ESL-PA-06-10-01



# Uncalibrated Building Energy Simulation Modeling Results

**Mushtaq Ahmad**
Associate Member ASHRAE

**Charles H. Culp, PhD, PE**
Fellow ASHRAE

*Received June 23, 2005; accepted April 17, 2006*

*Uncalibrated simulations have provided useful data but often with questionable accuracy. For this study, a protocol was developed for performing the uncalibrated simulations and then applied to four buildings for which consumption data were available. The protocol implementation involved using two levels, which allowed a total of 40 hours to survey the building, read the as-built information, and build the DOE-2.1E input file. The consumption data were not available to the simulation engineer until after the uncalibrated simulations were completed. The discrepancies between the simulated and measured total yearly building energy use varied over ±30% with one outlier. The results show that discrepancies ranged over ±90% between the simulations and the measured data for individual components such as chilled water, hot water, and electricity consumption. Although the small sample size limits the overall conclusions that can be drawn, this study shows that uncalibrated simulations can have very low accuracy in predicting the energy use in a building. This study shows the need for calibration when energy use will be used for financial decisions. Uncalibrated models, however, may be quite useful for determining trade-offs between various equipment or building scenarios.*

## INTRODUCTION

The use of detailed energy simulation software has increased tremendously in the past ten years as applications in energy conservation and efficiency grow. These energy simulations often target energy retrofits, which focus on decreasing the energy use of an operational building by installing high-efficiency equipment, improving envelopes, or optimizing operating conditions. A range of simulation software programs exist, some in the public domain (DOE-2, BLAST) and others as proprietary software from different HVAC companies such as TRACE from Trane and HAP from Carrier (Ayres and Stamper 1995). Some software packages have a Microsoft™ Windows-based front end. EnergyGauge (FSEC 2005) and VisualDOE (Eley 2005) provide a Windows-based entry so the user does not have to decipher the DOE-2.1E text file. One subtle issue with most front-end programs is that many assumptions, parameters, and defaults are built in and are often not readily available or known by the user. The advantage of programs such as DOE-2 is that the user acquires a clear understanding of the input values, assumptions, parameters, and defaults. The disadvantage of programs like DOE-2 is the extensive level of effort required to simulate a building. There has been extensive research on sensitivity analysis of simulation variables (Corson 1992; Jones and Hepting 2001; Lam and Hui 1996) and calibrated simulations (Bou-Saada and Haberl 1998; Bronson et al. 1992; Liu and Claridge 1998). Reddy (2006) reviewed and summarized the literature for calibrated simulation procedures and tools.

**Mushtaq Ahmad** is a research engineering associate II in the Energy Systems Laboratory and **Charles H. Culp** is an associate professor in the Department of Architecture and associate director of the Energy Systems Laboratory, Texas A&M University, College Station, TX.

The use of uncalibrated simulation has become more common in the energy industry to determine and report energy savings from various energy conservation measures. This study was designed to quantify the expected range of discrepancies when uncalibrated simulations are used to calculate energy savings. The procedure followed was to analyze the performance of four uncalibrated simulation models using DOE-2.1E Version 119 (Ayres and Stamper 1995) as the simulation package. The four buildings were randomly selected from a building data base (LoanSTAR 2005). Three of the four buildings selected as the test sample are located on the main and west campuses of a large university. The fourth building, the John B. Connally Building, is located off-campus. The three central campus buildings are supplied by the central chiller plant, while the John B. Connally Building has its own HVAC plant. The Wisenbaker Engineering Research Center is analyzed in detail in this paper. Summary data are provided on the other buildings.

## METHODOLOGY AND TEST PROTOCOL

As energy prices increase, the interest in saving energy has increased. Simulation provides a mechanism to determine where savings opportunities exist or energy inefficiency occurs in a building. With historical data often not available, uncalibrated simulations allow a method to analyze the energy consumption of a building. A test protocol was developed to put realistic constraints on available resources, including time, simulation skill, and simulation software. This test protocol was designed to be a time-limited, blind, uncalibrated simulation. The intent of this research was to determine what the range of discrepancies would be for various buildings using uncalibrated simulations.

Measurements covering building energy use over several years existed as part of the ongoing monitoring of numerous campus buildings. Each building's energy data were not made available until after the simulations and the analysis of the simulation results were completed. The energy use data were then compared to the simulated energy use.

The test protocol required a simulation engineer with a strong working knowledge (at least one year of experience) with the simulation software used and a publicly available and peer reviewed simulation software. We selected DOE-2.1E because it was created and is maintained by the US Department of Energy and is freely available. The simulation engineer, a graduate student at the time, had more than one year of experience with DOE-2.1E and had taken a graduate-level course on using DOE-2.1E.

In addition, the test protocol was designed with an upper limit on the time allowed to acquire building data and build the simulation input file. Two simulation models were created for each of the four buildings. The two simulation models were designated as Level 1 and Level 2. The time allowed to build the input files for the Level 1 model was constrained to 20 hours, although one crept up to 22 hours. The time limit for the Level 2 model allowed up to an additional 20 hours. Although the time limits were somewhat arbitrary, these limits keep the time to simulate a building in the realm of usability by industry. The time used for creating the input file for each model was logged. The time consumed depended upon the effort required to get the building information and the complexity of the building layout. Table 1 summarizes the amount of time spent creating the two simulation models in each of the four buildings.

The emphasis of the Level 1 model was on defining the correct geometry and the as-built HVAC systems. Defining the correct geometry required more than 70% of the total time spent developing the Level 1 model. The four buildings have different layouts, so the time required in creating each Level 1 model also differed. The Wehner Business Administration Building required 17 of the 22 hours to complete just the building layout because of the complex geometry.

The Level 1 model has the following characteristics:

- No thermal mass
- Physically correct layout and geometry

**Table 1. Time Spent Developing the Level 1 and Level 2 Simulation Models**

| Building | Actual Time Spent on the Level 1 Model | Additional Time Spent on the Level 2 Model |
|---|---|---|
| | Up to 20 Hours | Up to 20 Additional Hours |
| Wisenbaker Engineering Research Center (WERC) | 18 | 13 |
| Harrington Tower | 20 | 13 |
| Wehner Business Administration Building | 22 | 11 |
| John B. Connally Building | 16 | 10 |

- Typical values obtained from general observation for occupancy, equipment, and lighting
- As-built definition of primary HVAC equipment
- Assumed typical values for HVAC parameters such as supply airflow and various other set-points

The Level 2 model added the following aspects to the Level 1 model:

- Thermal mass
- Site-specific values for occupancy, equipment, and lighting obtained from detailed site surveys
- As-built definition of all the different HVAC systems employed
- As-built information about the HVAC operating parameters from current operating conditions from the maintenance engineers

The time spent creating the Level 2 model focused on detailed building surveys and meeting with the maintenance personnel in order to get the correct as-built drawings and current operation of the buildings and also to add thermal mass into the simulation. This phase required that all of the construction materials be defined for the layers of the walls, floors, and ceilings. In addition, all interior walls used for zoning had to be defined so the weighting factors would be specified correctly. In the system and plants input section of the file, the correct size and supply airflow were entered from the as-built data obtained from maintenance personnel, instead of allowing the simulation model to calculate zone airflow and equipment sizing. This created a simulation model that closely resembled the as-built details of the real building.

Once the simulations were complete, the results from these simulation models were then compared to measured hourly data from the four sample buildings. The three on-campus buildings, which have chilled and hot water supplied by the central power plant, have logged data for the chilled water and hot water consumption and the whole building electric. Chilled water, hot water, and electrical data were measured in each building to ensure that the measurements captured all energy being supplied to each building. Data were available for the year in which the simulation was performed. The fourth building has a separate HVAC plant. Therefore, the whole building electric included the chiller kWh consumption. The boiler gas consumption for this building was not available.

An interesting aspect of this study was to analyze where the simulations had the highest discrepancies in determining energy use from the uncalibrated simulations. For this purpose, a sensitivity analysis was performed by selecting specific variables from the different sections of the simulation input file. Emphasis was placed on the parameters in the systems section of the input file since extensive research in the sensitivity of parameters in the DOE-2.1E simulation program shows that system-based parameters such as outside air fraction and equipment performance and efficiency can change a building's energy use by as much as 30% (Corson 1992; Lam and Hui 1996). Although the window-to-wall ratio and U-factors for the envelope components can also affect the outcome of a simulation, the effect is usually less than 10% on the overall energy consumption (Corson 1992). The following four parameters were studied in the current work:

- Thermal mass
- Outside air fraction
- Fan schedule
- Thermostat schedule

In addition to these parameters, exterior wall U-factors, glazing types, and economizer parameters were also analyzed. The effect of these parameters on the simulation result was negligible. From the analysis of the impact of these variables on the simulation output, it was found that for internal load-dominated buildings, the effect of thermal mass was less than 10% of the total energy use since the envelope loads for such buildings are a very small percentage of the total loads, which mostly consist of occupancy, lighting, and plug loads. The outside air fraction has a significant impact on the simulation results. A change from 10% outside air to 25% outside air can change the total energy consumption by more than 20%. Major discrepancies with measured data can occur in a simulation model if incorrect assumptions are made for the outside air fraction for a particular system. A detailed analysis of these results is presented in Ahmad (2003).

## Discrepancy Analysis

The daily averages of the hourly data from the simulated and measured data were used to calculate the percent discrepancy for chilled water, hot water, and electricity consumption. Since the goal was to determine if the simulation predicts the actual consumption, the percent discrepancy was used to show the differences between the measured data and the simulated values. Equation 1 shows the mathematical representation for the percent discrepancy.

$$\%\ \text{Discrepancy} = \left( \frac{\sum_{i=1}^{365} y_{m,i} - \sum_{i=1}^{365} y_{s,i}}{\sum_{i=1}^{365} y_{m,i}} \right) \times 100 \tag{1}$$

where

$y_{s,i}$ = set of simulated values (365 average daily energy consumption values)
$y_{m,i}$ = set of measured values (365 average daily energy consumption values)

Researchers have used various statistical parameters to judge the accuracy of the simulated data against the measured. In an early research project, Torres-Nunci (1989) calibrated a simulation by visually analyzing the differences between the measured and simulated energy consumption through scatter plots. Hinchey (1991) created several simulation models ranging from one zone to eighteen zones and found that for an internal-load-dominated building the effect of zoning was negligible. Her annual energy consumption results showed a difference of 3.5% between a one-zone and an eighteen-zone model. This result was obtained by calculating residuals of the measured and simulated data. In the current research, averaged hourly consumption values and simple percentage differences were also used.

Bronson et al. (1992) used monthly percentage differences to calibrate a simulation model to non-weather-dependent loads. The final calibrated model was within approximately 1% of the measured data for the six-month comparison period. However, for weather-dependent loads, the percentage discrepancy increased. Their reported chilled water calculated discrepancy was 1.6%, while the hot water calculated discrepancy was –9.6%. Several other researchers have used this method and have claimed accuracies within 1%.

Bou-Saada and Haberl (1998) and Haberl and Bou-Saada (1998) used coefficient of variance of the root mean square error, CV(RMSE), and the mean bias error, MBE, to define the accuracy of the calibrated model. The above-mentioned method was first used by Kreider and Haberl (1994). Bou-Saada and Haberl (1998) stated that these indices were more accurate in determining the level of calibration than the simple percentage difference of the residual analysis. Using daily or monthly percentage differences tends to average out the variations that are present in hourly data. For calibrating building simulation models, CV (RMSE) and MBE hourly are widely used. The International Performance Measurement and Verification Protocol (IPMVP) and ASHRAE Guideline 14 also recommend this analysis to characterize modeling errors for savings verification (Haberl and Bou-Saada 1998; Kreider and Haberl 1994; Haberl and Thamilseran 1994; IPMVP 2002; ASHRAE 2002). Since the current study does not include the calibration of the simulation models, the use of average percentage discrepancy to compare Level 1 and Level 2 models was determined to be sufficient.

## Analysis

Daily averages of the measured and simulated chilled water consumption, hot water consumption, and whole building electricity consumption were compared for each of the four buildings. The statistical parameter defined above was then used to define the degree of difference between the simulation models and the actual operation of each building. The results from both the Level 1 and Level 2 simulation models were compared against the measured data. This analysis was performed to check whether entering as-built and design-operating values for the building would reduce the discrepancy in the simulation model when compared with the measured data. The analysis performed on one of the buildings is presented in this paper. A detailed analysis of all the buildings studied is available in Ahmad (2003).

## Wisenbaker Engineering Research Center

Wisenbaker Engineering Research Center (WERC) is a 16,450.43 $m^2$ (177,071 $ft^2$) building located on the main campus of a university. This is a multipurpose building, divided mainly between laboratories and offices. WERC also contains a large material-testing lab. The main difference between the Level 1 model and the Level 2 model for this building is thermal mass and system description. In order to consider thermal mass in DOE-2.1E, the materials used in the construction have to be defined in layers. In addition, all partitions, interior walls, and the ceiling have to be defined with the correct coordinates. For the Level 1 input file, the HVAC equipment was entered as a single system that served the complete building. In the Level 2 input file, each different HVAC system in the building had to be entered. For example, WERC uses fan-coil units to condition the basement, single-zone constant-volume reheat supply air to condition the materials laboratory, and variable-volume system supply air to condition the rest of the building. Each of these were entered into the Level 2 input file for the areas served. In addition, the airflow rates through the different air handlers were obtained from the design data, where assumed values were used in the Level 1 model. In the Level 2 model, lighting and equipment wattage densities were also adjusted according to observations. Tables 2a and 2b summarize the

**Table 2a. Description of the Envelope, Loads, and Space Conditions for the WERC Models**

| Wisenbaker Engineering Research Center | | |
|---|---|---|
| **Sections of the Input file** | **Level 1 - 18 Hours Total** | **Level 2 - 13 Hours Total** |
| **Loads - Level of Effort** | **12 Hours Spent on Loads** | **5 Hours Spent on Loads** |
| **Envelope** | Quick construction, no thermal mass considered, instantaneous heat gain/loss | Thermal mass considered, detailed construction is defined for all the envelope elements |
| | All floors and exterior details defined according to as-built drawings | All floors and exterior details defined according to drawings. All the interior floors and ceilings defined with the correct coordinates |
| | 4 floors, 8 zones | 3 floors + basement, 8 zones |
| | Conditioned and glazed area obtained from field measurements and as-built drawings | Conditioned and glazed area obtained from field measurements and as-built drawings |
| **Schedules** | Typical schedules for an office building with 50% load on weekends to account for graduate students | Typical schedules for an office building with 50% load on weekends to account for graduate students |
| **Shading** | No shading | Shading due to adjacent buildings applied |
| **Space conditions** | | |
| **General space** | 200 sq ft /person (18.6 sq m/ person) | 150 sq ft /person (13.9 sq m/person) (survey based) |
| | 1.5 W/sq ft (16.1 W/sq m) for lighting | 1.5 W/sq ft (16.1 W/sq m) for lighting |
| | 3.0 W/sq ft (32.3 W/ sq m) for equipment | 3.0 W/sq ft (32.3 W/ sq m) for equipment |
| **Laboratory** | 300 sq ft /person (27.9 sq m/ person) | 300 sq ft /person (27.9 sq m/ person) |
| | 1.5 W/sq ft (16.1 W/sq m) for lighting | 2 W/sq ft (21.5 W/ sq m) for lighting |
| | 3.5 W/sq ft (37.7 W/ sq m) for equipment | 3.5 W/sq ft (37.7 W/ sq m) for equipment |
| | People heat gain is 850 Btu/ hr (249.1 W) for slight physical work | |
| **Basement** | Treated as general space, with no ground coupling of the exterior walls | 150 sq ft /person (13.9 sq m/person) (survey based) |
| | | 1.5 W/sq ft (16.1 W/sq m) for lighting |
| | | 3.0 W/sq ft (32.3 W/ sq m) for equipment |

main differences between the Level 1 and Level 2 models. Figure 1 compares daily chilled water consumption for the Level 1 and 2 models with measured data from WERC.

For outside temperatures above 21.1°C (70°F), both the Level 1 and Level 2 simulations show chilled water consumption at approximately 25% less than that measured. The measured values were several times higher than the simulated values for temperatures below 12.8°C (55°F). The high consumption of measured chilled water at lower temperatures may indicate a mechanical problem. However, since the building was internal-load-dominated, it could also be requiring ~20,515 kWh/day (70 MMBtu/day) of chilled water for the winter months.

During a discussion with the building engineer, it was found that there were numerous maintenance problems associated with the operation of the air-handlers. Most of the problems were related to the controls and the valves. These operational problems had been completely repaired by October 2002.

Measured data for both chilled and hot water consumption were available for the post-commissioning period for 2004. These data were compared with the two simulation models, which

**Table 2b. Description of the Schedules, Zone Commands, and System Specifications for the WERC Models**

| Wisenbaker Engineering Research Center | | |
|---|---|---|
| **Sections of the Input file** | **Level 1 - 18 Hours Total** | **Level 2 - 13 Hours Total** |
| **Systems - Level of Effort** | **6 Hours Spent on Systems** | **8 Hours Spent on Systems** |
| **Type** | Dual Duct VAV | 7 Single Duct VAV w/ terminal reheat,<br>1 Single Zone Constant Volume,<br>40 Fan Coil units |
| **Schedules** | | |
| **Fans** | 100% during peak hours, 50% during weekends | 100% during peak hours,<br>50% during weekends |
| **Temperature** | Winter set point is 70ºF (21.1ºC)<br>w/ setback to 60ºF (15.6ºC),<br>Summer set point is 76ºF (24.4ºC)<br>w/ setup to 78ºF (25.6ºC) | No setbacks,<br>Summer set point is 78ºF (25.6ºC),<br>Winter set point is 68ºF (20ºC) |
| **Reset** | No reset for heating and cooling | Only reset for cooling,<br>Supply temperature is 63ºF (17.2ºC) if outside temperature is 65ºF (18.3ºC),<br>Set to 55ºF (12.8ºC) if outside is at 80ºF (26.7ºC) |
| **Zone Commands** | | |
| **General space** | 1.0 cfm/sq ft (5.1 l/s per sq m) | From spec sheets, varies by zone |
| | 20cfm/person (9.44 l/s per person) outside air | From spec sheets, varies by zone |
| | Inside temperature 72ºF (22.2ºC) for heating and 77ºF(25ºC) for cooling | Inside temperatures are the same as thermostat setpoints |
| **Plenum** | Inside temperature 70ºF(21.1ºC) for heating and 95ºF(35ºC) for cooling | Inside temperature 70ºF(21.1ºC) for heating and 95ºF(35ºC) for cooling |
| **Lab** | 1.0 cfm/sq ft (5.1 l/s per sq m) | 1.0 cfm/sq ft (5.1 l/s per sq m) |
| | 25 cfm/person (11.8 l/s per person)outside air | 2000 cfm (944 l/s) (from design spec sheets) |
| | Heating design temperature 72ºF (22.2ºC)<br>Cooling design temperature 77ºF (25ºC) | Heating design temperature 70ºF (21.1ºC)<br>Cooling design temperature 95ºF (35ºC) |
| **System Specification** | | |
| | Max and min supply temperatures 105ºF (40.6ºC) and 55ºF(12.8ºC) | Max and min supply temperatures 105ºF (40.6ºC) and 55ºF(12.8ºC) |
| | VAV cycling down to 50% of low loads | VAV cycling down to 50% of low loads, the temperature rise across the reheat coil is 50ºF (10ºC), cool reset is being used with the fan coil units, the rest of the details are from the spec sheets |

show that chilled and hot water consumption has been reduced considerably. Chilled water was reduced from an average daily consumption of 28,325 kWh/day (96.65 MMBtu/day) to 23,865 kWh/day (81.43 MMBtu/day). This is a 15.7% reduction in the average daily use. Hot water consumption was reduced from 6,008 kWh/day (20.5 MMBtu/day) to 3,361 kWh/day (11.47 MMBtu/day), a reduction of 44%. Figure 2 shows a comparison between simulated (both Level 1 and Level 2 models) and post-commissioning measured data. The simulations were run using the weather data for 2004. The post-commissioning data indicate that chilled water consumption at low temperatures was between 8,792 kWh/day (30 MMBtu/day) and 14,653 kWh/day (50 MMBtu/day), which shows that the internal load drives the energy consumption. The simulated values show that the simulation models were not taking into account chilled water consumption at low temperatures.

The variation of simulated hot water consumption from the measured data was significant for both simulation models. Discrepancies can arise from incorrectly establishing the values in the

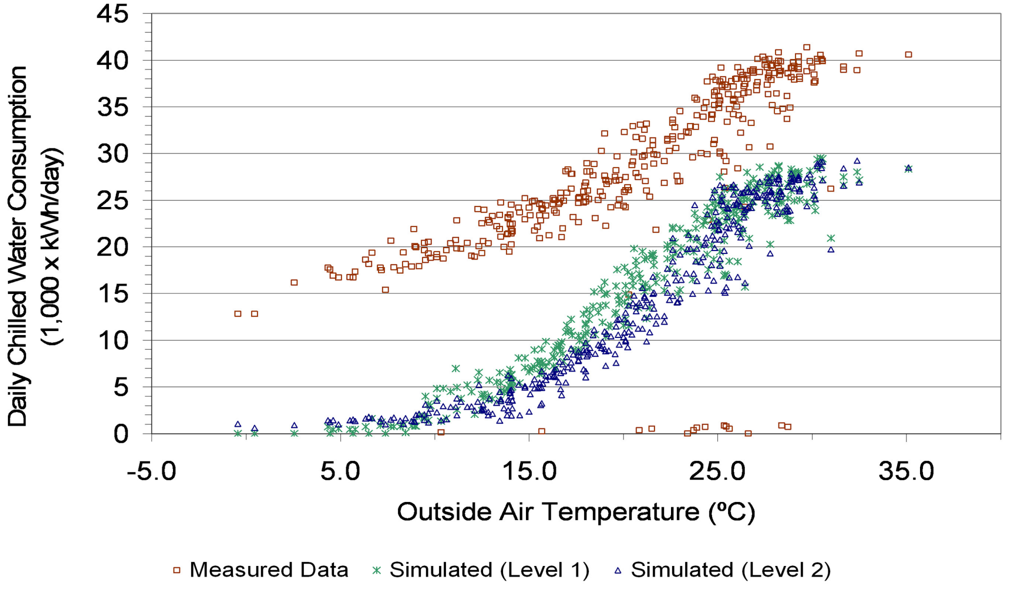


**Figure 1. Comparison of simulated daily chilled water consumption for the Level 1 and Level 2 models with 1999 measured data for WERC.**

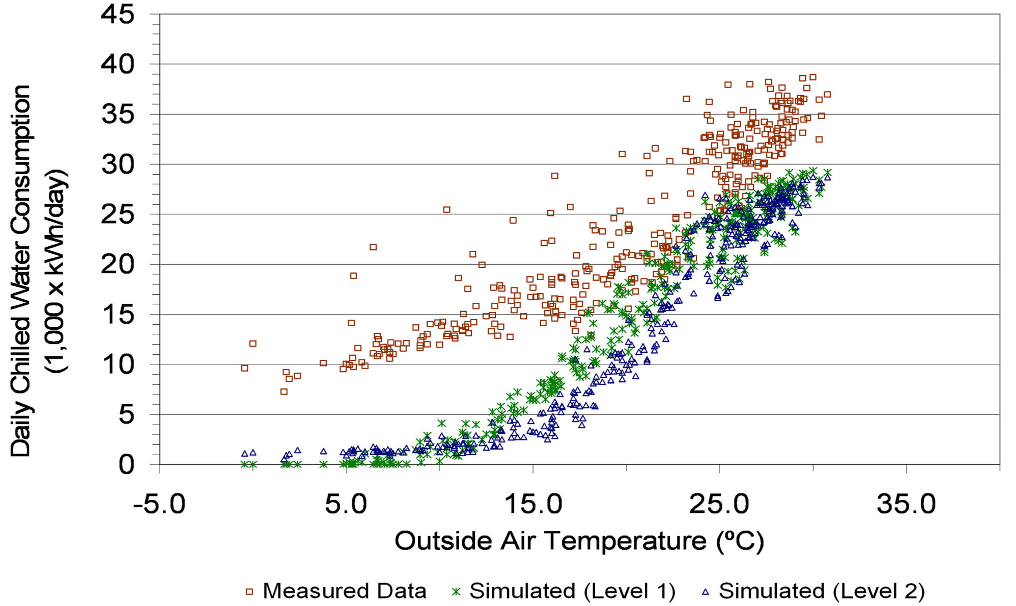


**Figure 2. Comparison of simulated daily chilled water consumption for the Level 1 and Level 2 models with measured data for WERC (2004 post-commissioning data).**

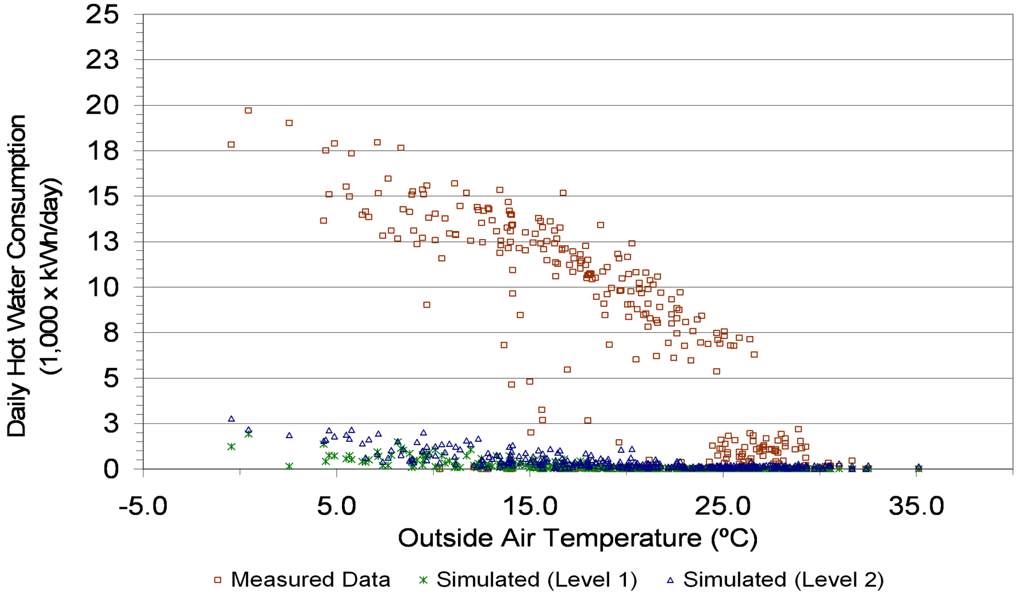


**Figure 3. Comparison of simulated daily hot water consumption for the Level 1 and Level 2 models with 1999 measured data for WERC.**

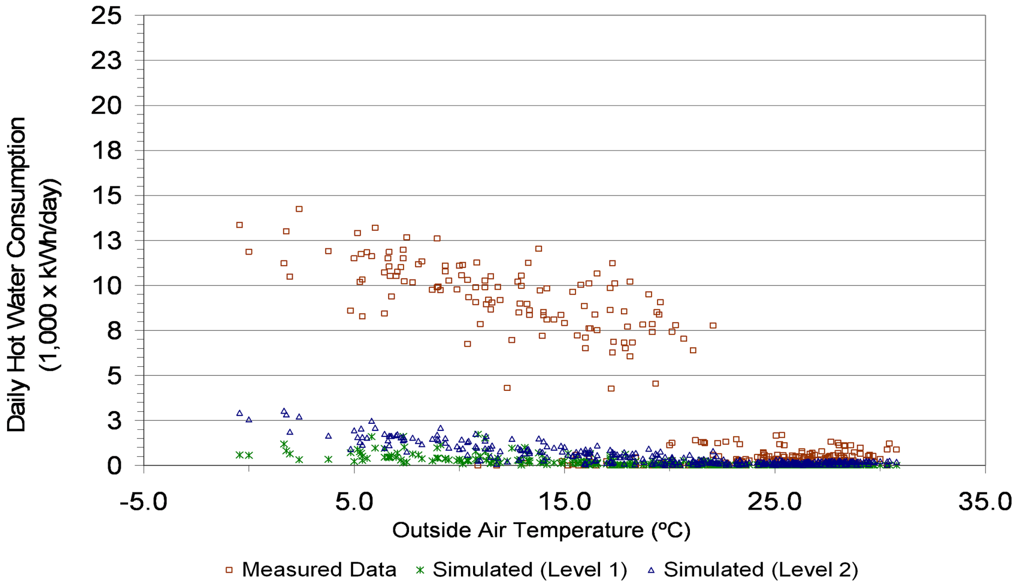


**Figure 4. Comparison of simulated daily hot water consumption for the Level 1 and Level 2 models with measured data for WERC (2004 post-commissioning data).**

input file or from malfunctioning heating and cooling equipment. Figures 3 and 4 compare simulated values against the measured data sets. During the retrocommissioning, the setpoint control of the hot water supply had been reset from 25°C (77°F) for 1999 operation to 20°C (68°F) for 2004 operation, as shown in the two measured data sets.

Figure 5 shows the 2004 whole building electrical consumption simulation and illustrates how DOE-2.1E handles electrical loading when the electrical loads do not include the heating or cooling. Note that the fans (all constant speed), lights, and other non-HVAC loads were on a specified schedule. The chilled and hot water were provided from the central plant. The actual use shows more variation than the simulation and also depicts a lower usage than the simulated values. These were about 25% to 30% lower than predicted by using the simulation input file. This unnatural-looking electrical usage occurs in simulations that rely on fixed schedules. Constant usage values are often hidden by HVAC usage when the building has electrically powered HVAC loads. Nonetheless, these inaccurate but constant load profiles remain present.

The total energy consumption for 1999 and 2004 are shown in Figures 6 and 7, respectively. The impact of the commissioning can be seen immediately. Nonetheless, the simulations still show significant discrepancies from the measured data. In the case of the WERC simulation, the measured data were higher than the simulated data.

The total energy consumption shows that the simulated values were less than the actual consumption. In 2004, when the outside temperature was above 23.9°C (75°F), the Level 1 simulation results were under the actual consumption by approximately 10%. Once the outside temperature drops below 18.3°C (65°F), the difference grows rapidly. Below 12.8°C (55°F), the difference is about a factor of two more than the 2004 simulation and over two times the 1999 simulation.

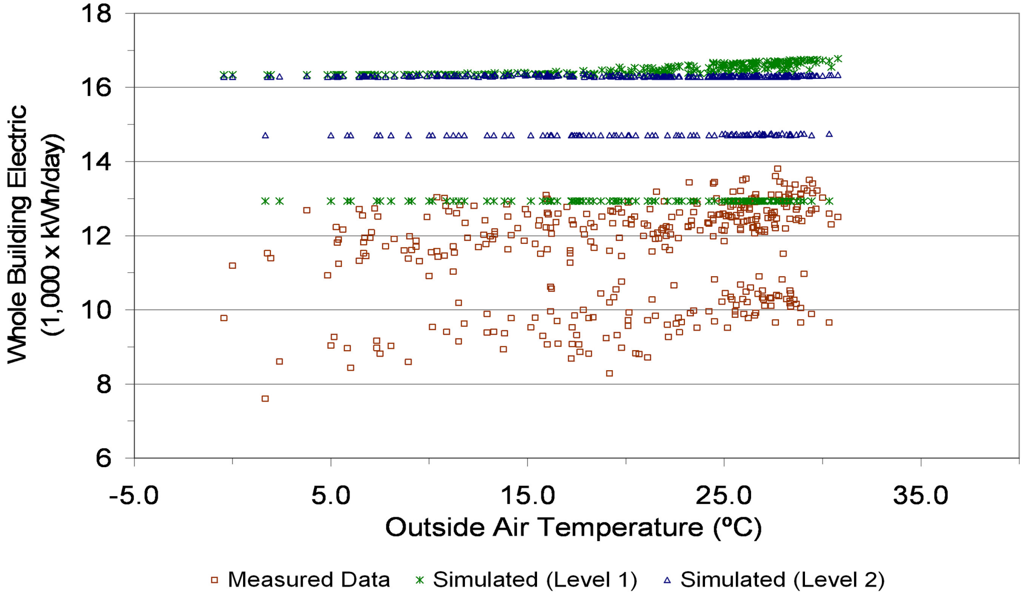


**Figure 5. Comparison of simulated daily whole building electric consumption for the Level 1 and Level 2 models with measured data for WERC (2004 post-commissioning data).**

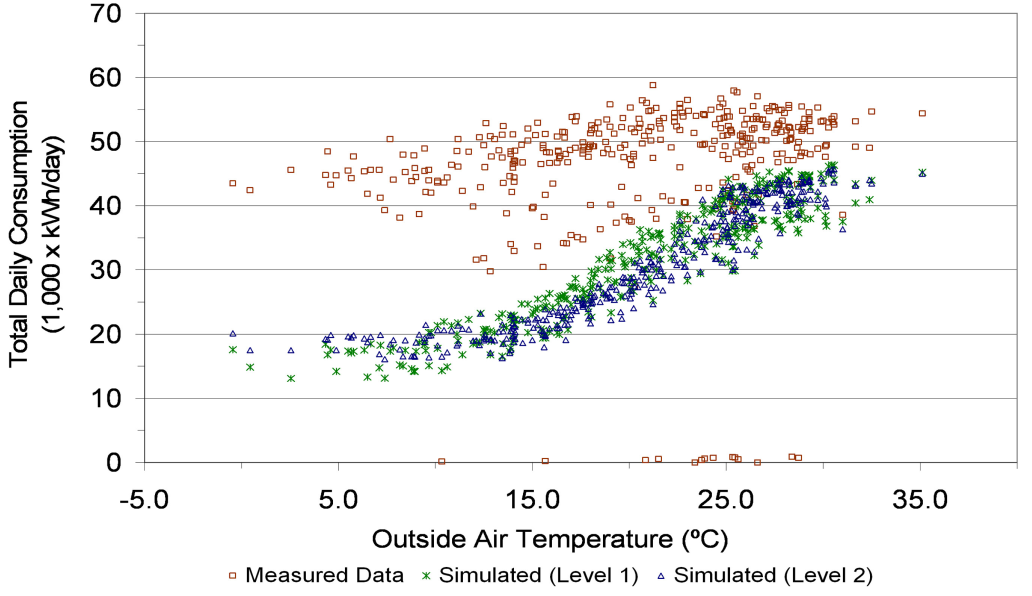


**Figure 6. Comparison of simulated daily total energy consumption for the Level 1 and Level 2 models with 1999 measured data for WERC.**

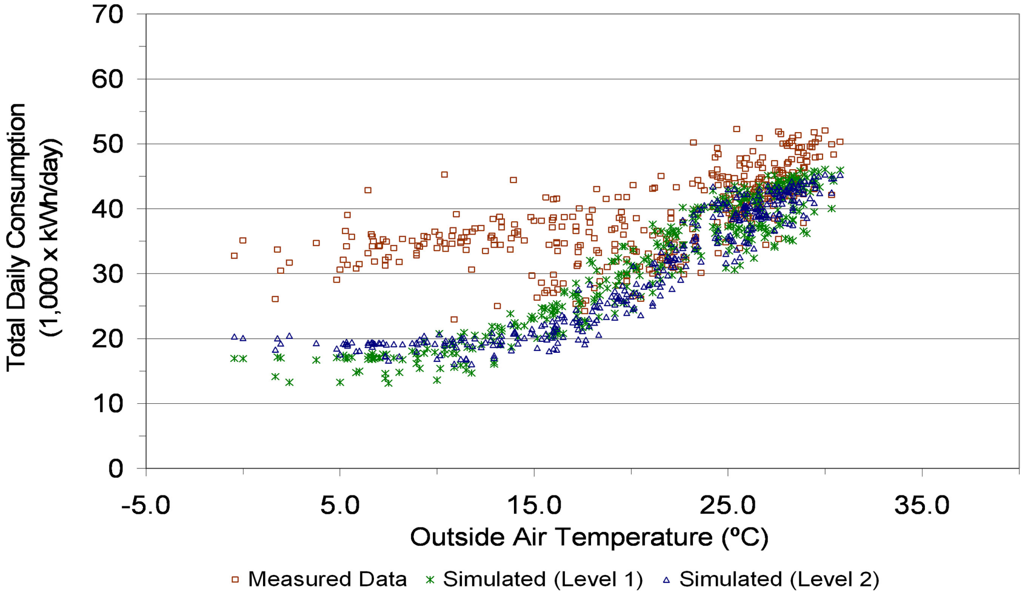


**Figure 7. Comparison of simulated daily total energy consumption for the Level 1 and Level 2 models with measured data for WERC (2004 post-commissioning data).**

## RESULTS

In WERC (177,071 ft$^2$ [16,450 m$^2$]), the simulation using 1999 data underestimates the energy use in all categories except the whole building electrical usage. Table 3 identifies the magnitude of these discrepancies for a full year's consumption. The Level 1 model actually performed slightly better, with a net discrepancy for total consumption of about 32%. The Level 2 model performed about the same, with a discrepancy of 34%. The modeled data when compared to the measured 2004 data, shown in Table 4, resulted in a smaller discrepancy than when compared to the 1999 data. This reflects the energy optimization done on WERC between 1999 and 2004. In this building, the calculated consumption was less than actual consumption. This may have been due to malfunctioning HVAC equipment (which was later found to be the case) or just mistakes in the parameters in the input files.

Results from the other buildings varied considerably, as is shown in Tables 5 through 7. This summary illustrates the wide variance that can be expected from uncalibrated simulations.

For Harrington Tower (130,844 ft$^2$ [12,156 m$^2$]), the Level 1 model was very close and the Level 2 model overestimated the energy use by almost 50%. The chilled water use was substantially overestimated. The hot water use varied considerably between the two modeling methods. The Level 1 model used around 8% of hot water compared to the Level 2 model. This behavior of the Level 1 model was apparent from the other simulation models as well. For the Wehner Business Administration Building, the Level 1 hot water consumption was 243,249 kWh/year (830 MMBtu/year) as compared to 655,307 kWh/year (2,236 MMBtu/year) for the Level 2 model. This very large difference in hot water consumption can be attributed to the use of defaults and assumptions in the Level 1 model as compared to as-built data in the Level 2 simulation. In the case of Harrington Tower, the difference was more obvious because the measured hot water consumption lies between the Level 2 and Level 1 model. This gives a percentage discrepancy ranging from 85% to –98%. The whole building electricity consumption was within about ±10%.

**Table 3. Comparison of Modeled to Measured 1999 Annual Energy Consumption for WERC**

| Wisenbaker Engineering Research Center - 1999 | | Yearly Consumption Comparisons | | | Percent Discrepancy | |
|---|---|---|---|---|---|---|
| | | Level 1 | Level 2 | Measured Data | Level 1 | Level 2 |
| Whole Building Electric | kWh | 5,618,288 | 5,791,367 | 4,414,958 | -27.3% | -31.2% |
| Chilled Water | kWh | 5,813,692 | 5,274,575 | 10,337,535 | 43.8% | 49.0% |
| Hot Water | kWh | 48,448 | 133,124 | 2,199,070 | 97.8% | 93.9% |
| Total Energy | kWh | 11,480,429 | 11,199,066 | 16,951,564 | 32.3% | 33.9% |

**Table 4. Comparison of Modeled to Measured 2004 Annual Energy Consumption for WERC (2004 Post-Commissioning Data)**

| Wisenbaker Engineering Research Center - 2004 | | Yearly Consumption Comparisons | | | Percent Discrepancy | |
|---|---|---|---|---|---|---|
| | | Level 1 | Level 2 | Measured Data | Level 1 | Level 2 |
| Whole Building Electric | kWh | 5,618,165 | 5,786,975 | 4,213,678 | -33.3% | -37.3% |
| Chilled Water | kWh | 5,817,506 | 5,271,995 | 8,702,776 | 33.2% | 39.4% |
| Hot Water | kWh | 56,170 | 176,873 | 1,228,368 | 95.4% | 85.6% |
| Total Energy | kWh | 11,491,842 | 11,235,843 | 14,144,821 | 18.8% | 20.6% |

**Table 5. Comparison of Modeled to Measured Annual Energy Consumption for Harrington Tower**

| Harrington Tower | | Yearly Consumption Comparisons | | | Percent Discrepancy | |
|---|---|---|---|---|---|---|
| | | Level 1 | Level 2 | Measured Data | Level 1 | Level 2 |
| Whole Building Electric | kWh | 2,248,804 | 2,706,987 | 2,515,397 | 10.6% | -7.6% |
| Chilled Water | kWh | 2,830,861 | 3,909,037 | 2,088,130 | -35.6% | -87.2% |
| Hot Water | kWh | 61,220 | 822,574 | 415,563 | 85.3% | -97.9% |
| Total Energy | kWh | 5,140,886 | 7,438,598 | 5,019,091 | -2.4% | -48.2% |

**Table 6. Comparison of Modeled to Measured Annual Energy Consumption for the Wehner Business Administration Building**

| Wehner Business Administration Building | | Yearly Consumption Comparisons | | | Percent Discrepancy | |
|---|---|---|---|---|---|---|
| | | Level 1 | Level 2 | Measured Data | Level 1 | Level 2 |
| Whole Building Electric | kWh | 4,231,335 | 3,481,477 | 2,439,598 | -73.4% | -42.7% |
| Chilled Water | kWh | 4,435,576 | 6,257,961 | 3,527,834 | -25.7% | -77.4% |
| Hot Water | kWh | 243,156 | 655,109 | 1,850,679 | 86.9% | 64.6% |
| Total Energy | kWh | 8,910,067 | 10,394,547 | 7,818,112 | -14.0% | -33.0% |

**Table 7. Comparison of Modeled to Measured Annual Energy Consumption for the John B. Connally Building**

| John B. Connally Building | | Yearly Consumption Comparisons | | | Percent Discrepancy | |
|---|---|---|---|---|---|---|
| | | Level 1 | Level 2 | Measured Data | Level 1 | Level 2 |
| Whole Building Electric | kWh | 2,840,789 | 2,872,021 | 2,470,157 | -15.0% | -16.3% |

The uncalibrated simulations performed for the Wehner Business Administration Building (192,000 $ft^2$ [17,837 $m^2$]) were closer than those for Harrington Tower. The consumption was overestimated by 14% and 33% for the Level 1 and Level 2 models, respectively.

For the John B. Connally Building (123,961 $ft^2$ [11,516 $m^2$]), only the whole building electric data were available. These data include the electrical consumption of the two on-site chillers. The simulated whole building electric was overestimated by 15% for the Level 1 model and by 16% for the Level 2 model.

Table 8 summarizes the percentage discrepancy between the measured and simulated data for the electrical, chilled water, hot water, and total energy consumption. For the John B. Connally Building, the percentage discrepancy was for the whole building electric. All other buildings received their chilled and hot water from a central plant. A minus sign indicates that the simulated data consumption was greater than the measured consumption.

## CONCLUSIONS

This research presents an initial study to document the performance of uncalibrated simulations. When the total energy for the building was calculated, discrepancies in the range of ±30% were observed, with occasional outliers. In general, uncalibrated simulations were observed to result in discrepancies from the measured data exceeding ±90% for individual components such as chilled water or hot water. From this study, we have drawn the following conclusions.

**Table 8. Percent Discrepancy Comparison**

| Sites | Electric | | CHW | | HW | | Total | |
|---|---|---|---|---|---|---|---|---|
| | Level 1 | Level 2 | Level 1 | Level 2 | Level 1 | Level 2 | Level 1 | Level 2 |
| Wisenbaker Engineering Resear Center (1999) | -27.3% | -31.2% | 43.8% | 49.0% | 97.8% | 93.9% | 32.3% | 33.9% |
| Wisenbaker Engineering Resear Center (2004) | -33.3% | -37.3% | 33.2% | 39.4% | 95.4% | 85.6% | 18.8% | 20.6% |
| Harrington Tower | 10.6% | -7.6% | -35.6% | -87.2% | 85.3% | -97.9% | -2.4% | -48.2% |
| Wehner Business Administration Building | -73.4% | -42.7% | -25.7% | -77.4% | 86.9% | 64.6% | -41.0% | -33.0% |
| John B. Connally Building | -15.0% | -16.3% | N/A | N/A | N/A | N/A | -15.0% | -16.0% |

Uncalibrated simulation models may not adequately represent the real operations of buildings. The data in Table 8 show a wide range of predicted results. This initial study illustrates the pitfalls of using uncalibrated simulations.

- The simulation overpredicted the electrical consumption in all cases except one. This could very well arise from lighting and/or motors being turned off more than the scheduled times. This could also arise from overestimating the plug load in the facility. Without submetering, this information was not available. In all buildings except the John B. Connally Building, chilled and hot water were supplied by a central plant. Figure 6 shows that the WERC predicted electric consumption was higher than the measured values.
- The high consumption in WERC at low outside temperatures indicated that reheat or leaking chilled water/hot water valves may be responsible for the high consumption. Retrocommissioning did reduce the chilled water use for WERC over the full outside air temperature range. This higher actual consumption may also arise from dysfunctional controls, such as an economizer.
- Hot water use exceeded the simulation predictions in all cases except one. This could have occurred from leaky reheat valves. At WERC, many valves were repaired when the building underwent retrocommissioning in 2003. The post-retrocommissioning consumption decreased by almost half. Harrington Tower had twice the hot water predicted than was measured, which corresponds to the chilled water being higher than predicted. The other buildings had over three to seven times the predicted consumption, indicating leaking valves or dysfunctional controls.
- When a building has electrically powered chillers without submetered energy use, the ability to estimate the operational problems of the building becomes further obscured. For example, when the simulation underestimated chilled water and overestimated electric use as compared to measured data, explanations could be inferred. The John B. Connally Building may or may not have high discrepancy with the chilled water and the non-chiller electric use. This cannot be ascertained without measuring the chiller consumption. Although the 16% overestimation of the actual energy use looks close, the simulation may or may not represent the operation of the building.

Creation of the Level 2 simulation models, which incorporated envelope details and basic system information, required an additional level of effort that varied from 10 to 13 hours. The results indicated that noticeable improvements were not obtained with the added effort over the simpler Level 1 modeling effort.

- If the simulations did not adequately represent the real operation of the various buildings, improving the level of detail in the envelope construction, schedules, and mechanical equipment may not improve the basic prediction capabilities of the simulation.

Substantial discrepancies exist in the uncalibrated simulations. Inefficient energy use in a building should bias the simulated energy results to be less than the measured energy since the simulations typically do not incorporate large inefficiencies. The results varied with three of the four building simulations, showing that the simulated energy use was greater than the measured energy use.

The next steps need to involve taking a larger sample of buildings to build a statistical basis for conclusions and explaining the differences between the simulation results and the measured results by submetering and more detailed analysis.

## REFERENCES

Ahmad, M. 2003. Systematic time-based study for quantifying the uncertainty of uncalibrated models in building energy simulations. Master's thesis, Department of Mechanical Engineering, Texas A&M University, College Station, TX.

ASHRAE. 2002. *Guideline 14-2002, Measurement of Energy and Demand Savings*. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Ayres, J.M., and E. Stamper. 1995. Historical development of building energy calculations. *ASHRAE Journal* 37(2):47–55.

Bou-Saada, T.E., and J.S. Haberl. 1998. Improved procedure for calibrated hourly simulation models. *DOE-2 User News* 18(1):25–30.

Bronson, D.J., S.B. Hinchey, J.S. Haberl, and D.L. O'Neal. 1992. A procedure for calibrating the DOE-2 simulation program to non-weather-dependent loads. *ASHRAE Transactions* 98(1):636–52.

Corson, G.C. 1992. Input and output sensitivity of building energy simulations. *ASHRAE Transactions* 98(1):618–26.

Eley. 2005. *VisualDOE*. Charles Eley Associates, San Francisco, CA.

FSEC. 2005. *EnergyGuage*. Florida Solar Energy Center, Cocoa, FL.

Haberl, J., and S. Thamilseran. 1994. Predicting hourly building energy use: The Great Energy Predictor Shootout II, measuring retrofit savings—Overview and discussion of results. *ASHRAE Transactions* 100(1):1104–18.

Haberl, J.S., and T.E. Bou-Saada. 1998. Procedures for calibrating hourly simulation models to the measured building energy and environmental data. *Journal of Solar Energy Engineering* 120(8):193–204.

Hinchey, S.B. 1991. Influence of thermal zone assumptions on DOE-2 energy use estimations of a commercial building. Master's thesis, Department of Mechanical Engineering, Texas A&M University, College Station, TX.

IPMVP. 2002. *International Performance Measurement and Verification Protocol*. Efficiency Valuation Organization, Washington, DC.

Jones, C.R., and C. Hepting. 2001. DOE-2.1E geometric modeling: The basic geometric approach versus the complex XYZ approach. *Proceedings from eSim 2001,* Session 1-3.

Kreider, J., and J. Haberl. 1994. Predicting hourly building energy use: The result of the 1993 Great Energy Predictor Shootout to identify the most accurate method for making hourly energy use predictions. *ASHRAE Journal* 36(8):72–81.

Lam, J.C., and S.C.M. Hui. 1996. Sensitivity analysis of energy performance in office buildings. *Building and Environment* 31(1):27–39.

LoanSTAR. 2005. Hourly data for electric, chilled water, and hot water for the buildings studied. Available from the Energy Systems Laboratory, Texas A&M University, College Station, TX.

Liu, M., and D.E. Claridge. 1998. Use of calibrated HVAC system models to optimize system operation. *Journal of Solar Energy Engineering* 120(5):108–13.

Reddy, T.A. 2006. Literature review on calibration of building energy simulation programs: Uses, problems, procedures, uncertainty, and tools. *ASHRAE Transactions* 112(1):226–40.

Torres-Nunci, N. 1989. Simulation modeling of energy consumption in Zachry Engineering Center. Master of Engineering project report, Department of Mechanical Engineering, Texas A&M University, College Station, TX.