

DEVELOPMENT OF A SIMPLIFIED SIMULATION TOOL FOR HIGH PERFORMANCE K-5 SCHOOLS IN HOT AND HUMID CLIMATES

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ABSTRACT

This paper presents the preliminary results of an effort to develop a simplified simulation-based tool for designing K-5 high performance schools in hot and humid climates. As a first step of the research, a survey to define the dominant school building shape was conducted in an independent school district in Central Texas. This survey used satellite views of the K-5 schools, where each school shape was classified based on the classification defined by Perkins (2001). In addition, more surveys and a literature review was performed to verify input parameters to drive the building size and other building characteristics. Once the simulation tool and the default parameters are developed, this tool is intended to be used to estimate building energy consumption with limited information about the school building. This paper reports on the classification scheme and automatic building shape generator, as well as preliminary results describing calibration of the simulation to a case study K-5 school.

BACKGROUND

With the growing concerns about increasing energy costs and the demand for healthy places to live and work, a high performance building (or green building) attracts attention because of its energy savings and environmentally friendly spaces. High performance buildings are buildings designed to maximize operational energy savings, improve comfort, health, and safety of occupants and visitors, and to limit detrimental effects on the environment (DDC 1999). Not surprisingly, schools are one of the popular target buildings for high performance applications. In particular, in a school, the energy efficiency and the IAQ (Indoor Air Quality) are considered the most important aspects when designing high performance schools. According to the National Center for Education Statistics (NCES), U.S. Schools spent nearly \$8 billion on energy costs in 2001, which is more than the cost of textbooks and supplies combined (Smith et al. 2003). In addition, about sixty-one percent of public

school districts reported a shortfall in funding to pay their energy bills. As a result, most school districts need to reduce energy expenditures. Therefore, the application of high performance strategies to new and existing schools can be an effective solution for this problem. However, there is a lack of comprehensive and easy-to-use tools for estimating the benefits of high performance schools in terms of energy savings.

Most of building energy simulation programs require specific knowledge of the building energy simulation tool and adequate time to develop a simulation input file for a building. Even though there are several easy-to-use simulation tools available today, in general, those tools were developed for residential buildings or commercial office buildings. Furthermore, those tools still require users to input detailed building information to be simulated. Therefore, a simplified simulation tool for designing high performance schools needs to be developed. With such a tool, a decision maker who has no building energy simulation knowledge can quickly and easily estimate the energy savings by applying high performance features to a new school building.

OBJECTIVES

The purpose of this study is to develop a simplified simulation tool for K-5 high performance schools in hot and humid climates. The tool will be developed using the DOE-2.1e building energy simulation program, and the special commands to manipulate the various input parameters. Once, the input file is developed, it will be used as a simulation engine of a web-based building energy simulation tool. This paper reports on the first stage of developing the simplified simulation tool and the preliminary results of the calibrated simulation for a case study school, which include:

- 1) A study of school building shapes and common spaces required for K-5 schools.
- 2) A survey of school shapes in a city in central Texas to identify the most common school shape.

- 3) Verification of input parameters to drive the building size and other building characteristics.
- 4) Preliminary results that describe the development of a prototype school geometry for the tool.

SCHOOL BUILDING CONFIGURATION

The first step of developing a prototype school is to define the most common school configuration in hot and humid climates based on literatures and a survey of existing schools. Perkins (2001) reviewed several possible school building configurations. According to Perkins, even though there are limitless possible building configurations for schools, most of these configurations can be synthesized into a few common shapes. Figure 1 shows the most common configurations used in school design according to Perkins. All the configurations contain classrooms, shared facilities such as auditorium, library, gym, and classroom nodes. Based on Perkins' configurations, a survey was conducted to identify the most common school shape in a city in Central Texas. School shapes have been identified using the satellite view of the schools, and each school shape was classified by the building configuration shown in Figure 1. Figure 2 presents the survey results. Of the eighteen K-5 schools in the city, the spine school configuration was identified as the most dominant school shape (i.e., 61% of total). The centralized resource plan, the courtyard plan, and a spine with single-loaded classroom wings are the next most frequent building shape (i.e., 11% each). Therefore, for this study, the spine plan was used to define the proposed prototype K-5 school geometry.

SCHOOL SPACES AND SIZE

In general, existing simplified building simulation tools need users to input detailed building width and depth in order to define a building geometry. Unfortunately, this procedure frustrates inexperienced users who are not familiar with a simulation too. The proposed simulation tool uses a simple input parameter which is number of students to define the building geometry. Since the gross square footage per student has been often used to size the school building in design stage, this parameter would be able to decide the total building square footage and the square footage of each space. According to 2007 Construction Report (School Planning & Management, 2007), the median space per student was 112.5, 122.2, and 131.2 sq.ft. for large school, medium school, and small school, respectively (see Table 1). Therefore, once users input the number of students for their school building, the total gross square footage of the school will be calculated by the

tool. Then, the total gross square footage will be divided into several spaces that are required in school building in general. Figure 3 shows the procedure how the building size and the each space size would be determined based on the number of students. In this simplified tool, a school building has 4 major spaces: 1) classrooms including library or media center, 2) cafeteria, 3) gymnasium, and 4) administration office.

| Name | Configuration |
|--|---------------|
| The Centralized resource plan | |
| The dumbbell plan | |
| The spine plan | |
| The courtyard plan | |
| A spine with single-loaded classroom wings | |
| A classroom-clustering model | |
| A courtyard with classroom-clustering plan | |

| | |
|--|--|
| | Major Circulation |
| | Classrooms |
| | Shared Facilities (i.e., auditorium, library, gym, etc.) |
| | Classroom Nodes (i.e., project rooms, faculty, offices, lavatories) |

Figure 1: Most common school building shapes
(Perkins, 2001)

The major spaces required in K-5 school were determined based on the information from the 2007 construction report and Perkins (2001). According to the 2007 construction report, over 90% of the new elementary school built in 2007 have those 4 major spaces. In order to decide the % area of the total square footage, several existing school building space profiles were reviewed including a typical K-5 school space profile in North Carolina, and a case study elementary school building in Central Texas. For the verification, the % space areas were compared to definition from Perkins (2001). Table 2 shows the % of total square feet per school. Most of the school building areas (i.e., 65 to 72% of total square feet) were occupied with the classrooms. The gymnasium, dining area, and the office area was about 10% each of the total building area. Figure 4 shows the relationship between number of students and the total gross square footage. In order to validate this, several actual building data points are superimposed over the graph in Figure 4. One set of the data points was from a typical K-5 school space

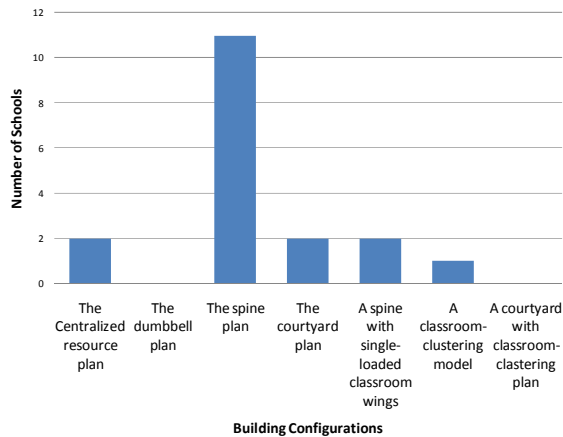


Figure 2: Survey results: building configurations

Table 1: Gross square footage per student

| | Median Number of Students | Median Size of Building (Sq.Ft.) | Median Space per student (Sq.Ft) |
|--|---------------------------|----------------------------------|----------------------------------|
| Smallest quarter (fewer than 540 students) | 450 | 59,965 | 131.2 |
| National Median | 700 | 88,000 | 122.2 |
| Largest quarter (800 to 1,800 students) | 865 | 98,000 | 112.5 |

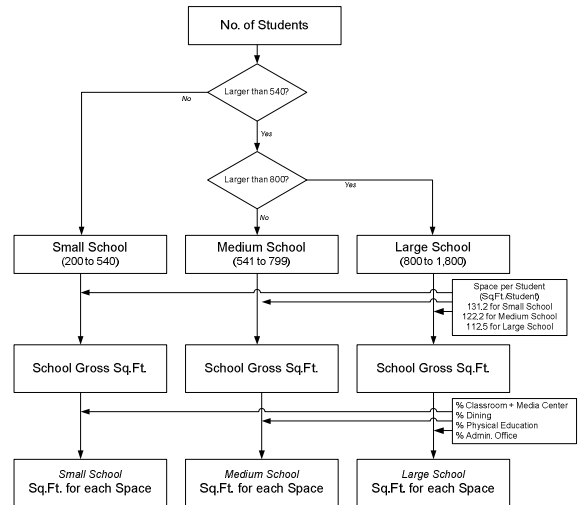


Figure 3: Calculation of the gross square footage

Table 2: % space area of total sq.ft. based on number of students

| Number of Student | Sq.Ft. /Student | % Classroom + Media Center (or Library) | % Dining | % Gym | % Admin. Office |
|-------------------|-----------------|---|----------|-------|-----------------|
| From 200 to 540 | 131.2 | 65 | 10 | 13 | 12 |
| 541 to 799 | 122.2 | 71 | 10 | 9 | 10 |
| 800 to 1,800 | 112.5 | 72 | 10 | 8 | 10 |

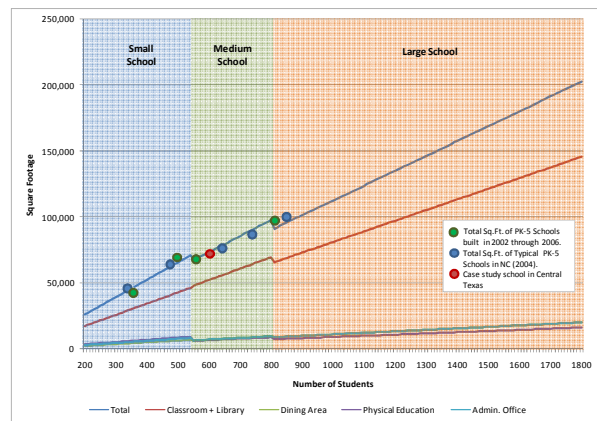


Figure 4: Total square footage changes by number of students

profile. Also, the data points of relatively new school buildings that have been built in 2002 through 2006 are plotted. Finally, a data point of a case study elementary school in Central Texas is plotted. The % difference between the actual gross square footage of these schools and the calculated gross square footage (i.e., sq.ft./student number of student) is 6%.

PROPOSED SCHOOL GEOMETRY

As described earlier, the spine plan geometry was selected for the prototype school geometry based on the survey. Since the existing school building shapes surveyed showed the modified spine plan rather than the original spine plan, the original plan configuration was modified as shown in Figure 5. In addition, the shared facility space was divided into three major spaces (i.e., gymnasium, cafeteria, and administration office) as defined earlier. Therefore, the prototype building consists of classroom + library (i.e., blue shaded), physical education (i.e., grey shaded), dining area (i.e., yellow shaded), and administration office (i.e., green shaded).

Next, in order to define the dimension of the simplified geometry, the average dimensions of each space (e.g., dimension of classrooms, width of corridor, height of classroom, gymnasium, cafeteria, and office, etc.) were researched from the case study school, North Carolina Public Schools facilities guidelines (Public Schools of North Carolina, 2003), and Perkins (2001). Figure 6 shows the prototype building shape.

As described earlier, the size of the total building and each 4 major spaces would be increased as number of students increases (See Figure 3). Since the simulation input will be developed using *macro* and *include* command in DOE-2.1e, the way of geometry changing was also simplified so that the macro input can be concise. In detail, the vertical length of a classroom wing is fixed as 66ft which is the sum of two classroom width (i.e., 58ft) and corridor width (i.e., 8ft). The width of classroom wing would grow as the number of students increases as shown in Figure 7. As for the shared facilities (i.e., physical education, dining area, and administration office), the widths of three spaces are fixed, and the vertical length of three spaces would grow as the number of students increases (also shown in Figure 7).

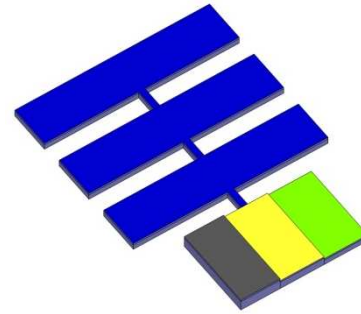


Figure 6: Prototype school shape

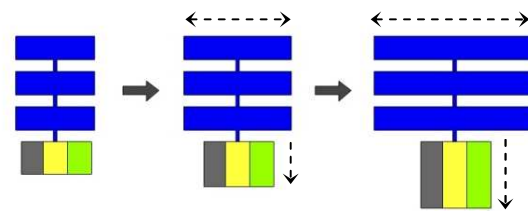


Figure 7: Change of school geometry as number of student increases

CASE STUDY SCHOOL

As mentioned earlier, the simplified simulation tool will be verified by comparing the simulation results with a case study elementary school in Central Texas. This section presents the preliminary results of the calibrated simulation of the case study school.

Building Description

The selected case study elementary school is one of six elementary schools in the same school district. As of 2006, about 600 students were enrolled. Total gross floor area is about 74,000 square feet. Figure 8 shows the satellite view of the school building. Based on the classification by Perkins (2001), the building configuration can be classified as a modified spine school configuration. The building is served by eight AHUs consisting of three different types of AHUs including: 1) four variable air volume systems for the classrooms and library, 2) three constant volume systems for a gym, cafeteria, and kitchen, and 3) one multi zone unit for administration offices.

Data Measurements

Several data sets from the case study school were measured and collected to be used for the initial simulation development and calibration. These sets included:

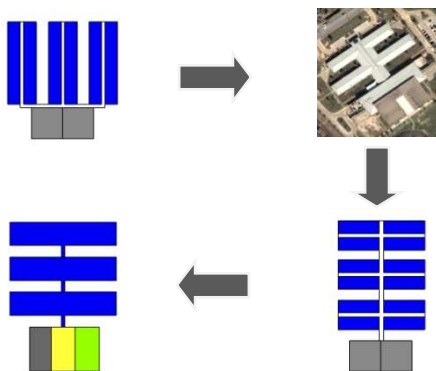


Figure 5: Simplification procedure



Figure 8: Satellite view of the case study school building

- 1) Original architectural and mechanical drawings of the building.
- 2) Building occupancy and HVAC schedule from the school district.
- 3) Hourly electricity use (i.e., whole building electricity, Motor Control Center (MCC), electricity use from Chiller 1 & 2) in 2006 from a data logger installed on site.
- 4) Monthly utility bills for electricity and natural gas in 2006.
- 5) Hourly weather data (i.e., dry bulb temperature, relative humidity, wind speed, horizontal solar radiation) from a local solar test bench and NOAA website.
- 6) Hourly temperature and relative humidity measurements from 7 portable data loggers installed in several points in the school.

Of these data, the drawings (1) and the schedules (2) have been used to develop as-built simulation, and the remainder of the data was used in the calibration procedure.

As-built Simulation

Based on the data obtained, an as-built simulation input was developed for the DOE-2.1e hourly building energy simulation program. Figure 9 illustrates the simulated as built building. Unfortunately, the initial as-built simulation result showed large discrepancy with the measured data, which can be often found in a building simulation result before calibration. In this study, the mean bias error (MBE), and the coefficient of variation of the root mean square error (CV(RMSE)) (Kreider and Haberl, 1994) were calculated to assess the goodness-of-fit of a simulation model. The

equation for the calculation of MBE (%) and the CV(RMSE) (%) is provided in Appendix of this paper.

According to the ASHRAE Guideline 14-2002 (2002) pp.41, “Models are declared to be calibrated if they produce MBE with $\pm 10\%$ and CV(RMSE) within $\pm 30\%$ when using hourly data, or $\pm 5\%$ and $\pm 15\%$ with monthly data.”. The calculated CV(RMSE) and MBE for the whole building electricity use is 45.8%, and -5.6%, respectively, which is slightly outside the range recommended by ASHRAE Guideline 14. Figure 10 shows the comparison of the daily simulated and the measured whole building electricity use. The left side graph shows the time series plots, and the right side graph is the scatter plot which presents the building electricity use as a function of outside temperature.

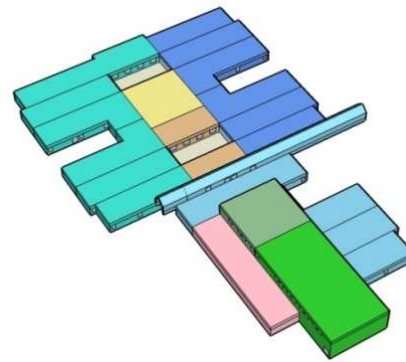


Figure 9: Simulated case study school building

Calibrated Simulation

In order to match the simulation result to the measured use, detailed calibration procedures were performed. After changing each input variable, the time series plots and the scatter plots (Figure 9) were generated, and the CV(RMSE) and MBE was calculated in order to evaluate the adequacy of a calibration.

The followings are the calibration steps and the description of each step.

- 1) *Actual 2006 weather file with measured solar radiation*

As-built simulation input was simulated with the TMY2 weather file for Houston, TX, which is relatively close to the building site. As a first step of calibration, the hourly weather data measured from the local solar test bench in 2006 was packed and used for the simulation instead.

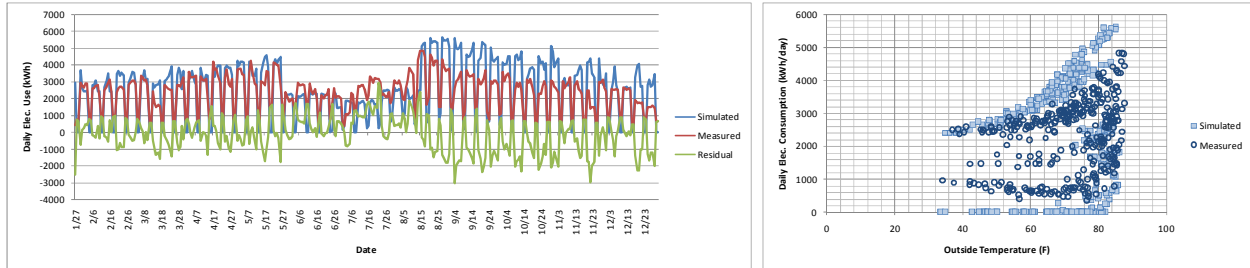


Figure 10: As-built simulation result (simulated vs. measured)

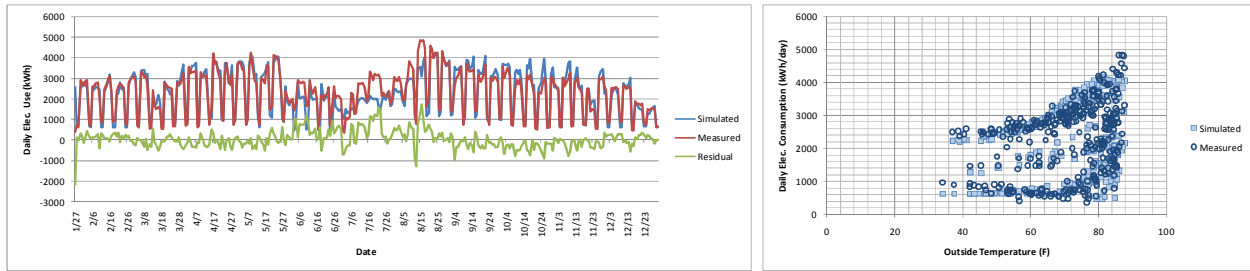


Figure 11: Calibrated simulation result (simulated vs. measured)

2) *Lighting & equipment schedule calibrated using ASHRAE's RP-1093 method (Abushakra et al. 2001)*

Original lighting & equipment schedule was modeled based on the information from the school district. Using the measured hourly lighting & equipment electricity uses in 2006 and the ASHRAE's RP-1093 method, new lighting & equipment schedules were developed, and these schedules replaced the original schedules. As shown in Figure 13, this step resulted almost 200% of increase in lighting and equipment energy consumptions, which explains that the as-built simulation underestimate the lighting & equipment energy use.

3) *Scroll chiller performance curve*

Since the DOE-2.1e has no option for scroll chiller, the original input was simulated with the centrifugal chiller performance curve which is included in DOE-2.1e. In this calibration step, a scroll chiller performance curve was obtained and replaced the original curve. This step decreased the space cooling energy use about 16.5%.

4) *Winkermann's method (Winkermann 1998) for the underground floor (i.e., U-effective value)*

Since the case study building has relatively large underground floor area (i.e., one story building), U-effective value was calculated and used for the underground floor in order to avoid unrealistic heat

transfer to the ground. As results, the energy uses except lighting and equipment decreased about 5.7%.

5) *The HVAC and room setpoint temperature and schedules from the measured data*

The HVAC and room setpoint temperatures and schedules that were measured using the portable loggers replaced the original setpoint temperatures and schedules that were obtained from the original drawings and the interview with the school district. This final calibration step decreased the energy uses except lighting and equipment about 24%.

The final calibrated simulation gives 19% of CV(RMSE) and 1.4% of MBE for the whole building electricity use, which is acceptable based on the ASHRAE Guideline 14. Figure 11 presents the time series and scatter plot of the final calibrated simulation and the measured data. Figure 12 and 13 show the change of the CV(RMSE) and MBE, and the change of the annual electricity use by category according to the calibration step, respectively.

Verification of the Simplified Tool

Once the simplified simulation tool is developed, the input variables from the calibrated simulation will be input into the simplified tool. Then, the simulated daily (or monthly) energy uses from this tool can be compared to the calibrated simulation result. Based on the comparison, the algorithm of the simplified tool will be modified for a better match.

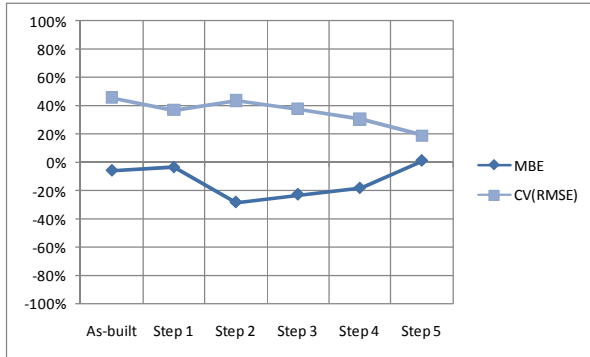


Figure 12: CV(RMSE) and MBE by calibration step

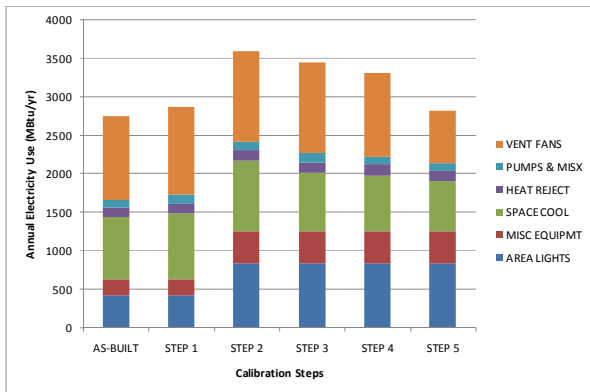


Figure 13: BEPS report by calibration step

FUTURE WORK

For the development of the prototype school building input, following tasks will be performed:

- 1) Survey on typical K-5 school building characteristics (e.g., lighting & equipment load (W/sq.ft.), glazing properties, wall and roof insulation, type of HVAC systems, type of chiller and boiler) in hot and humid climates to define the default value.
- 2) Define input parameters for the tool: tentative input parameters are as following:
 - Building location and orientation
 - Number of Students
 - Roof and wall Insulation Level (R-value)
 - Window-to-Wall Ratio
 - Glazing (U-Factor, SHGC, and Shading)
 - Daylighting Option
 - Lighting & Equipment Load
 - Type of HVAC system
 - Chiller and Boiler and SWH efficiency

- Solar PV and Solar Thermal

- 3) Develop the school input file with *macro* and *include* command

As previously mentioned, the simulation results from this tool using limited input parameters will be compared and verified with the detailed simulation results of the case study school in Central Texas. After the verification, several high performance features such as high performance glazing, more insulation for wall and roof, high efficient chiller and boiler, daylight strategy, and the use of solar energy can be simulated individually or combined together with this tool to estimate the energy savings in quick and easy way.

SUMMARY

This paper explored the preliminary results of an effort to develop a simplified simulation-based tool for designing K-5 high performance schools in hot and humid climates. The preliminary results includes 1) development of automatic building shape generator, and 2) a calibrated-simulation of a case study K-5 school. As a dominant school building geometry, the modified spine plan was defined based on the survey on actual school buildings and the classification defined by Perkins (2001). The proposed school building is composed of four main spaces (i.e., classrooms+library, gymnasium, cafeteria, and office), and the size of these spaces increases proportionally as the number of students increases.

A calibrated simulation of a case study K-5 school was performed to be used later for the verification of the developed simplified tool. The calibrated simulation gives 19% of CV(RMSE) and 1.4% of MBE for the whole building electricity use, which is acceptable based on the ASHRAE Guideline 14.

Once the simplified high performance K-5 school simulation tool will be developed, users can quickly and easily estimate the energy savings by applying high performance features to a new school building.

APPENDIX

MBE (%) and CV(RMSE) (%) can be calculated as followings:

$$MBE (\%) = \frac{\sum_{i=1}^n \text{Residual}_i}{M} \times 100$$

$$CV(RMSE) (\%) = \frac{\sqrt{\frac{\sum_{i=1}^n \text{Residual}^2_i}{n-p}}}{M} \times 100$$

Where,

- n is the number of data points,
- p is the total number of regression parameters in the model,
- M is the mean value of the dependent variable of the set.

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