3        |
| 21  | 1,129.1      | 156.2        | 62  | 815.2        | 303.5        |
| 22  | 1,071.4      | 156.0        | 63  | 803.7        | 236.6        |
| 23  | 970.8        | 358.8        | 64  | 340.4        | 423.9        |
| 24  | 335.6        | 529.3        | 65  | 701.3        | 274.8        |
| 25  | 652.0        | 649.7        | 66  | 1,073.0      | 240.3        |
| 26  | 1,010.2      | 207.2        | 67  | 991.7        | 317.9        |
| 27  | 728.3        | 209.4        | 68  | 761.7        | 662.0        |
| 28  | 880.4        | 260.8        | 69  | 698.3        | 208.0        |
| 29  | 589.6        | 305.5        | 70  | 747.8        | 201.6        |
| 30  | 727.5        | 346.4        | 71  | 754.6        | 306.4        |
| 31  | 721.9        | 507.1        | 72  | 999.1        | 571.5        |
| 32  | 804.6        | 230.5        | 73  | 1,000.5      | 297.8        |
| 33  | 776.9        | 273.6        | 74  | 680.0        | 392.8        |
| 34  | 324.9        | 261.2        | 75  | 681.8        | 284.0        |
| 35  | 1,436.0      | 654.6        | 76  | 876.9        | 264.4        |
| 36  | 881.3        | 231.9        | 77  | 966.1        | 253.6        |
| 37  | 889.0        | 293.1        | 78  | 1,179.8      | 356.0        |
| 38  | 744.9        | 269.3        | 79  | 552.3        | 280.9        |
| 39  | 966.6        | 349.8        | 80  | 640.1        | 360.7        |
| 40  | 541.3        | 226.6        | 81  | 1,045.9      | 293.0        |
| 41  | 1,268.9      | 435.6        | Avg. | 817.0    | 303.6        |

5. Analysis of Variance (ANOVA)

The variables that have a significant contribution at the 5% significance level (p-value) in ANOVA were selected as contributing energy factors; the non-significant parameter (p-values greater than 0.05) were eliminated. Among 20, only seven variables, e.g., Width and Height of Classroom, Wall U-factor (Exterior wall), Window U-factor (Façade), SHGC (Façade), WWR (Façade), Shading, Infiltration Quantity, and Orientation variables turned out to be significant factors for heating energy consumption. In a similar vein, the following five variables e.g., SHGC (Façade), WWR (Façade), Shading, Infiltration Quantity and Orientation variables were found to be significant contributors to cooling energy consumption.

In Table 7, and Table 8., the results of the study indicate that in terms of the contribution to heating energy consumption, Infiltration Quantity contributes the most (34.7%) followed by Orientation (24.7%), Wall U-factor (Exterior) (7.2%), SHGC (Façade) (5.7%), Window U-factor (Façade) (3.4%), Classroom Size (Width) (2.9%), and Classroom Size (Height) (2.0%). On the other hand, in the case of cooling energy consumption, observed contributions are of the following order: SHGC (Façade) (44.6%), Shading (14.2%), Orientation (10.6%), WWR (Façade) (7.6%), and Infiltration Quantity (2.6%). Apart from these, other variables' contributions were small enough to ignore.

These comparative contribution rates are illustrated in Fig.4. and Fig.5. The more the variables contribute to energy consumption, the steeper the gradient will be. In the graphs, 0 corresponds to the average heating and cooling energy consumption. Positive (+) values indicate that values are larger than the average consumption.

### Table 7. Percentage Contribution to Heating Energy Consumption

| Strategy | Contribution Rate (%) | Performance Level of Heating Energy Consumption (kWh/class.yr) |
|----------|-----------------------|---------------------------------------------------------------|
|          |                       | 0 | 1 | 2     |
| A        | 2.9%                  | -51.4 | -7.5 | 59.0 |
| B        | 2.0%                  | -52.9 | 15.4 | 37.5 |
| H        | 7.2%                  | 92.2 | -21.5 | -70.8 |
| J        | 3.4%                  | 63.2 | -9.0 | -54.1 |
| P        | 5.7%                  | 75.3 | -0.5 | -74.8 |
| S        | 34.7%                 | 170.7 | 15.0 | -185.7 |
| F        | 24.7%                 | -135.9 | -26.7 | 162.6 |

### Table 8. Percentage Contribution to Cooling Energy Consumption

| Strategy | Contribution Rate (%) | Performance Level of Cooling Energy Consumption (kWh/class.yr) |
|----------|-----------------------|---------------------------------------------------------------|
|          |                       | 0 | 1 | 2     |
| P        | 44.6%                 | -90.6 | -17.8 | 108.4 |
| M        | 7.6%                  | -41.7 | -1.9 | 43.5 |
| R        | 14.2%                 | 65.0 | -30.8 | -44.3 |
| S        | 2.6%                  | -26.8 | 0.1 | 26.5 |
| F        | 10.2%                 | -49.7 | 1.3 | 48.3 |
intensity, and negative (-) values mean that they are lower than the average intensity.

6. Development of Sustainable Design Guideline
The building delivery process of sustainable building requires instantaneous feedback in order for the designer to make an informed decision. Such informative support should be comprehensive enough to include geometry, envelope and systems. The guideline consists of important energy design variables, results of energy sensitivity, priority of variables, and examples of decision-making. (Fig.6.)

7. Conclusion
This study intends to develop a sustainable design guideline for school buildings, which can be simply used to support a fundamental understanding of basic building physics. This will allow designers to interpret the performance evaluation result feedback, which drives them to make iterative changes during the early design stage of the sustainable design process. The ANOVA analysis was also conducted and the following conclusions are drawn from the investigation:

1) Through an intensive literature search, the main factors affecting energy consumption reduction were selected. The factors examined for the analysis include: the width of classroom, height of classroom, number of classrooms per story, ceiling height, width of corridor, orientation, location of core, insulation performance (exterior wall, interior wall, windows), window/wall ratio (façade, interior wall, rear), shading, infiltration quantity and window performance (Solar Heat Gain Coefficient).

2) By using orthogonal arrays, the number of simulations was reduced to 81. With the results of simulations, analysis of variance was conducted. Infiltration Quantity (heating) and Solar Heat Gain Coefficient (Façade) (cooling) were found to contribute most: followed by Orientation, Wall U-factor (Exterior) for heating; and Shading, Orientation and WWR (Façade) for cooling.

Therefore architects should be attentive to the Infiltration Quantity (tightness of window), Solar Heat Gain Coefficient, Orientation, Wall U-factor, Shading, WWR (Façade) concerning energy-conscious primary school building design. They should also give priority to the design variables selected in this research during the early design stage if they are to effectively design energy conscious primary schools.

The application of the proposed guideline can be limited to the design of a simple school building of which the design parameters are within the range of the boundaries prescribed in the study. However, the proposed methodology using orthogonal arrays can be further exploited to develop a wide range of sustainable design guidelines for various building types.

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Fig.6. Sustainable Design Guideline for Primary School
References
1) DCSF (Department for Children, School, and Families). (2010) Road to zero carbon final report of the Zodo carding task force.
2) Dong-yun, H. (2009) Study on architectural planning to enhance sustainability of school buildings. The Graduate School of Hanyang University.
3) EPA (Environment Protection Agency). www.epa.gov
4) Hong TH. et al. (2012) LCC and LCCO2 analysis of green roofs in elementary schools with energy saving measures. Energy and Buildings, 45, p.230.
5) Jin Chul Park, Min Hee Chung, Eon Ku Rheo. (2011) Field Survey on the Indoor Environment of Elementary Schools for Planning of Environment Friendly School Facilities, Journal of Asian Architecture and Building Engineering, 10, p.2.
6) Jin-II, J. (2009) Korea Education Development Institute. A study on the development of Zero-Energy. Green school model 2.
7) Kazuhide Ito, Shuzo Murakami. (2010) Cost-effectiveness Analysis of Improved Indoor Temperature and Ventilation Conditions in School Buildings, Journal of Asian Architecture and Building Engineering, 9, p.2.
8) Lim, Donggu (2009) A Proposal for Design of elementary school with Multi-use programs using Mat Design method. The graduate School of Architecture in Kyung Hee University.
9) Ministry of Education & Human Resources Development (2003). A study on the revision of Standards for School Facilities.
10) Shady Attia. et al. (2012) Simulation-based decision support tool for early stages of zero-energy building design, Energy and Buildings, Energy and Buildings 49, pp.2-15.
11) Taehoon Hong. et al. (2012) A decision support model for reducing electric energy consumption in elementary school facilities. Applied Energy, 95, p.263.
12) Tae-Woo Kim. et al. (2012) Energy consumption characteristics of the elementary schools in South Korea.
13) Yung-Jin, Y. et al. (2001) A study on Model of Heating and Cooling Systems for Energy Conservation in School Buildings. Journal of Air-Conditioning and Refrigeration 2001-S-164, pp.966-970.