ANL/DIS-14/1

# Evaluation of the Efficacy of Bayesian Calibration: Interim Project Report

Decision and Information Sciences Division

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# Evaluation of the Efficacy of Bayesian Calibration: Interim Project Report

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# Summary

This project evaluated the efficacy of applying Bayesian calibration to EnergyPlus building energy models under different levels of data uncertainty. Small, medium, and large office buildings were modeled with input uncertainty consistent with data collection from the three standard ASHRAE audit levels. It was shown that Bayesian calibration both adjusts parameter values closer to the true values, while simultaneously reducing the uncertainty in the parameter values. Consequently, Bayesian-calibrated EnergyPlus models enhance the reliability of energy use predictions by more closely matching monthly utility bills with much reduced uncertainty compared with uncalibrated models. Suggestions for follow-up work to enhance the utility of Bayesian calibration include:

- Development of faster calibration algorithms;
- Development of guidance for applying Bayesian methods to energy modeling for the three levels of auditing, including identification of uncertain parameters and results analysis;
- Creation of a modeler's resource for input parameter uncertainty data;
- Enhancement of methodology to account for correlations when applied to interval utility data; and
- Enhancement of methodology to calibrate individual inputs based on additional measured data (e.g., submetered data) rather than only whole building energy use.

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# 1 Calibration Methodology: Bayesian Calibration

We apply Bayesian inference as a new approach to calibrate uncertain parameters in energy models, while accounting for uncertainty in the calibration process. Bayesian calibration is an alternative to traditional, expert-intensive approaches that require "tweaking" of energy model input parameters to match measured data. Typically, traditional approaches deterministically search for a single solution that minimizes the discrepancy between predicted and measured energy use while ignoring many feasible solutions that may have higher likelihoods. Rather, the Bayesian approach derives the most likely distributions (posterior distributions) of uncertain parameters and applies them, using Monte Carlo Methods, to generate distributions of energy performance model outcomes. Comparison between the deterministic and Bayesian calibration is well summarized in Heo et al. (2012a).

The Bayesian paradigm treats a probability as a numerical estimate of the degree of belief in a hypothesis. Under this paradigm, our prior belief in true values of calibration parameters, $\theta$, is quantified as prior density functions $p(\theta)$. The prior distributions are updated, given measured data on building performance, through the Bayes' theorem defined in Equation 1. The conditional probability, $p(y \mid \theta)$, refers to a likelihood function that drives the updating process by comparing how closely model outcomes, $y$, created with testing parameter values, $\theta$, match the measured data. The likelihood function is derived on the basis of the mathematical formulation developed by Kennedy and O'Hagan (2001).

$$p(\theta \mid y) \propto p(\theta) \times p(y \mid \theta) \tag{1}$$

Since the posterior distributions, $p(\theta \mid y)$, cannot be analytically derived for nonlinear energy models, they are numerically approximated from one joint multivariate distribution through the Metropolis-Hastings Method (one of the Markov Chain Monte Carlo methods). The method explores the parameter space by sampling a proposed point based on the current point in an iterative manner, and accepts the proposed point when it meets an acceptance criterion (Gelman et al. 2004). As a result, the method provides a set of accepted parameter values that approximate theoretical posterior distributions. Detailed information about the mathematical formulation is provided in Heo et al. (2012b).

Figure 1 depicts the full Bayesian calibration process. In practice, the selection of calibration parameters and manual testing of parameter values are often subject to experts' judgment, which has been recognized as a major problem that undermines the quality of calibration results (Reddy and Maor 2006). In the Bayesian approach, expert judgment is replaced with a formal process based on prior uncertainty quantification and parameter screening. First, uncertainties in model input parameters are quantified on the basis of evidential knowledge collected from a pool of sources (e.g., site surveys, technical papers, industry reports and standards). Then, a parameter screening method, specifically the Morris Method, is applied to identify the most influential parameters with respect to their effects on energy use. The Morris Method draws samples in the parameter space by changing one parameter value at a time and computes an elementary effect per parameter that explains the average change in the model output resulting from the change in

the parameter value (Morris 1991). The method efficiently evaluates the sensitivity of many uncertain parameters with a small number of samples, and can still explain the effects of individual parameters on the model output in a global sense. The most dominant parameters identified by the parameter screening are calibrated by the Bayesian calibration module with three types of inputs: (1) prior density functions of calibration parameters, (2) a set of model inputs and outputs exploring the parameter space, and (3) measured energy use.

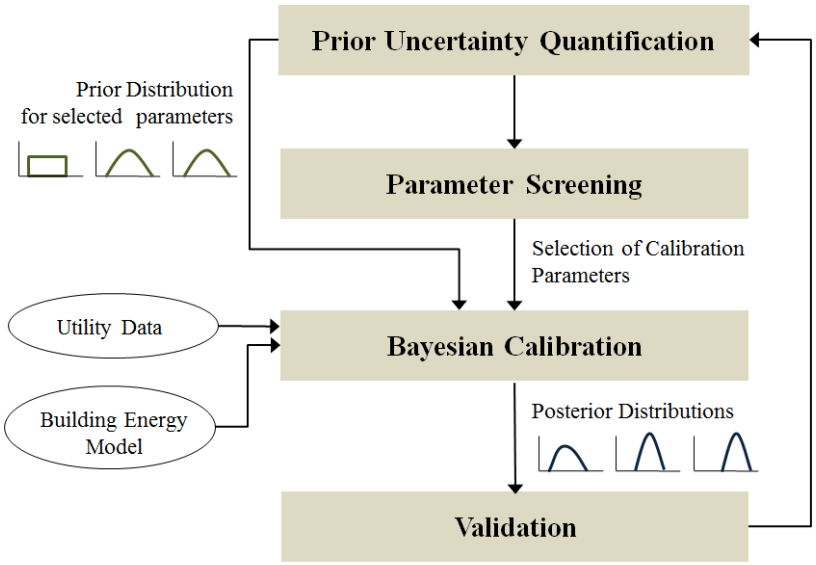


Figure 1: Full Process for Calibrating Energy Models (Source: Heo et al. 2012a)

# 2 Evaluation Framework

This project evaluates the efficacy of Bayesian calibration on enhancing the reliability of a baseline energy model under different levels of energy audits. In practice, calibration is deployed to compute feasible values for uncertain model input parameters that are typically unattainable from a pool of available data. Indeed, attaining correct values for model parameters depends on the level of data available for constructing an energy model, which is closely related to the audit level. Table 1 summarizes the three levels of data available depending on the audit level, modified from ASHRAE Research Project 1051-RP (Reddy and Maor 2006). The audit level directly impacts the accuracy of the base model in capturing actual building behavior, and, consequently, affects the magnitude of uncertainty in the predictions. Level 1 provides information about building geometry and thermal properties from as-built drawings but provides no information about heating, ventilation, and air-conditioning (HVAC) system characteristics and operational states, and building use and operation schedules. In addition to as-built drawings, Level 2 obtains HVAC system specifications and building use and operation schedules from walk-through site visits. At this level, lighting and appliance power densities are estimated on the basis of equipment inventory. In addition to the information in Level 2, Level 3 provides measured data on system operational states and end-use energy data. These metered data enable accurate estimations of control state variables and lighting and appliance power densities, while significantly reducing uncertainty arising from measurement errors.

Table 1: Level of Data Available for Different Audit Levels

| | Types of Data Available for Modeling | Level 1 | Level 2 | Level 3 |
|---|---|---|---|---|
| Utility bills (1 yr) | Calibration | X | X | X |
| As-built drawings | Building geometry and thermal properties | X | X | X |
| Walk-through site visits | System inventory and specification, building use and operation strategies | | X | X |
| Detailed audit | System operational states | | | X |
| Monitored end-use data | Lighting, appliance power consumption, and domestic heating water (DHW) demand | | | X |

Under the three audit levels, we evaluated the efficacy of Bayesian calibration of EnergyPlus models for three types of office buildings constructed before 1980, located in Chicago: (1) small office building, (2) medium office building, and (3) large office building. We used the U.S. Department of Energy (DOE) commercial reference buildings and associated EnergyPlus models developed by the National Renewable Energy Laboratory (NREL) for this study (NREL 2012). The efficacy of Bayesian calibration was assessed under a controlled virtual reality setup. For each type of office building, we generated a “real” building by quantifying uncertainty in model parameter from audit Level 3, randomly selecting model input values from the ranges of quantified uncertainties, and adding random measurement errors ranging between −2% and 2%. Then, the energy consumptions predicted by the “real” building model became the “utility bills” against which base models were calibrated. Calibrated models were evaluated

against "real" buildings under two evaluation criteria: (a) the accuracy of calibration parameter values and (b) the accuracy of calibrated model predictions. We used coefficient of variation of the root mean square error (CVRMSE) as a statistical measure specified in Equation (2). $P_i$ denotes a predicted energy use for period $i$, $O_i$ an observed energy use for period $i$, and $\bar{O}$ the mean of all observed energy uses. CVRMSE quantifies the discrepancy between testing values and targeting values in a normalized manner; a value of 1.0 indicates the discrepancy is equivalent to the average targeting values. ASHRAE Guideline 14 stipulates that CVRMSE should be within 15%, with the use of monthly data, for a calibrated model to be deemed valid. The first criterion, (a), compares posterior distributions against true values from the "real" buildings; the second criterion, (b), compares model predictions against utility bills.

$$CVRMSE = \frac{\sqrt{\sum_{i=1}^{n} (O_i - P_i)^2 / n}}{\bar{O}} \tag{2}$$

# 3 Calibrating Accurate-level Model (Level 3)

Table 2 lists the rankings of uncertain parameters obtained by the Morris Method for the three types of reference office building models at Level 3. Main effect (elementary effect) values were used to relatively rank uncertain parameters in each office building, but they cannot compare the effect of uncertain parameters across the case buildings in a normative manner. At this level, the base models were constructed on the basis of audit data that provide accurate estimates for all model parameters except infiltration and system efficiency. As a result, infiltration rate is the most dominant parameter, followed by heating system efficiency, infiltration rate reduction while the mechanical system is on, and fan system efficiency. However, for the large office building, heating setpoint temperature during occupied hours is one of the top four parameters rather than fan system efficiency. Overall, the three office buildings resulted in similar rankings of uncertain parameters; infiltration rate is by far the most influential parameter, while the system-related parameters had a much smaller effect on energy use. For all the cases, since the top four parameters have a much higher main effect on energy use than the other parameters, we naturally selected them for calibration. We also selected the top four parameters for calibration at the other levels to equivalently compare the effect of Bayesian calibration across different model levels.

Table 2: Rankings of Uncertain Parameters for the Three Office Buildings (Main effect × $10^9$)

| Rank | Small Office | | Medium Office | | Large Office | |
|---|---|---|---|---|---|---|
| | Model Parameter | Main Effect | Model Parameter | Main Effect | Model Parameter | Main Effect |
| 1 | Infiltration rate | 928 | Infiltration rate | 2,071 | Infiltration rate | 15,840 |
| 2 | Heating system efficiency | 178 | Fan system efficiency | 391 | Heating system efficiency | 4,495 |
| 3 | Infiltration rate reduction | 110 | Heating system efficiency | 377 | Heating setpoint T – occupied | 2,330 |
| 4 | Fan system efficiency | 78 | Infiltration rate reduction | 343 | Infiltration rate reduction | 1,980 |
| 5 | Heating setpoint T – unoccupied | 33 | Cooling setpoint T – occupied | 182 | Cooling setpoint T – occupied | 1,735 |
| 6 | Heating setpoint T – occupied | 31 | Heating setpoint T – occupied | 166 | Appliance power density | 350 |
| 7 | Cooling system efficiency | 22 | Cooling system efficiency | 163 | Fan system efficiency | 350 |
| 8 | Fan pressure rise | 15 | Outside airflow | 122 | Pump motor efficiency | 300 |

Table 3 summarizes CVRMSE values that compare the posterior distributions of the top four parameters against true values from the “real” buildings. All the parameters selected for calibration, except infiltration rate, already have quite low CVRMSE values, ranging between 0.01 and 0.20 before calibration. For these parameters, calibration did not noticeably improve the accuracy of parameter values compared with the prior distributions. However, for infiltration rate, calibration greatly reduced the discrepancy between the parameter values and the true value. As shown in Figure 2, Bayesian calibration greatly narrows the range of feasible values while

updating the posterior distribution to move toward the true value regardless of where it is located.

Table 3: Evaluation of Calibration Parameter Values against True Parameter Values

| | CVRMSE in Parameter Values | | |
|---|---|---|---|
| | Before Calibration | After Calibration | Difference |
| **Small Office** | | | |
| Infiltration rate | 1.08 | 0.34 | 0.74 |
| Heating system efficiency | 0.19 | 0.19 | 0.01 |
| Infiltration rate reduction | 0.20 | 0.21 | −0.00 |
| Fan system efficiency | 0.16 | 0.15 | 0.00 |
| **Medium Office** | | | |
| Infiltration rate | 6.35 | 0.80 | 5.56 |
| Fan system efficiency | 0.09 | 0.06 | 0.04 |
| Heating system efficiency | 0.08 | 0.07 | 0.01 |
| Infiltration rate reduction | 0.17 | 0.17 | 0.00 |
| **Large Office** | | | |
| Infiltration rate | 0.65 | 0.19 | 0.46 |
| Heating system efficiency | 0.08 | 0.06 | 0.01 |
| Heating setpoint T - occupied | 0.01 | 0.01 | 0.00 |
| Infiltration rate reduction | 0.20 | 0.21 | −0.01 |

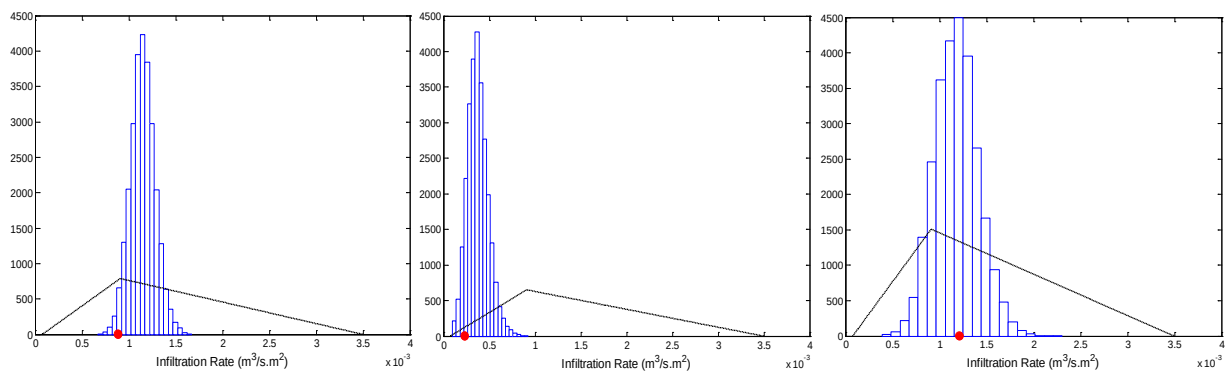


Figure 2: Posterior Distribution of Infiltration Rate for Small Office (left), Medium Office (middle), and Large Office (right) (Dashed lines show prior distributions, blue bars show posterior distributions, and red points show "true" values.)

Table 4 shows CVRMSE values that quantify the accuracy of predicted energy consumptions by the calibrated model and the uncalibrated model. Overall, calibration enhanced the accuracy of model predictions for the three office buildings. Calibration significantly reduced the discrepancy between model predictions and utility bills for gas consumptions and had a lesser effect on reducing the already small discrepancy in electricity consumptions. This trend was

expected because the calibration significantly updated the infiltration rate, which heavily influences gas use for heating and has a smaller effect on electricity use for cooling. This trend may be valid only for cold climate zones, including the case studies.

Table 4: Evaluation of Model Predictions against Utility Bills

| | CVRMSE in Electricity Prediction | | CVRMSE in Gas Prediction | |
|---|---|---|---|---|
| | Before Calibration | After Calibration | Before Calibration | After Calibration |
| Small Office | 0.19 | 0.04 | 0.76 | 0.13 |
| Medium Office | 0.07 | 0.03 | 2.56 | 0.30 |
| Large Office | 0.02 | 0.02 | 0.52 | 0.13 |

Figure 3 displays energy consumptions predicted by the calibrated model (red) and the uncalibrated model (blue) compared with utility bills (black) for the medium office building. In these plots, solid dots refer to the expected value of the probabilistic outcomes, and whiskers refer to the 95% confidence intervals of the outcomes. The uncalibrated model predicted electricity use with quite narrow confidence intervals, which coincides well with utility bills. Indeed, the uncalibrated model meets the ASHRAE requirement (CVRMSE below 15%) for predicting electricity use. For gas consumptions, the uncalibrated model computed wider confidence intervals, and the discrepancy between expected values and utility bills was higher than the AHSRAE requirement. Calibration substantially reduced the large discrepancy and results in the model to meet the ASHRAE requirement. Thus, even at this high level of audit data used for constructing the base models, calibration can be necessary to improve the reliability of energy simulation models.

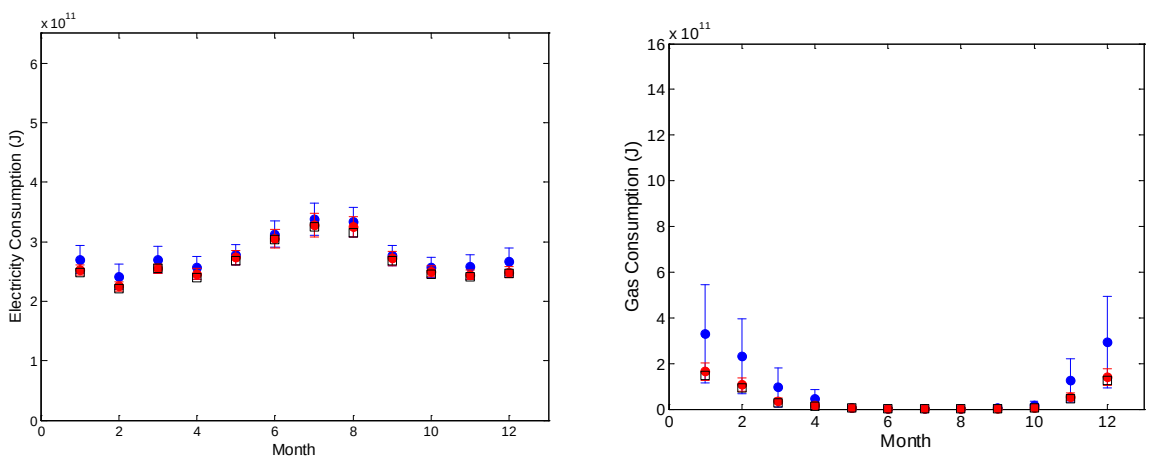


Figure 3: Predicted Energy Consumption (red – calibrated, blue – uncalibrated) against Measurements (black) for the Medium Office Building

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# 4 Calibrating Intermediate-level Model (Level 2)

Table 5 summarizes the ranking of uncertain parameters for three reference office building models at Level 2. In comparison with Level 3, the base models are constructed without measured data about system operation states and internal gains (i.e., energy consumptions for lighting and appliances). Consequently, model parameters related to those missing information hold a much higher magnitude of uncertainty compared with Level 3, in which their uncertainty arises only from measurement errors. As a result, the most dominant parameters identified by the Morris Method include outside airflow, appliance power density, and fan pressure rise, in addition to infiltration rate and heating system efficiency identified as the dominant parameters at Level 3.

Table 5: Rankings of Uncertain Parameters for the Three Office Buildings (Main effect × $10^9$)

| Rank | Small Office | | Medium Office | | Large Office | |
|---|---|---|---|---|---|---|
| | Model Parameter | Main Effect | Model Parameter | Main Effect | Model Parameter | Main Effect |
| 1 | Infiltration rate | 1,028 | Outside airflow | 6,106 | Outside airflow | 6,106 |
| 2 | Outside airflow | 785 | Appliance power density | 2,595 | Appliance power density | 2,595 |
| 3 | Heating system efficiency | 409 | Infiltration rate | 2,237 | Infiltration rate | 2,237 |
| 4 | Fan pressure rise | 211 | Heating system efficiency | 1,307 | Heating system efficiency | 1,307 |
| 5 | Appliance power density | 190 | Fan pressure rise | 981 | Fan pressure rise | 981 |
| 6 | Infiltration rate reduction | 113 | Fan system efficiency | 384 | Fan system efficiency | 384 |
| 7 | Fan system efficiency | 57 | Heating setpoint T – occupied | 320 | Heating setpoint T – occupied | 320 |
| 8 | Lighting power density | 25 | Lighting power density | 284 | Lighting power density | 284 |

Table 6 shows CVRMSE values that quantify the discrepancy between posterior distributions and true parameter values for the three reference office building models at Level 2. Overall, before calibration, CVRMSE values of their prior distributions for infiltration rate, outside airflow, and appliance power density were quite large, whereas CVRMSE values for heating system efficiency were as small as those at Level 3. For those parameters with large discrepancy, Bayesian calibration significantly reduced CVRMSE values by moving the posterior distributions toward the true values while greatly reducing uncertainty in the distributions (i.e., distribution width), as shown in Figure 4. However, for the parameters with small discrepancy, the posterior distributions were little changed from the prior distributions, an effect which was also observed at Level 3. This trend implies that calibrating these four dominant parameters may be sufficient to update energy models at this level; however, testing the efficacy of Bayesian calibration with a larger set of parameters was also investigated to confirm the implication.

Table 6: Evaluation of Calibration Parameter Values against True Parameter Values

| | CVRMSE in Parameter Values | | Difference |
|---|---|---|---|
| | Before Calibration | After Calibration | |
| **Small Office** | | | |
| Infiltration rate | 1.05 | 0.32 | 0.73 |
| Outside airflow | 4.28 | 1.29 | 3.00 |
| Heating system efficiency | 0.19 | 0.21 | -0.01 |
| Fan pressure rise | 0.43 | 0.27 | 0.16 |
| **Medium Office** | | | |
| Outside airflow | 4.22 | 0.38 | 3.84 |
| Appliance power density | 0.73 | 0.24 | 0.49 |
| Infiltration rate | 6.35 | 1.93 | 4.42 |
| Heating system efficiency | 0.08 | 0.07 | 0.01 |
| **Large Office** | | | |
| Outside airflow | 4.20 | 0.43 | 3.77 |
| Appliance power density | 0.71 | 0.10 | 0.61 |
| Infiltration rate | 0.65 | 0.37 | 0.28 |
| Heating system efficiency | 0.08 | 0.06 | 0.01 |

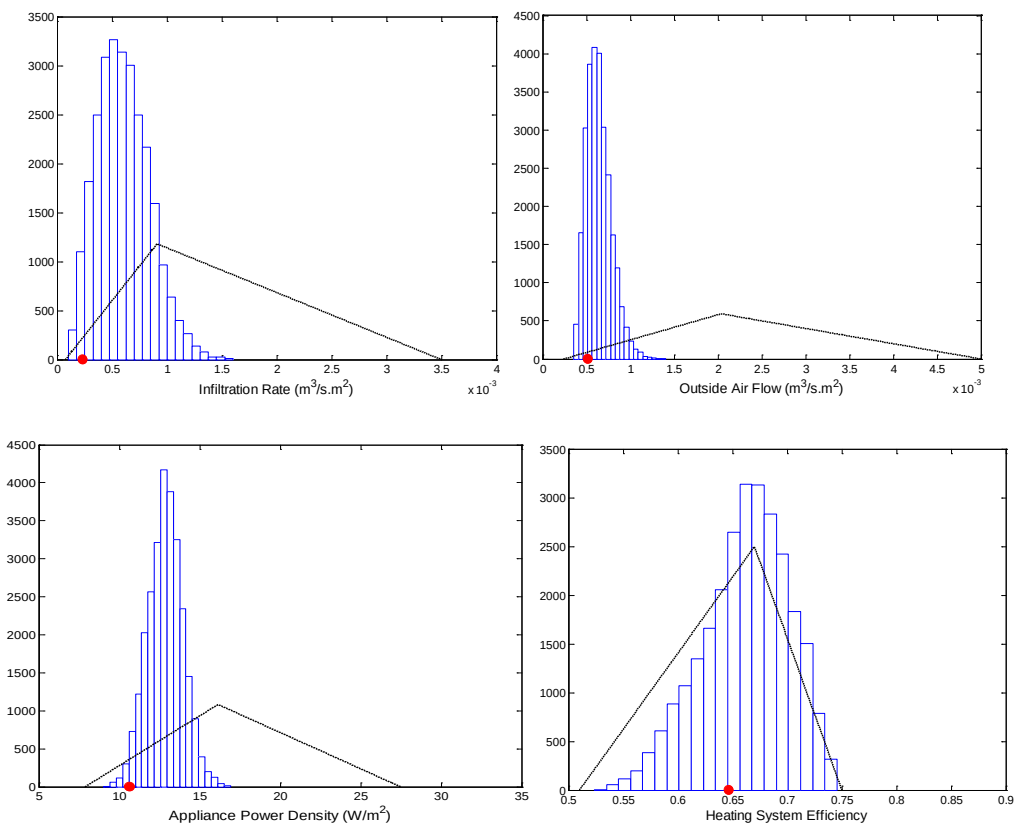


Figure 4: Calibration Results for the Medium Office Building (Dashed lines show prior distributions, blue bars show posterior distributions, and red points show "true" values.)

Table 7 shows CVRMSE values that compare energy use predicted by the calibrated model and the uncalibrated model against utility bills for the three office building models at Level 2. Overall, calibration significantly improved the accuracy of model predictions for both electricity consumptions and gas consumptions. The calibrated models resulted in low CVRMSE values, less than 0.25, for all the cases except for gas consumptions for the medium office building. As shown in Figure 5, the calibrated model over-predicts gas consumptions compared with the utility bills. This large discrepancy arises from the large magnitude of uncertainty still remaining in infiltration rates and outside airflow compared with uncertainty existing in these parameters at Level 3. At Level 2, the posterior distribution for the infiltration rate ranged between $0.10 \times 10^{-3}$ and $1.60 \times 10^{-3}$, with an average value of $0.60 \times 10^{-3}$, whereas its range at Level 3 was almost half ($0.10 \times 10^{-3}$ to $0.93 \times 10^{-3}$), with an average value of $0.40 \times 10^{-3}$ (shown in Figure 2). This comparison suggests that calibration has limitations in updating calibration parameter values to accurately match true values when the base models hold a large magnitude of uncertainty because of the lack of available data. The lack of data can confound the interactions among parameters, such as widening the parameter space to be explored. The effect of parameter interactions on the poorer calibration results is a topic for future study. Nonetheless, calibration enhanced the reliability of model predictions by an order of magnitude, and the resulting calibrated models at Level 2 were competitive with the uncalibrated models at Level 3.

Table 7: Evaluation of Model Predictions against Utility Bills

| | CVRMSE in Electricity Prediction | | CVRMSE in Gas Prediction | |
|---|---|---|---|---|
| | Before Calibration | After Calibration | Before Calibration | After Calibration |
| Small Office | 0.18 | 0.12 | 1.79 | 0.25 |
| Medium Office | 0.29 | 0.08 | 10.14 | 1.39 |
| Large Office | 0.61 | 0.16 | 1.42 | 0.18 |

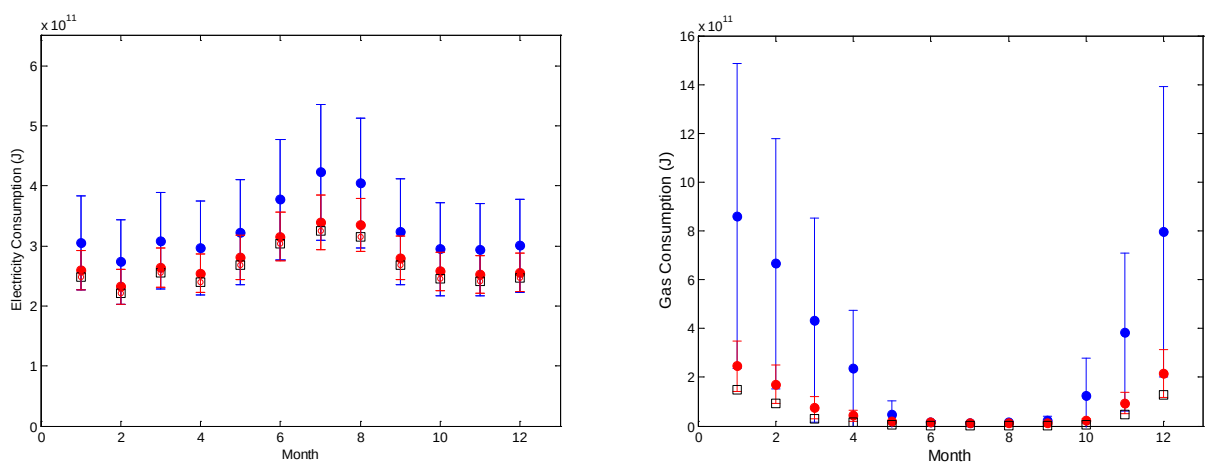


Figure 5: Predicted Energy Consumption (red – calibrated, blue – uncalibrated) against Measurements (black) for the Medium Office Building

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# 5 Calibrating Crude-level Model (Level 1)

Table 8 summarizes the rankings of uncertain parameters with respect to their effect on energy use for the three office building models at Level 1. At this level, the base models were constructed only from as-built drawings that provided information only about building geometry and construction specifications. Consequently, the three office buildings at this level resulted in similar rankings; the top dominant parameters include outside airflow, appliance power density, lighting power density, infiltration, and heating system efficiency. Appliance and lighting power densities become more dominant at this level because their uncertainty ranges were estimated on the basis of the field survey (Knight and Dunn 2003). The field survey investigated internal power consumptions across various office buildings compared with Level 2, in which they are estimated on the basis of the equipment inventory specific to the case building. For Level 1, these influential parameters will have a major effect on energy use predictions, similar to that of the top parameter.

Table 8: Rankings of Uncertain Parameters for the Three Office Buildings (Main effect × $10^9$)

| Rank | Small Office | | Medium Office | | Large Office | |
|---|---|---|---|---|---|---|
| | Model Parameter | Main Effect | Model Parameter | Main Effect | Model Parameter | Main Effect |
| 1 | Infiltration rate | 887 | Outside airflow | 6,215 | Appliance power density | 29,461 |
| 2 | Outside airflow | 714 | Appliance power density | 4,058 | Outside airflow | 18,388 |
| 3 | Heating system efficiency | 465 | Lighting power density | 1,935 | Lighting power density | 17,706 |
| 4 | Appliance power density | 289 | Heating system efficiency | 1,916 | Infiltration rate | 15,341 |
| 5 | Fan pressure rise | 250 | Infiltration rate | 1,903 | Pump head | 12,026 |
| 6 | Heating setpoint T – occupied | 198 | Fan pressure rise | 1,819 | Heating system efficiency | 10,661 |
| 7 | Lighting power density | 187 | Heating setpoint T – occupied | 1,233 | Heating setpoint T – occupied | 4,770 |
| 8 | Fan system efficiency | 124 | Fan system efficiency | 1,162 | Pump motor efficiency | 3,831 |

Table 9 summarizes CVRMSE values that compare calibration parameter values against true values for the three office buildings. For all the parameters except heating system efficiency, the posterior distributions coincide with the true values much better than the prior distributions. Figure 6 shows the posterior distributions for the medium office building; they substantially reduced uncertainty while their expected values more closely matched the true values. However, for the heating system efficiency, little change was observed between the prior and the posterior distributions. In addition, the calibration resulted in wider ranges of feasible values in the posterior distributions than those at Level 2 because of the large magnitude of uncertainty associated with the limited measurement data. In fact, larger levels of uncertainty reside in various parameters and, per study design, only four parameters were calibrated against utility bills. Nevertheless, Bayesian calibration still led to reasonable results that improved the accuracy of the baseline model.

Table 9: Evaluation of Calibration Parameter Values against True Parameter Values

| | CVRMSE in Parameter Values | | |
|---|---|---|---|
| | Before Calibration | After Calibration | Difference |
| **Small Office** | | | |
| Infiltration rate | 1.08 | 0.39 | 0.69 |
| Outside airflow | 4.18 | 1.18 | 3.00 |
| Heating system efficiency | 0.29 | 0.31 | −0.02 |
| Appliance power density | 0.96 | 0.86 | 0.10 |
| **Medium Office** | | | |
| Outside airflow | 4.22 | 0.30 | 3.92 |
| Appliance power density | 0.96 | 0.49 | 0.47 |
| Lighting power density | 0.34 | 0.27 | 0.07 |
| Heating system efficiency | 0.13 | 0.16 | −0.03 |
| **Large Office** | | | |
| Appliance power density | 0.95 | 0.17 | 0.78 |
| Outside airflow | 4.18 | 0.48 | 3.70 |
| Lighting power density | 0.84 | 0.18 | 0.65 |
| Infiltration rate | 0.65 | 0.33 | 0.32 |

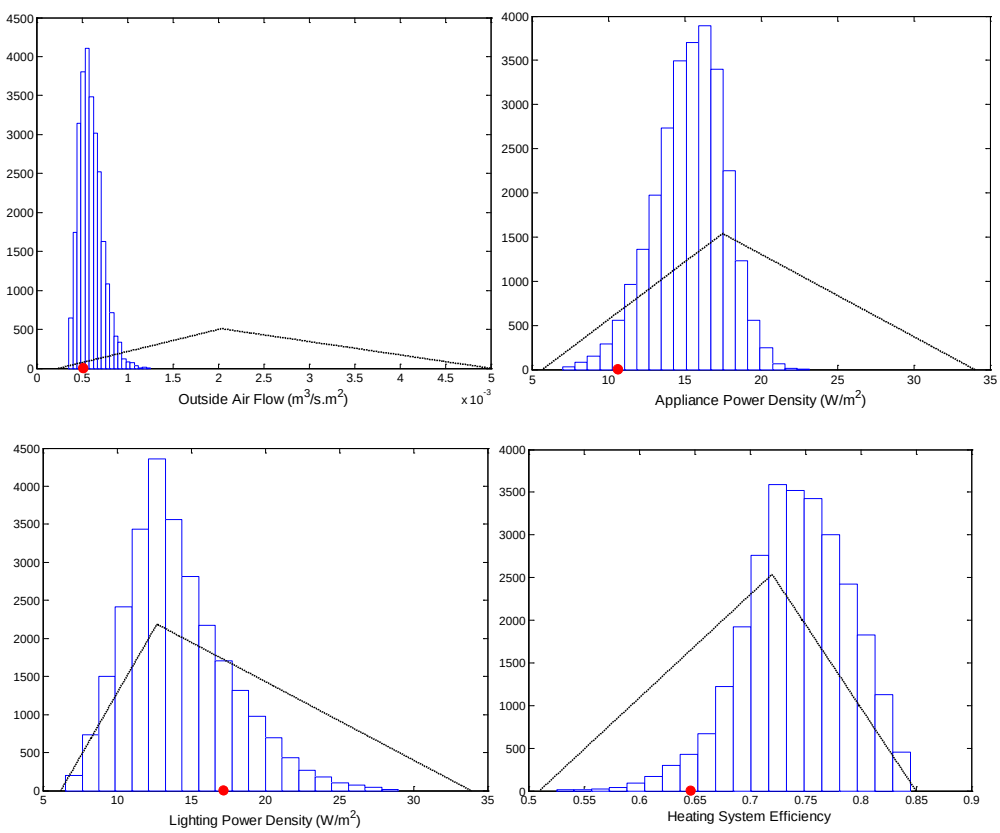


Figure 6: Bayesian Calibration Results for the Medium Office Building (Dashed lines show prior distributions, blue bars show posterior distributions, and red points show "true" values.)

Table 10 shows CVRMSE values that compare model predictions against utility bills for the three office buildings. Overall, calibration greatly reduced CVRMSE values in model predictions as the result of correcting calibration parameter values. As shown in Figure 7, the calibrated model over-predicted gas consumption as compared with the utility bills. However, for the medium office building case, the calibrated model still resulted in the high CVRMSE value of 8.63 for predicted gas use, which suggests that calibrating four parameters at this level may not be sufficient to obtain reliable predictions as expected. As expected, the number of influential parameters increased as the model level went down, with less data collected for modeling. Thus, Section 6 explores the effect of a larger set of calibration parameters on enhancing model reliability.

Table 10: Evaluation of Model Predictions against Utility Bills

| | CVRMSE in Electricity Prediction | | CVRMSE in Gas Prediction | |
|---|---|---|---|---|
| | Before Calibration | After Calibration | Before Calibration | After Calibration |
| Small Office | 1.17 | 0.75 | 5.64 | 0.86 |
| Medium Office | 1.56 | 0.57 | 31.47 | 8.63 |
| Large Office | 3.65 | 0.74 | 4.94 | 1.05 |

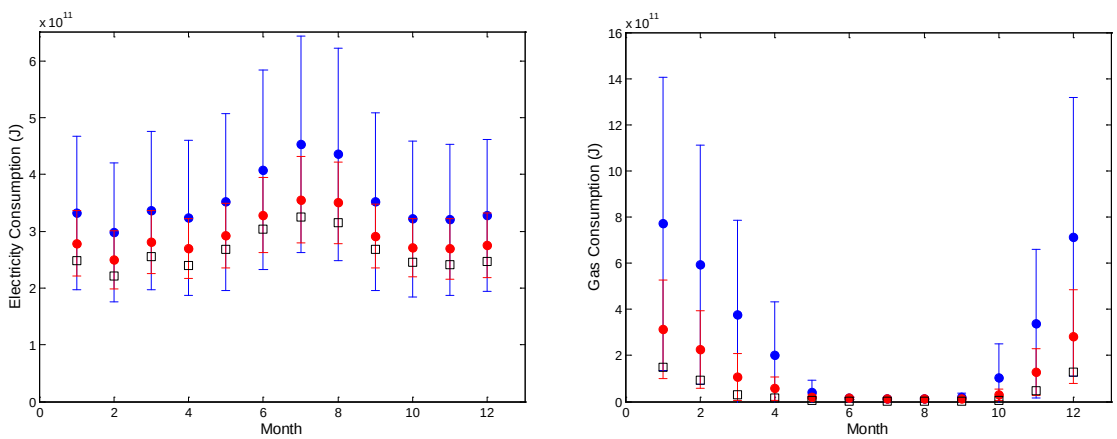


Figure 7: Predicted Energy Consumption (red –calibrated, blue – uncalibrated) against Measurements (black) for the Medium Office Building

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# 6 Calibration with a Larger Set of Parameters

We calibrated the top eight parameters at Levels 1 and 2 for the medium office building to examine whether a larger number of calibration parameters at lower model levels helps enhance the reliability of the calibrated models. Table 11 compares CVRMSE values from calibrating the eight parameters with those from calibrating the four parameters. At Level 2, calibrating the larger number of parameters did not improve the accuracy of posterior distributions noticeably for the four parameters in the initial strategy or for the other parameters introduced in the new calibration exercise. Consequently, calibrating four more parameters did not improve the accuracy of model predictions much, as shown in Table 12. However, at Level 1, calibrating the top eight parameters reduced CVRMSE values in model predictions by half, mainly by significantly reducing uncertainty in infiltration rate (ranked as the fifth). This upgrade suggests that Model Level 1 needs a larger set of parameters, including outside airflow, appliance power density, lighting power density, heating system efficiency, and infiltration rate to assure the reliability of the calibrated model. Nevertheless, the CVRMSE value in gas predictions is still high. Further model improvement requires advanced Bayesian calibration algorithms that calibrate uncertain parameters with an extensive set of measurement data, including hourly data or submetered data in addition to monthly utility bills.

Table 11: Evaluation of Calibration Parameter Values from Calibrating Eight Parameters

| | CVRMSE in Parameter Values | | |
|---|---|---|---|
| | Before Calibration | Calibrating 4 Parameters | Calibrating 8 Parameters |
| **Medium Office Model: Level 2** | | | |
| Outside airflow | 4.22 | 0.38 | 0.33 |
| Appliance power density | 0.73 | 0.24 | 0.26 |
| Infiltration rate | 6.35 | 1.93 | 2.02 |
| Heating system efficiency | 0.08 | 0.07 | 0.07 |
| Fan pressure rise | 0.44 | –[a] | 0.46 |
| Fan efficiency | 0.09 | – | 0.09 |
| Heating setpoint T - occupied | 0.01 | – | 0.01 |
| Lighting power density | 0.07 | – | 0.06 |
| **Medium Office Model: Level 1** | | | |
| Outside airflow | 4.22 | 0.30 | 0.45 |
| Appliance power density | 0.96 | 0.49 | 0.42 |
| Lighting power density | 0.34 | 0.27 | 0.27 |
| Heating system efficiency | 0.13 | 0.16 | 0.15 |
| Infiltration rate | 6.41 | – | 2.04 |
| Fan pressure rise | 0.38 | – | 0.32 |
| Heating setpoint T - occupied | 0.03 | – | 0.03 |
| Fan pressure rise | 0.31 | – | 0.30 |

[a] A dash indicates that the parameter was not part of the calibration.

Table 12: Evaluation of Model Predictions against Utility Bills

| | CVRMSE in Electricity Prediction | | CVRMSE in Gas Prediction | |
|---|---|---|---|---|
| | Calibrating 4 Parameters | Calibrating 8 Parameters | Calibrating 4 Parameters | Calibrating 8 Parameters |
| Model Level 2 | 0.08 | 0.07 | 1.39 | 1.22 |
| Model Level 1 | 0.57 | 0.29 | 8.63 | 3.86 |

# 7 Conclusions and Further Work

This project evaluated the efficacy of Bayesian calibration of EnergyPlus building energy models given uncertainty consistent with different ASHRAE audit levels. Case studies with three types of office buildings demonstrated that for all audit levels, Bayesian calibration yields posterior distributions that correspond well to true values while significantly reducing uncertainty in parameter values. Consequently, calibrated models enhance the reliability of their predictions, more closely matching utility bills with much reduced uncertainty compared with uncalibrated models. In addition, the calibration exercises with three EnergyPlus reference office buildings provide the following useful information for calibrating other office building cases:

- Uncertainty quantified in model parameters depending on the audit level (Appendix A for small office building, Appendix B for medium office building, and Appendix C for large-office building), and

- Summary of dominant parameters needed to be calibrated depending on the audit level.

In order to enhance the practicality of Bayesian calibration, further methods development is planned in this project to:

- Investigate alternative algorithms and techniques for speeding up Bayesian calibration (e.g., parallel processing algorithms for Monte Carlo Morris Method simulations);

- Develop in depth guidance for applying Bayesian methods to calibrate EnergyPlus models for three levels of available data, including identification of uncertain parameters, derivation of uncertainty data, selection of calibration parameters, and analysis of results.

- Create a modeler's resource for input parameter uncertainty data with the objective of significantly reducing the upfront effort required to evaluate building energy performance under uncertainty; and

- Program an OpenStudio wrapper for Bayesian calibration of EnergyPlus models.

In addition, further development of the Bayesian methods to achieve the following capabilities is suggested:

- Bayesian calibration module that handles hourly data: The current module regards each data point as independent, which is a valid assumption for monthly energy consumptions. If one wants to use hourly measurement data, the calibration module needs to account for correlations among time-series hourly energy use data. Further research should be conducted to design a covariance matrix in the module to capture the correlations. In addition, it will be worth assessing whether using finer resolutions

of measured data for calibration helps enhance the reliability of calibrated models further.

- Bayesian hierarchical model that can calibrate models with various sources of monitored data: The current module is limited to the cases in which measured data are at one level, typically at whole-building level. A Bayesian hierarchical model could map sparse measured data at different levels (e.g., submetered data, utility bills) to a different set of parameters under the hierarchical structure. This model could exploit more information from different sources of data to improve the accuracy of the baseline model further, compared with the current module.

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# Appendix A: Small Office Building

## A.1 Uncertainty Quantification

Table A.1: Uncertainty in Envelope-related Parameters for Three Levels of Models

| Envelope Type | Model Parameter | Base | Min | Max | Std. Dev. | Reference |
|---|---|---|---|---|---|---|
| IEAD nonres roof insulation/ | Conductivity (W/m • K) | 0.05 | 0.04 | 0.05 | 5% | Macdonald 2002 |
| Steel frame nonres wall | Density (kg/m$^3$) | 265.00 | 259.70 | 270.30 | 1% | |
| insulation | Specific heat (J/kg • K) | 836.80 | 631.78 | 1,041.82 | 12% | |
| Std. wood, 6 in. | Conductivity (W/m • K) | 0.12 | 0.11 | 0.13 | 5% | |
| | Density (kg/m$^3$) | 540.00 | 529.20 | 550.80 | 1% | |
| | Specific heat (J/kg • K) | 1,210.00 | 913.55 | 1,506.45 | 12% | |
| Wood siding | Conductivity (W/m • K) | 0.11 | 0.10 | 0.12 | 5% | |
| | Density (kg/m$^3$) | 544.62 | 533.73 | 555.51 | 1% | |
| | Specific heat (J/kg • K) | 1,210.00 | 913.55 | 1,506.45 | 12% | |
| | Thermal absorptance | 0.90 | 0.86 | 0.94 | 0.02 | |
| | Solar absorptance | 0.78 | 0.70 | 0.86 | 0.04 | |
| 1/2-in. gypsum | Conductivity (W/m • K) | 0.16 | 0.14 | 0.18 | 5% | |
| | Density (kg/m$^3$) | 784.90 | 769.20 | 800.60 | 1% | |
| | Specific heat (J/kg • K) | 830.00 | 626.65 | 1,033.35 | 12% | |
| HW concrete | Conductivity (W/m • K) | 1.31 | 1.18 | 1.44 | 5% | |
| | Density (kg/m$^3$) | 2,240.00 | 2,195.20 | 2,284.80 | 1% | |
| | Specific heat (J/kg • K) | 836.80 | 631.78 | 1,041.82 | 12% | |
| | Thermal absorptance | 0.90 | 0.86 | 0.94 | 0.02 | |
| | Solar absorptance | 0.70 | 0.62 | 0.78 | 0.04 | |
| Roof membrane | Conductivity (W/m • K) | 0.16 | 0.14 | 0.18 | 5% | |
| | Density (kg/m$^3$) | 1,121.29 | 1,098.86 | 1,143.72 | 1% | |
| | Specific heat (J/kg • K) | 1,460.00 | 1,102.30 | 1,817.70 | 12% | |
| | Thermal absorptance | 0.90 | 0.86 | 0.94 | 0.02 | |
| | Solar absorptance | 0.70 | 0.64 | 0.76 | 0.03 | |
| Metal decking | Conductivity (W/m • K) | 45.01 | 40.51 | 49.51 | 5% | |
| | Density (kg/m$^3$) | 7,680.00 | 7,526.40 | 7,833.60 | 1% | |
| | Specific heat (J/kg • K) | 418.40 | 315.89 | 520.91 | 12% | |
| Std. AC02 | Conductivity (W/m • K) | 0.06 | 0.05 | 0.06 | 5% | |
| | Density (kg/m$^3$) | 288.00 | 282.24 | 293.76 | 1% | |
| | Specific heat (J/kg • K) | 1,339.00 | 1,010.95 | 1,667.06 | 12% | |
| Carpet pad | Thermal resistance | 0.22 | 0.19 | 0.24 | 5% | Macdonald 2002 |
| Mat-air-wall | Thermal resistance | 0.21 | 0.19 | 0.23 | 5% | |
| Fixed assembly window | U value (W/m$^2$ • K) | 3.52 | 3.17 | 3.87 | 5% | |
| | Solar heat gain coefficient (SHGC) | 0.41 | 0.39 | 0.42 | 0.01 | Loutzenhiser et al. 2009 |
| Infiltration rate per exterior surface area (m$^3$/s • m$^2$) | | 0.00091 | 0.00007 | 0.00350 | – | Emmerich et al. 2005; ASHRAE 2009 |
| Infiltration rate reduction while mechanical system on | | 0.38 | 0.25 | 0.50 | – | VanBronkhorst et al. 1995 |

Table A.2: Uncertainty in Building Use-related Parameters for Three Levels of Models

| Building Use Parameter | Model Level | Base | Min | Max | Tolerance | Reference |
|---|---|---|---|---|---|---|
| Occupant density ($m^2$/person) | 1 | 11.10 | 4.30 | 22.80 | –[a] | Knight and Dunn 2003 |
| | 2, 3 | 18.58 | 16.72 | 20.44 | 10% | – |
| Lighting power density ($W/m^2$) | 1 | 12.70 | 6.20 | 33.90 | – | Knight and Dunn 2003 |
| | 2 | 18.00 | 16.00 | 20.00 | 2.0 | Lighting Research Center 2006 |
| | 3 | 19.48 | 19.09 | 19.87 | 2% | Seal and McGranaghan 2010 (Figure 2) |
| Appliance power density ($W/m^2$) | 1 | 17.50 | 5.70 | 34.00 | – | Knight and Dunn 2003 |
| | 2 | 16.15 | 7.89 | 27.50 | – | Inventory (Thornton et al. 2010), Uncertainty (Macdonald 2002; IVF 2005) |
| | 3 | 10.76 | 10.54 | 10.98 | 2% | Seal and McGranaghan 2010 (Figure 2) |
| Occupant metabolic rate (W/person) | 1, 2, 3 | 120.00 | 70.00 | 130.00 | – | Macdonald 2002 |
| Cooling setpoint temp – occupied (°C) | 1 | 24.00 | 22.50 | 25.50 | – | Mendell and Mirer 2008: modified due to E+ constraint |
| | 2, 3 | 24.00 | 23.28 | 24.72 | 3% | Kim 2011 (Table 6.7) |
| Cooling setpoint temp – unoccupied (°C) | 1 | 26.50 | 25.00 | 28.00 | – | – |
| | 2, 3 | 26.70 | 25.90 | 27.50 | 3% | Kim 2011 (Table 6.7) |
| Heating setpoint temp – occupied (°C) | 1 | 21.00 | 19.50 | 22.50 | – | Mendell and Mirer 2008: modified due to E+ constraint |
| | 2, 3 | 21.00 | 20.37 | 21.63 | 3% | Kim 2011 (Table 6.7) |
| Heating setpoint temp – unoccupied (°C) | 1 | 16.50 | 15.00 | 18.00 | – | – |
| | 2, 3 | 15.60 | 15.13 | 16.07 | 3% | Kim 2011 (Table 6.7) |
| Domestic heating water (DHW) peak flow rate ($m^3$/s) | 1, 2 | 0.0000049 | 0.0000044 | 0.0000131 | – | ASHRAE 2011 (Figure 50.24) |
| | 3 | 0.0000032 | 0.0000028 | 0.0000035 | 10.0% | Kim 2011 (Table 6.7) |

[a] A dash indicates no assigned/applicable tolerance.

Table A.3: Uncertainty in System-related Parameters for Three Levels of Models

| System-related Parameter | Model Level | Base | Min | Max | Range | Factor | Reference |
|---|---|---|---|---|---|---|---|
| Outdoor airflow per area ($m^3/s \cdot m^2$) | 1, 2 | 0.00204 | 0.00024 | 0.00501 | – | – | Persily and Gorfain 2004 |
| | 3 | 0.00054 | 0.00048 | 0.00059 | 10.0% | Tolerance | Kim 2011 (Table 6.7) |
| Fan efficiency | 1 | 0.66 | 0.36 | 0.85 | 0.55–0.88 | Efficiency (as-new) | Radgen et al. 2008 (Table 3) |
| | | | | | 0.1–1.0% | Degradation | Griffith et al. 2008 |
| | 2, 3 | 0.46 | 0.35 | 0.52 | 6.0% | Tolerance | AMCA Standard 211-05, 2012 |
| | | | | | 0.1–1.0% | Degradation | Griffith et al. 2008 |
| Pressure rise (Pa) | 1 | 466.73 | 77.86 | 1207.13 | 0.50–1.50 | Specific fan power (SFP) (W/l • s) | Radgen et al. 2008 (Table 19) |
| | 2 | 356.64 | 104.05 | 668.72 | 0.50–1.50 | SFP (W/l • s) | Radgen et al. 2008 (Table 19) |
| | 3 | 622.00 | 603.34 | 640.66 | 3.0% | Tolerance | Kim 2011 (Table B.5) |
| Fan motor efficiency | 1 | 0.70 | 0.43 | 0.95 | 0.65–0.98 | Efficiency (as-new) | Radgen et al. 2008 (page 84) |
| | | | | | 0.1–1.0% | Degradation | Griffith et al. 2008 |
| | 2, 3 | 0.71 | 0.54 | 0.80 | 0.5% | Tolerance | IEC Standard 60034-2-1, 2007 |
| | | | | | 0.1–1.0% | Degradation | Griffith et al. 2008 |
| Cooling system rated coefficient of performance (COP) | 1 | 3.10 | 1.69 | 4.46 | 2.56–4.62 | Efficiency (as-new) | Southern California Edison 2005 |
| | 2, 3 | 2.93 | 2.24 | 3.27 | 5.0% | Tolerance | ANSI/AHRI Standard 210/240, 2008 (page 22) |
| | | | | | 0.1–1.0% | Degradation | Griffith et al. 2008 |
| Degradation coefficient for partial-load performance curve | 1 | 0.25 | 0.06 | 0.26 | – | – | Hu 2009 (Table 4.14) |
| | 2, 3 | 0.25 | 0.24 | 0.26 | 5.0% | Tolerance | ANSI/AHRI Standard 210/240, 2008 (page 22) |
| Gas burner efficiency | 1 | 0.72 | 0.51 | 0.85 | 0.78–0.88 | Efficiency (as-new) | Kemna et al. 2007 (page 247) |
| | | | | | 0.1–1.0% | Degradation | Griffith, 2008 |
| | 2, 3 | 0.67 | 0.51 | 0.75 | 2.0% | Tolerance | Kemna et al. 2007 (page 30) |
| | | | | | 0.1–1.0% | Degradation | Griffith et al. 2008 |

**Table A.3: Uncertainty in System-related Parameters for Three Levels of Models (Cont.)**

| System-related Parameter | Model Level | Base | Min | Max | Range | Factor | Reference |
|---|---|---|---|---|---|---|---|
| DHW pump motor efficiency | 1 | 0.70 | 0.43 | 0.95 | 0.65–0.98 | Efficiency (as-new) | Radgen et al. 2008 (page 84) |
| | | | | | 0.1–1.0% | Degradation | Griffith et al. 2008 |
| | 2, 3 | 0.86 | 0.66 | 0.97 | 0.5% | Tolerance | IEC 60034-2-1 2007 |
| | | | | | 0.1–1.0% | Degradation | Griffith et al. 2008 |
| DHW thermal efficiency | 1 | 0.72 | 0.51 | 0.85 | 0.78–0.88 | Efficiency (as-new) | Kemna et al. 2007 (page 247) |
| | | | | | 0.1–1.0% | Degradation | Griffith et al. 2008 |
| | 2, 3 | 0.69 | 0.53 | 0.77 | 2.0% | Tolerance | Kemna et al. 2007 (page 30) |
| | | | | | 0.1–1.0% | Degradation | Griffith et al. 2008 |
| Water heater setpoint temperature | 1, 2 | 60.00 | 40.50 | 82.22 | – | – | ASHRAE 2011 (Table 50.3) |
| | 3 | 60.00 | 58.20 | 61.80 | 3.0% | Tolerance | Kim 2011 (Table 6.7) |

## A.2 Parameter Screening

Table A.4 summarizes the ranking of uncertainty parameters for the three levels of the small office building models. The base model at Level 3 was constructed with the detail audit data monitored for all model parameters except infiltration and system efficiency. As a result, the most dominant parameters are (1) infiltration rate, (2) heating system efficiency, (3) infiltration rate reduction, and (4) fan system efficiency. Infiltration rate has by far the highest effect on energy consumption, while the other parameters have a much smaller effect. In comparison with Level 3, the base model at Level 2 was constructed without information about system operation states and end-use energy consumptions. Consequently, the most influential parameters include outside airflow and fan pressure rise in addition to infiltration rate and heating system efficiency. Infiltration rate is the most important parameter, while the operation-related parameters also have a major effect on energy use at this level. The base model at Level 1 was constructed only on the basis of as-built drawings. As a result, the top four parameters include a building use-related parameter (appliance power density) in addition to the top three parameters at Level 2. At this level, the top eight parameters also have a main effect as high as the top four parameters at Level 3.

Table A.4: Ranking of Uncertain Parameters for Three Levels of Models

| Rank | Model Level 1 | | Model Level 2 | | Model Level 3 | |
|---|---|---|---|---|---|---|
| | Model Parameter | Main Effect | Model Parameter | Main Effect | Model Parameter | Main Effect |
| 1 | Infiltration rate | $887 \times 10^9$ | Infiltration rate | $1{,}028 \times 10^9$ | Infiltration rate | $928 \times 10^9$ |
| 2 | Outside airflow | $714 \times 10^9$ | Outside airflow | $785 \times 10^9$ | Heating system efficiency | $178 \times 10^9$ |
| 3 | Heating system efficiency | $465 \times 10^9$ | Heating system efficiency | $409 \times 10^9$ | Infiltration rate reduction | $110 \times 10^9$ |
| 4 | Appliance power density | $289 \times 10^9$ | Fan pressure rise | $211 \times 10^9$ | Fan system efficiency | $78 \times 10^9$ |
| 5 | Fan pressure rise | $250 \times 10^9$ | Appliance power density | $190 \times 10^9$ | Heating setpoint T - unoccupied | $33 \times 10^9$ |
| 6 | Heating setpoint T – occupied | $198 \times 10^9$ | Infiltration rate reduction | $113 \times 10^9$ | Heating setpoint T – occupied | $31 \times 10^9$ |
| 7 | Lighting power density | $187 \times 10^9$ | Fan system efficiency | $57 \times 10^9$ | Cooling system efficiency | $22 \times 10^9$ |
| 8 | Fan system efficiency | $124 \times 10^9$ | Lighting power density | $25 \times 10^9$ | Fan pressure rise | $15 \times 10^9$ |

## A.3 Calibration Results

Figure A.1 shows the posterior distributions of the four calibration parameters (blue histogram) updated from the prior distributions (black line), compared with the true parameter values (red dot). At Level 3, the posterior distribution for the infiltration rate greatly changed from the prior distribution, thus reducing uncertainty while its expected value moved closer to the true value. For the other calibration parameters, however, the posterior distributions did not change much from the prior distributions. At Level 2, the posterior distributions for infiltration rate, outside airflow, and fan pressure rose swiftly toward the true values from the prior distributions while significantly reducing uncertainty. However, for fan pressure rise, the true value did not match the expected value but was located within the bounds of the distribution. At Level 1, the calibration results were similar to those at Level 2, except for appliance power density. For appliance power density, the true value was slightly off the bounds of the posterior distribution; however, the discrepancy between the posterior distribution and the true value was noticeably reduced by significantly reducing uncertainty.

**Model Level 1**

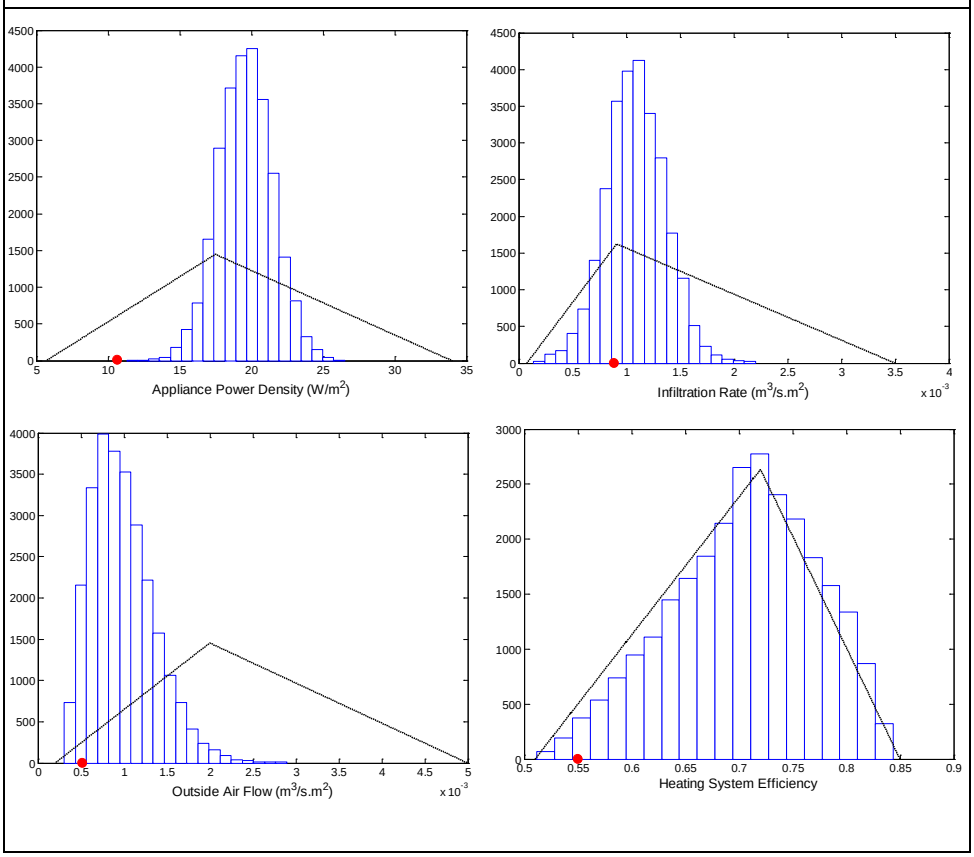
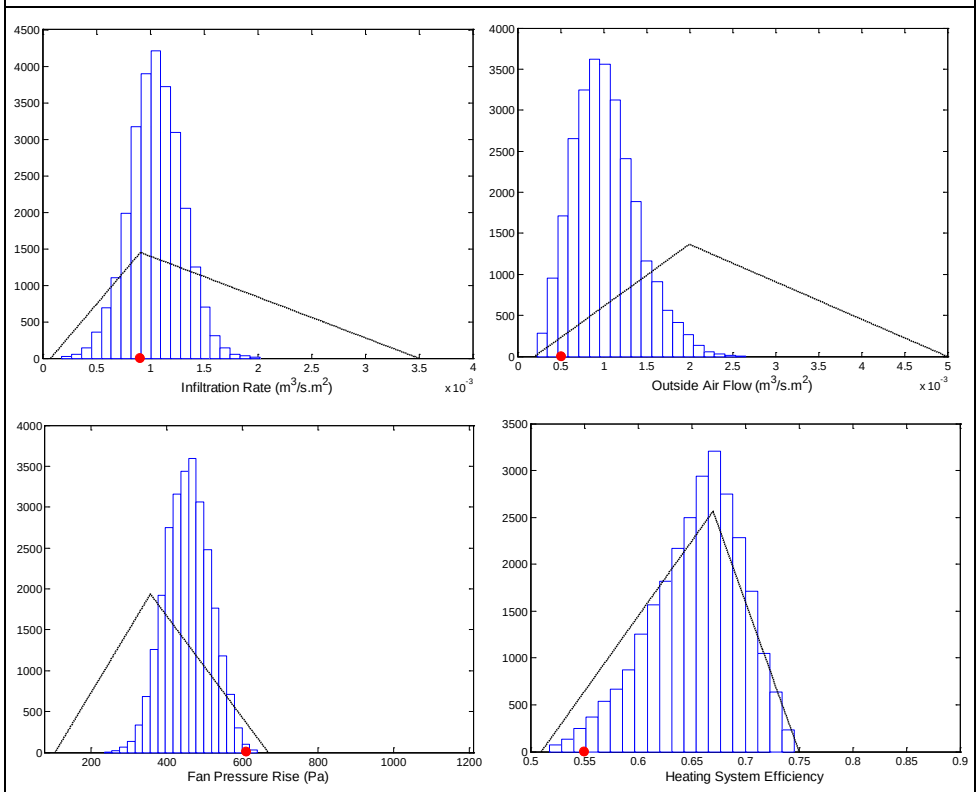



Figure A.1: Bayesian Calibration Results for the Three Levels of Models

**Model Level 2**




**Model Level 3**

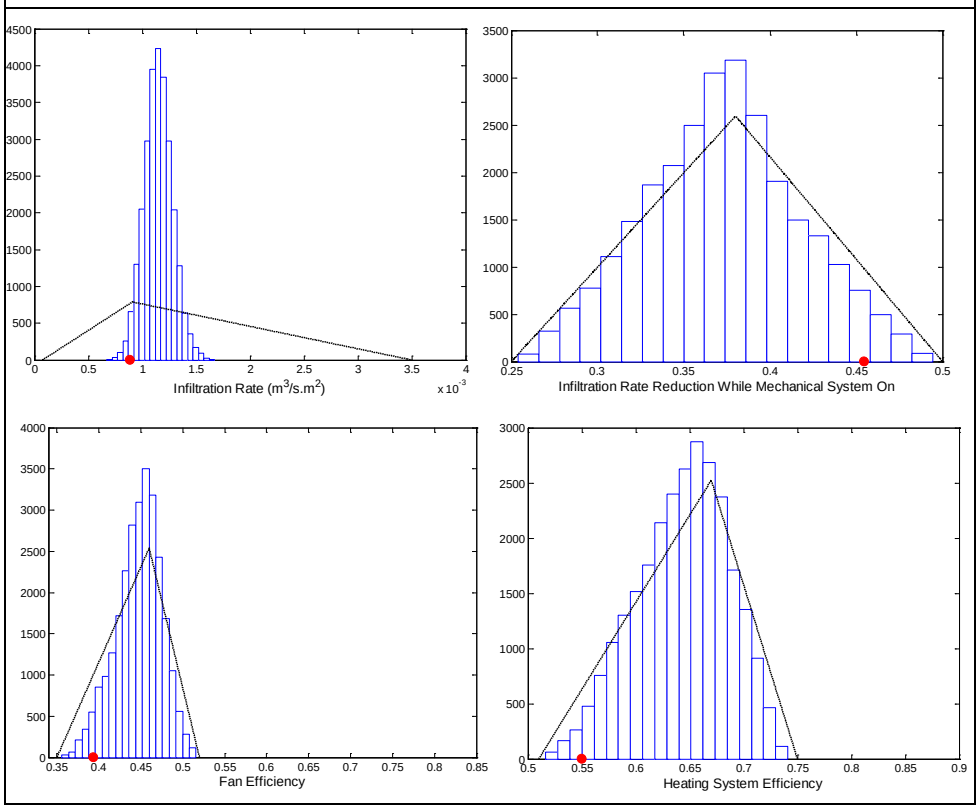


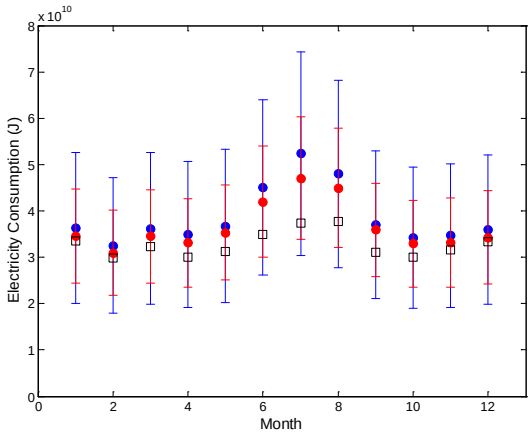

Figure A.1: Bayesian Calibration Results for the Three Levels of Models (Cont.)

## A.4 Model Predictions

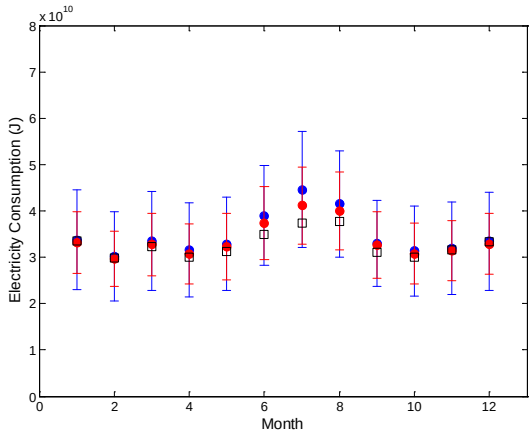
Figure A.2 compares electricity and gas consumptions predicted by the calibrated model (red) and the uncalibrated model (blue) against measured consumptions (black). In the plots, solid dots refer to the expected value of predicted energy consumptions, and whiskers refer to 95% confidence intervals of model predictions. For all levels, calibration enhanced the reliability of model predictions by greatly reducing uncertainty in predictions, while computing expected energy use values closely matching the measurement data. However, at Level 1, the discrepancy between predictions and measurements was observed for electricity energy consumptions.

**Electricity Consumption**

**Model Level 1**




**Model Level 2**




**Model Level 3**

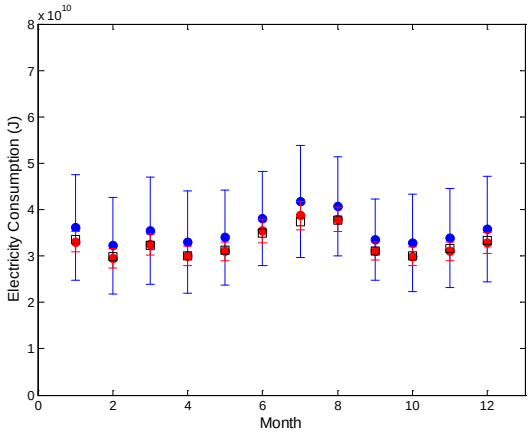
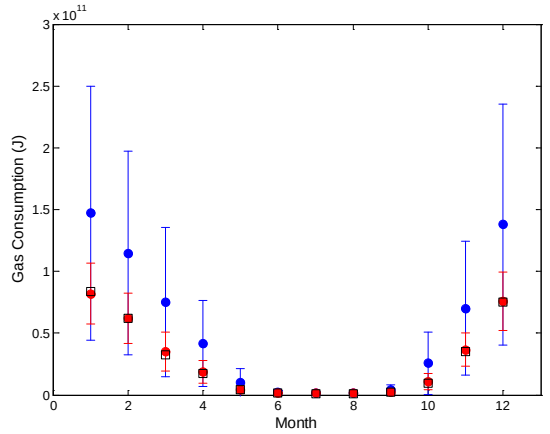


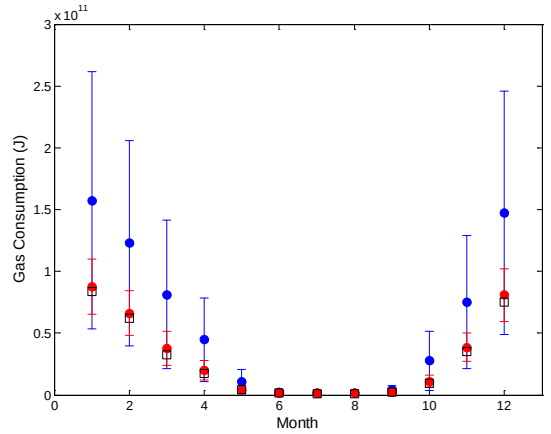

Figure A.2: Predicted Electricity and Gas Consumption Compared with Measured Data

**Gas Consumption**

**Model Level 1**




**Model Level 2**




**Model Level 3**

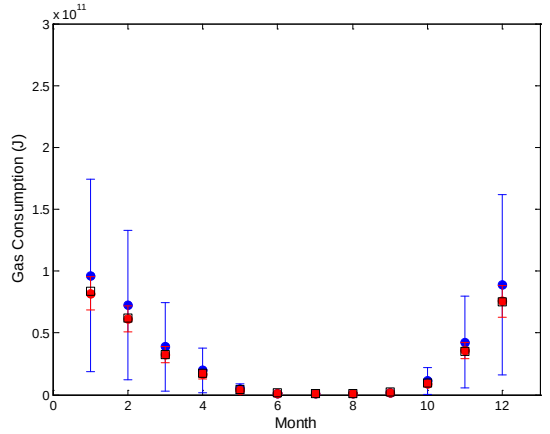



Figure A.2: Predicted Electricity and Gas Consumption Compared with Measured Data (Cont.)

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# Appendix B: Medium Office Building

## B.1 Uncertainty Quantification

Table B.1: Uncertainty in Envelope-related Parameters for Three Levels of Models

| Envelope Type | Model Parameter | Base | Min | Max | Std. Dev. | Reference |
|---|---|---|---|---|---|---|
| IEAD nonres roof insulation/ | Conductivity (W/m • K) | 0.05 | 0.04 | 0.05 | 5% | Macdonald 2002 |
| Steel frame nonres wall | Density (kg/m$^3$) | 265.00 | 259.70 | 270.30 | 1% | |
| insulation | Specific heat (J/kg • K) | 836.80 | 631.78 | 1,041.82 | 12% | |
| Std. wood, 6 in. | Conductivity (W/m • K) | 0.12 | 0.11 | 0.13 | 5% | |
| | Density (kg/m$^3$) | 540.00 | 529.20 | 550.80 | 1% | |
| | Specific heat (J/kg • K) | 1,210.00 | 913.55 | 1,506.45 | 12% | |
| Wood siding | Conductivity (W/m • K) | 0.11 | 0.10 | 0.12 | 5% | |
| | Density (kg/m$^3$) | 544.62 | 533.73 | 555.51 | 1% | |
| | Specific heat (J/kg • K) | 1,210.00 | 913.55 | 1,506.45 | 12% | |
| | Thermal absorptance | 0.90 | 0.86 | 0.94 | 0.02 | |
| | Solar absorptance | 0.78 | 0.70 | 0.86 | 0.04 | |
| 1/2-in. gypsum | Conductivity (W/m • K) | 0.16 | 0.14 | 0.18 | 5% | |
| | Density (kg/m$^3$) | 784.90 | 769.20 | 800.60 | 1% | |
| | Specific heat (J/kg • K) | 830.00 | 626.65 | 1,033.35 | 12% | |
| HW concrete | Conductivity (W/m • K) | 1.31 | 1.18 | 1.44 | 5% | |
| | Density (kg/m$^3$) | 2,240.00 | 2,195.20 | 2,284.80 | 1% | |
| | Specific heat (J/kg • K) | 836.80 | 631.78 | 1,041.82 | 12% | |
| | Thermal absorptance | 0.90 | 0.86 | 0.94 | 0.02 | |
| | Solar absorptance | 0.70 | 0.62 | 0.78 | 0.04 | |
| Roof membrane | Conductivity (W/m • K) | 0.16 | 0.14 | 0.18 | 5% | |
| | Density (kg/m$^3$) | 1,121.29 | 1,098.86 | 1,143.72 | 1% | |
| | Specific heat (J/kg • K) | 1,460.00 | 1,102.30 | 1,817.70 | 12% | |
| | Thermal absorptance | 0.90 | 0.86 | 0.94 | 0.02 | |
| | Solar absorptance | 0.70 | 0.64 | 0.76 | 0.03 | |
| Metal decking | Conductivity (W/m • K) | 45.01 | 40.51 | 49.51 | 5% | |
| | Density (kg/m$^3$) | 7,680.00 | 7,526.40 | 7,833.60 | 1% | |
| | Specific heat (J/kg • K) | 418.40 | 315.89 | 520.91 | 12% | |
| Mat-CC05 4 HW concrete | Conductivity (W/m • K) | 1.31 | 1.18 | 1.44 | 5% | |
| | Density (kg/m$^3$) | 2,240.00 | 2,195.20 | 2,284.80 | 1% | |
| | Specific heat (J/kg • K) | 836.80 | 631.78 | 1,041.82 | 12% | |
| Std. AC02 | Conductivity (W/m • K) | 0.06 | 0.05 | 0.06 | 5% | Macdonald 2002 |
| | Density (kg/m$^3$) | 288.00 | 282.24 | 293.76 | 1% | |
| | Specific heat (J/kg • K) | 1,339.00 | 1,010.95 | 1,667.06 | 12% | |
| Carpet pad | Thermal resistance | 0.22 | 0.19 | 0.24 | 5% | |
| Mat-air-wall | Thermal resistance | 0.21 | 0.19 | 0.23 | 5% | |
| Fixed assembly window | U value (W/m$^2$ • K) | 3.52 | 3.17 | 3.87 | 5% | |
| | Solar heat gain coefficient (SHGC) | 0.41 | 0.39 | 0.42 | 0.01 | Loutzenhiser et al. 2009 |
| Infiltration rate per exterior surface area (m$^3$/s • m$^2$) | | 0.00091 | 0.00007 | 0.00350 | – | Emmerich et al. 2005; ASHRAE 2009 |
| Infiltration rate reduction while mechanical system on | | 0.38 | 0.25 | 0.50 | – | VanBronkhorst et al. 1995 |

Table B.2: Uncertainty in Building Use-related Parameters for Three Levels of Models

| Building Use Parameter | Model Level | Base | Min | Max | Tolerance | Reference |
|---|---|---|---|---|---|---|
| Occupant density ($m^2$/person) | 1 | 11.10 | 4.30 | 22.80 | –[a] | Knight and Dunn 2003 |
| | 2, 3 | 18.58 | 16.72 | 20.44 | 10% | - |
| Lighting power density ($W/m^2$) | 1 | 12.70 | 6.20 | 33.90 | – | Knight and Dunn 2003 |
| | 2 | 18.00 | 16.00 | 20.00 | 2.0 | Lighting Research Center 2006 |
| | 3 | 16.89 | 16.55 | 17.23 | 2% | Seal and McGranaghan 2010 (Figure 2) |
| Appliance power density ($W/m^2$) | 1 | 17.50 | 5.70 | 34.00 | – | Knight and Dunn 2003 |
| | 2 | 16.15 | 7.89 | 27.50 | – | Inventory (Thornton et al. 2010), Uncertainty (Macdonald 2002; IVF 2005) |
| | 3 | 10.76 | 10.54 | 10.98 | 2% | Seal and McGranaghan 2010 (Figure 2) |
| Occupant metabolic rate (W/person) | 1, 2, 3 | 120.00 | 70.00 | 130.00 | – | Macdonald 2002 |
| Cooling setpoint temp – occupied (°C) | 1 | 24.00 | 22.50 | 25.50 | – | Mendell and Mirer 2008: modified due to E+ constraint |
| | 2, 3 | 24.00 | 23.28 | 24.72 | 3% | Kim 2011 (Table 6.7) |
| Cooling setpoint temp – unoccupied (°C) | 1 | 26.50 | 25.00 | 28.00 | – | – |
| | 2, 3 | 26.70 | 25.90 | 27.50 | 3% | Kim 2011 (Table 6.7) |
| Heating setpoint temp – occupied (°C) | 1 | 21.00 | 19.50 | 22.50 | – | Mendell and Mirer 2008: modified due to E+ constraint |
| | 2, 3 | 21.00 | 20.37 | 21.63 | 3% | Kim 2011 (Table 6.7) |
| Heating setpoint temp – unoccupied (°C) | 1 | 16.50 | 15.00 | 18.00 | – | – |
| | 2, 3 | 15.60 | 15.13 | 16.07 | 3% | Kim 2011 (Table 6.7) |
| Domestic water demand (DHW) peak flow rate ($m^3$/s) | 1, 2 | 0.0000158 | 0.0000144 | 0.0000428 | –- | ASHRAE 2011 (Figure 50.24) |
| | 3 | 0.0000104 | 0.0000094 | 0.0000114 | 10.0% | Kim 2011 (Table 6.7) |

[a] A dash indicates no assigned/applicable tolerance.

Table B.3: Uncertainty in System-related Parameters for Three Levels of Models

| System-related Parameter | Model Level | Base | Min | Max | Range | Factor | Reference |
|---|---|---|---|---|---|---|---|
| Outdoor airflow per person ($m^3/s \cdot m^2$) | 1, 2 | 0.00204 | 0.00024 | 0.00501 | – | – | Persily and Gorfain 2004 |
| | 3 | 0.00054 | 0.00048 | 0.00059 | 10.0% | Tolerance | Kim 2011 (Table 6.7) |
| Fan efficiency | 1 | 0.66 | 0.36 | 0.85 | 0.55–0.88 | Efficiency (as-new) | Radgen et al. 2008 (Table 3) |
| | | | | | 0.1–1.0% | Degradation | Griffith et al. 2008 |
| | 2, 3 | 0.49 | 0.38 | 0.55 | 6.0% | Tolerance | AMCA Standard 211-05, 2012 |
| | | | | | 0.1–1.0% | Degradation | Griffith et al. 2008 |
| Pressure rise (Pa) | 1 | 462.00 | 77.40 | 1211.25 | 0.50–1.50 | Specific fan power (SFP) (W/l • s) | Radgen et al. 2008 (Table 19) |
| | 2 | 356.64 | 104.05 | 668.72 | 0.50–1.50 | SFP (W/l • s) | Radgen et al. 2008 (Table 19) |
| | 3 | 622.00 | 603.34 | 640.66 | 3.0% | Tolerance | Kim 2011 (Table B.5) |
| Fan motor efficiency | 1 | 0.70 | 0.43 | 0.95 | 0.65–0.98 | Efficiency (as-new) | Radgen et al. 2008 (page 84); |
| | | | | | 0.1–1.0% | Degradation | Griffith et al. 2008 |
| | 2, 3 | 0.73 | 0.55 | 0.81 | 0.5% | Tolerance | IEC Standard 60034-2-1, 2007 |
| | | | | | 0.1–1.0% | Degradation | Griffith et al. 2008 |
| Cooling system rated coefficient of performance (COP) | 1 | 3.10 | 1.69 | 4.46 | 2.56–4.62 | Efficiency (as-new) | Southern California Edison 2005 |
| | 2, 3 | 2.92 | 2.23 | 3.26 | 5.0% | Tolerance | ANSI/AHRI Standard 210/240, 2008 (page 22) |
| | | | | | 0.1–1.0% | Degradation | Griffith et al. 2008 |
| Degradation coefficient for partial-load performance curve | 1 | 0.25 | 0.06 | 0.26 | – | – | Hu 2009 (Table 4.14) |
| | 2, 3 | 0.25 | 0.24 | 0.26 | 5.0% | Tolerance | ANSI/AHRI Standard 210/240, 2008 (page 22) |
| Gas burner efficiency | 1 | 0.72 | 0.51 | 0.85 | 0.78–0.88 | Efficiency (as-new) | Kemna et al. 2007 (page 247) |
| | | | | | 0.1–1.0% | Degradation | Griffith et al. 2008 |
| | 2,3 | 0.67 | 0.51 | 0.75 | 2.0% | Tolerance | Kemna et al. 2007 (page 30) |
| | | | | | 0.1 – 1.0% | Degradation | Griffith et al. 2008 |

**Table B.3: Uncertainty in System-related Parameters for Three Levels of Models (Cont.)**

| System-related Parameter | Model Level | Base | Min | Max | Range | Factor | Reference |
|---|---|---|---|---|---|---|---|
| DHW pump motor efficiency | 1 | 0.70 | 0.43 | 0.95 | 0.65–0.98 | Efficiency (as-new) | Radgen et al. 2008 (page 84) |
| | | | | | 0.1–1.0% | Degradation | Griffith et al. 2008 |
| | 2,3 | 0.73 | 0.56 | 0.82 | 0.5% | Tolerance | IEC Standard 60034-2-1, 2007 |
| | | | | | 0.1–1.0% | Degradation | Griffith et al. 2008 |
| DHW thermal efficiency | 1 | 0.72 | 0.51 | 0.85 | 0.78–0.88 | Efficiency (as-new) | Kemna et al. 2007 (page 247) |
| | | | | | 0.1–1.0% | Degradation | Griffith et al. 2008 |
| | 2, 3 | 0.69 | 0.53 | 0.77 | 2.0% | Tolerance | Kemna et al. 2007 (page 30) |
| | | | | | 0.1–1.0% | Degradation | Griffith et al. 2008 |
| Water heater setpoint temperature | 1, 2 | 60.00 | 40.50 | 82.22 | – | – | ASHRAE 2011 (Table 50.3) |
| | 3 | 60.00 | 58.20 | 61.80 | 3.0% | Tolerance | Kim 2011 (Table 6.7) |

## B.2 Parameter Screening

Table B.4 lists the ranking of uncertain parameters for the three medium office building models depending on the audit level. At Level 3, infiltration rate was by far the most dominant parameter followed by fan system efficiency, heating system efficiency, and infiltration rate reduction. The latter three parameters, however, had a much smaller effect on energy use than infiltration rate. At Level 2, outside airflow and appliance power density impacted energy use much more than infiltration rate because uncertainty in these two parameters greatly increases because of the lack of available data at this level. At Level 1, the top four parameters are outside airflow, appliance power density, lighting power density, and heating system efficiency. One interesting observation is that infiltration rate (ranked as the most influential parameter at Level 3) is in fifth place at this level, tightly followed by fan pressure rise and heating setpoint temperature.

Table B.4: Ranking of Uncertain Parameters for Three Levels of Models

| Rank | Model Level 1 | | Model Level 2 | | Model Level 3 | |
|---|---|---|---|---|---|---|
| | Model Parameter | Main Effect | Model Parameter | Main Effect | Model Parameter | Main Effect |
| 1 | Outside airflow | $6{,}215 \times 0^9$ | Outside airflow | $6{,}106 \times 10^9$ | Infiltration rate | $2{,}071 \times 0^9$ |
| 2 | Appliance power density | $4{,}058 \times 0^9$ | Appliance power density | $2{,}595 \times 10^9$ | Fan system efficiency | $391 \times 10^9$ |
| 3 | Lighting power density | $1{,}935 \times 0^9$ | Infiltration rate | $2{,}237 \times 10^9$ | Heating system efficiency | $377 \times 10^9$ |
| 4 | Heating system efficiency | $1{,}916 \times 0^9$ | Heating system efficiency | $1{,}307 \times 10^9$ | Infiltration rate reduction | $343 \times 10^9$ |
| 5 | Infiltration rate | $1{,}903 \times 0^9$ | Fan pressure rise | $981 \times 10^9$ | Cooling setpoint T – occupied | $182 \times 10^9$ |
| 6 | Fan pressure rise | $1{,}819 \times 0^9$ | Fan system efficiency | $384 \times 10^9$ | Heating setpoint T – occupied | $166 \times 10^9$ |
| 7 | Heating setpoint T – occupied | $1{,}233 \times 0^9$ | Heating setpoint T – occupied | $320 \times 10^9$ | Cooling system efficiency | $163 \times 10^9$ |
| 8 | Fan system efficiency | $1{,}162 \times 0^9$ | Lighting power density | $284 \times 10^9$ | Outside airflow | $122 \times 10^9$ |

## B.3 Calibration Results

Figure B.1 displays the posterior distributions of the calibration parameters (blue histogram) updated from the prior distributions (black line), compared against the true parameter values (red dot). At Level 3, the posterior distribution for infiltration greatly reduced uncertainty and shifted the lower bound toward the true value. For the other parameters, the posterior distributions did not change much from the prior distributions, although some of them slightly changed their distribution shape. On the other hand, at Level 2, the posterior distributions for infiltration rate, outside airflow, and appliance power density were significantly updated from their prior distributions; they greatly reduced uncertainty by narrowing the range of feasible values toward the true value. The posterior distribution for heating system efficiency did not change much. At Level 1, calibration also updated the posterior distributions to move toward the true value while reducing uncertainty. However, it was observed that for outside airflow, calibration yielded a posterior distribution quite similar to that at Level 2, whereas for appliance power density and heating system efficiency, calibration resulted in a wider range of feasible values in the posterior distributions. This comparison implies that at Level 1, monthly utility bills are not sufficient to reduce a larger magnitude of uncertainty in the model to be competitive with the calibrated model at Level 2.

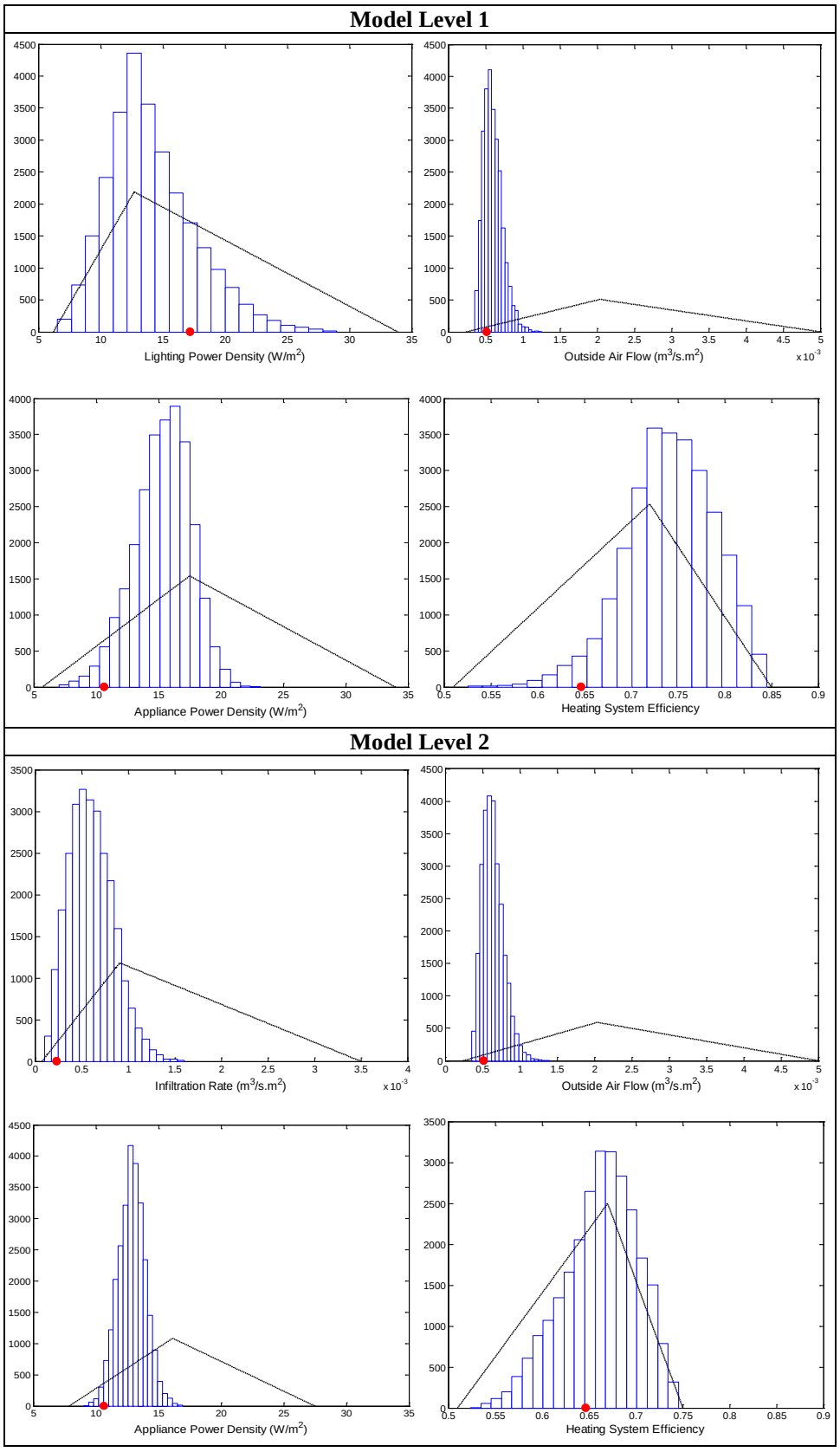



Figure B.1: Bayesian Calibration Results for Three Levels of Models

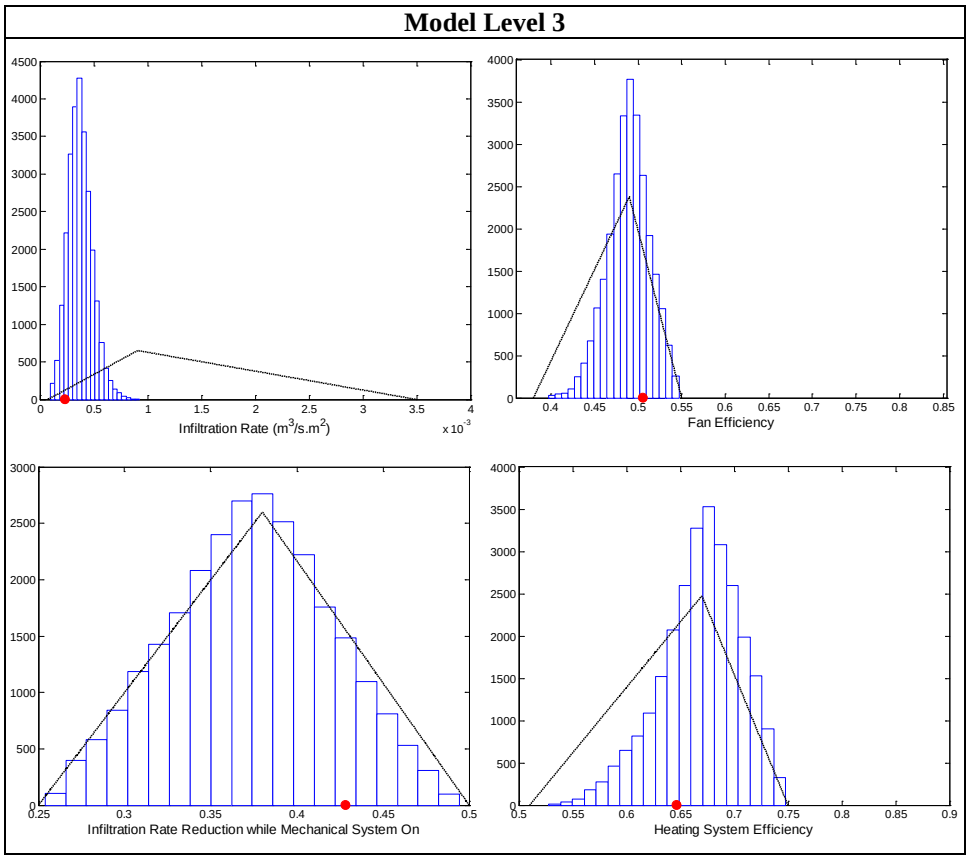


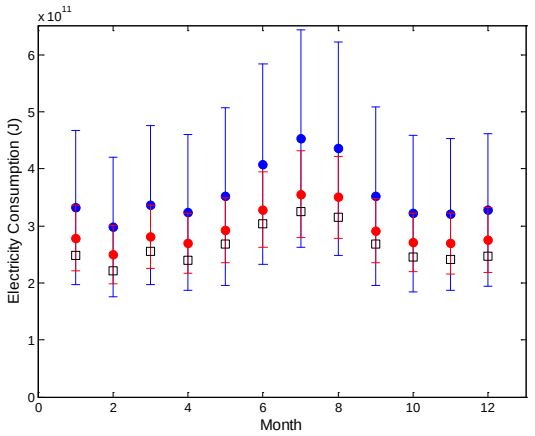

Figure B.1: Bayesian Calibration Results for Three Levels of Models (Cont.)

## B.4 Model Predictions

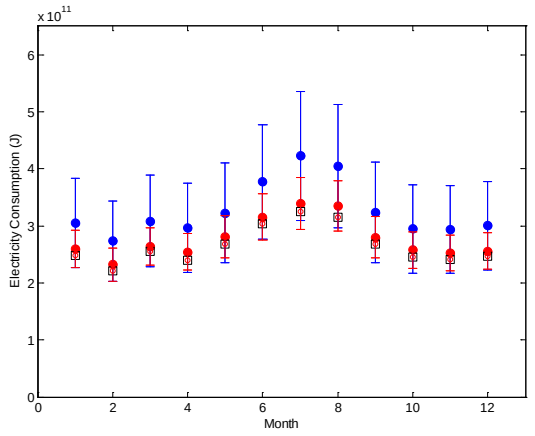
Figure B.2 displays electricity and gas consumptions predicted by the calibrated model (red), those predicted by the uncalibrated model (blue), and utility bills (black). At all levels, calibration significantly reduced uncertainty in model predictions while correcting the model to predict energy use closely matching utility bills. However, compared with Level 3, which yielded quite narrow confidence intervals for predictions, Level 1 still embeds the large magnitude of uncertainty in predictions, although uncertainty enormously decreased after calibration.

**Electricity Consumption**

**Model Level 1**




**Model Level 2**




**Model Level 3**

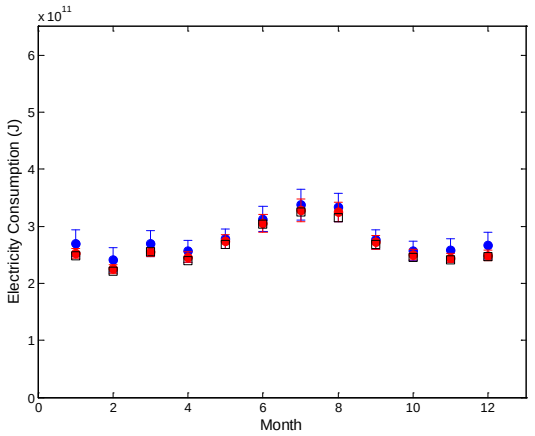
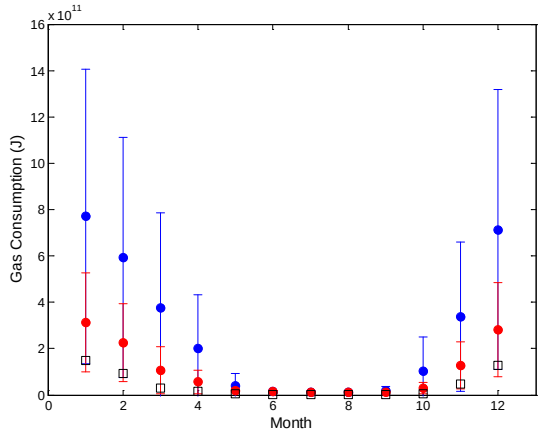


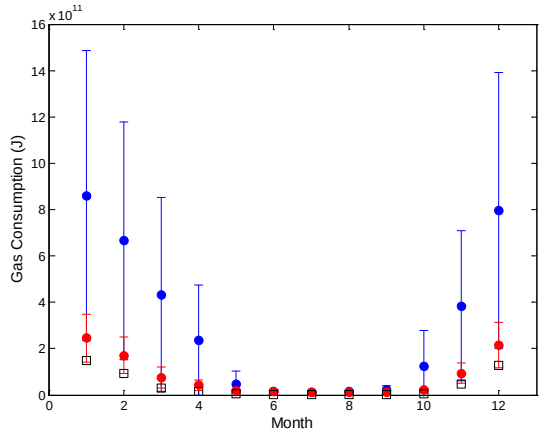

Figure B.2: Predicted Electricity and Gas Consumption Compared with Measured Data

**Gas Consumption**

**Model Level 1**




**Model Level 2**




**Model Level 3**

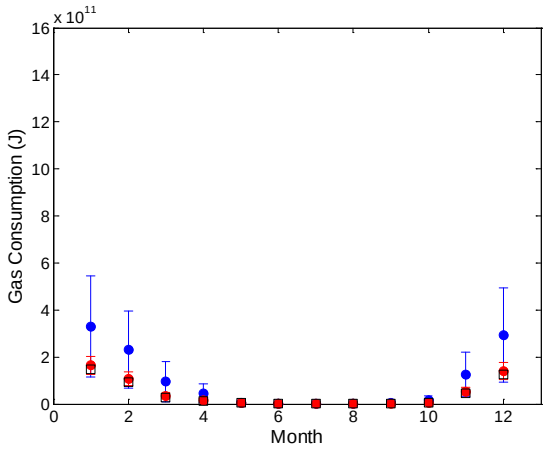



Figure B.2: Predicted Electricity and Gas Consumption Compared with Measured Data (Cont.)

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# Appendix C: Large Office Building

## C.1 Uncertainty Quantification

Table C.1: Uncertainty in Envelope-related Parameters for Three Levels of Models

| Envelope Type | Model Parameter | Base | Min | Max | Std. Dev. | Reference |
|---|---|---|---|---|---|---|
| IEAD nonres roof insulation/ | Conductivity (W/m • K) | 0.05 | 0.04 | 0.05 | 5% | Macdonald 2002 |
| UG wall nonres insulation/ | Density (kg/m$^3$) | 265.00 | 259.70 | 270.30 | 1% | |
| Mass nonres wall insulation | Specific heat (J/kg • K) | 836.80 | 631.78 | 1,041.82 | 12% | |
| Std wood, 6-in. | Conductivity (W/m • K) | 0.12 | 0.11 | 0.13 | 5% | |
| | Density (kg/m$^3$) | 540.00 | 529.20 | 550.80 | 1% | |
| | Specific heat (J/kg • K) | 1,210.00 | 913.55 | 1,506.45 | 12% | |
| 1/2-in. gypsum | Conductivity (W/m • K) | 0.16 | 0.14 | 0.18 | 5% | |
| | Density (kg/m$^3$) | 784.90 | 769.20 | 800.60 | 1% | |
| | Specific heat (J/kg • K) | 830.00 | 626.65 | 1,033.35 | 12% | |
| 1-in. stucco | Conductivity (W/m • K) | 0.69 | 0.62 | 0.76 | 5% | |
| | Density (kg/m$^3$) | 1,858.00 | 1,820.84 | 1,895.16 | 1% | |
| | Specific heat (J/kg • K) | 837.00 | 631.94 | 1,042.07 | 12% | |
| | Thermal absorptance | 0.90 | 0.86 | 0.94 | 0.02 | |
| | Solar absorptance | 0.92 | 0.86 | 0.98 | 0.03 | |
| HW concrete/ | Conductivity (W/m • K) | 1.31 | 1.18 | 1.44 | 5% | |
| 8-in. HW concrete | Density (kg/m$^3$) | 2,240.00 | 2,195.20 | 2,284.80 | 1% | |
| | Specific heat J/kg • K) | 836.80 | 631.78 | 1,041.82 | 12% | |
| | Thermal absorptance | 0.90 | 0.86 | 0.94 | 0.02 | |
| | Solar absorptance | 0.70 | 0.62 | 0.78 | 0.04 | |
| Roof membrane | Conductivity (W/m • K) | 0.16 | 0.14 | 0.18 | 5% | |
| | Density (kg/m$^3$) | 1,121.29 | 1,098.86 | 1,143.72 | 1% | |
| | Specific heat (J/kg • K) | 1,460.00 | 1,102.30 | 1,817.70 | 12% | |
| | Thermal absorptance | 0.90 | 0.86 | 0.94 | 0.02 | |
| | Solar absorptance | 0.70 | 0.64 | 0.76 | 0.03 | |
| Metal decking | Conductivity (W/m • K) | 45.01 | 40.51 | 49.51 | 5% | |
| | Density (kg/m$^3$) | 7,680.00 | 7,526.40 | 7,833.60 | 1% | |
| | Specific heat (J/kg • K) | 418.40 | 315.89 | 520.91 | 12% | |
| Mat-CC05 4 HW concrete | Conductivity (W/m • K) | 1.31 | 1.18 | 1.44 | 5% | |
| | Density (kg/m$^3$) | 2,240.00 | 2,195.20 | 2,284.80 | 1% | |
| | Specific heat (J/kg • K) | 836.80 | 631.78 | 1,041.82 | 12% | |
| Std. AC02 | Conductivity (W/m • K) | 0.06 | 0.05 | 0.06 | 5% | |
| | Density (kg/m$^3$) | 288.00 | 282.24 | 293.76 | 1% | |
| | Specific heat (J/kg • K) | 1,339.00 | 1,010.95 | 1,667.06 | 12% | |
| Carpet pad | Thermal resistance | 0.22 | 0.19 | 0.24 | 5% | |
| Mat-air-wall | Thermal resistance | 0.21 | 0.19 | 0.23 | 5% | |
| Fixed assembly window | U value (W/m$^2$ • K) | 3.52 | 3.17 | 3.87 | 5% | |
| | Solar heat gain coefficient (SHGC) | 0.41 | 0.39 | 0.42 | 0.01 | Loutzenhiser et al. 2009 |
| Infiltration rate per exterior surface area (m$^3$/s • m$^2$) | | 0.00091 | 0.00007 | 0.00350 | – | Emmerich et al. 2005; ASHRAE 2009 |
| Infiltration rate reduction while mechanical system on | | 0.38 | 0.25 | 0.50 | – | VanBronkhorst et al. 1995 |

Table C.2: Uncertainty in Building Use-related Parameters for Three Levels of Models

| Building Use Parameter | Model Level | Base | Min | Max | Tolerance | Reference |
|---|---|---|---|---|---|---|
| Occupant density ($m^2$/person) | 1 | 11.10 | 4.30 | 22.80 | –[a] | Knight and Dunn 2003 |
| | 2, 3 | 18.58 | 16.72 | 20.44 | 10% | – |
| Lighting power density ($W/m^2$) | 1 | 12.70 | 6.20 | 33.90 | – | Knight and Dunn 2003 |
| | 2 | 18.00 | 16.00 | 20.00 | 2.0 | Lighting Research Center 2006 |
| | 3 | 16.89 | 16.55 | 17.23 | 2% | Seal and McGranaghan 2010 (Figure 2) |
| Appliance power density ($W/m^2$) | 1 | 17.50 | 5.70 | 34.00 | – | Knight and Dunn 2003 |
| | 2 | 16.15 | 7.89 | 27.50 | – | Inventory (Thornton et al. 2010), Uncertainty (Macdonald 2002; IVF 2005) |
| | 3 | 10.76 | 10.54 | 10.98 | 2% | Seal and McGranaghan 2010 (Figure 2) |
| Occupant metabolic rate (W/person) | 1, 2, 3 | 120.00 | 70.00 | 130.00 | – | Macdonald 2002 |
| Cooling setpoint temp – occupied (°C) | 1 | 24.00 | 22.50 | 25.50 | | Mendell and Mirer 2008: modified due to E+ constraint |
| | 2, 3 | 24.00 | 23.28 | 24.72 | 3% | Kim 2011 (Table 6.7) |
| Cooling setpoint temp – unoccupied (°C) | 1 | 26.50 | 25.00 | 28.00 | – | – |
| | 2, 3 | 26.70 | 25.90 | 27.50 | 3% | Kim 2011 (Table 6.7) |
| Heating setpoint temp – occupied (°C) | 1 | 21.00 | 19.50 | 22.50 | – | Mendell and Mirer 2008: modified due to E+ constraint |
| | 2, 3 | 21.00 | 20.37 | 21.63 | 3% | Kim 2011 (Table 6.7) |
| Heating setpoint temp – unoccupied (°C) | 1 | 16.50 | 15.00 | 18.00 | – | – |
| | 2, 3 | 15.60 | 15.13 | 16.07 | 3% | Kim 2011 (Table 6.7) |
| Domestic water demand (DHW) peak flow rate ($m^3$/s) | 1, 2 | 0.0000158 | 0.0000144 | 0.0000428 | – | ASHRAE 2011 (Figure 50.24) |
| | 3 | 0.0000104 | 0.0000094 | 0.0000114 | 10.0% | Kim 2011 (Table 6.7) |

[a] A dash indicates no assigned/applicable tolerance.

### Table C.3: Uncertainty in System-related Parameters for Three Levels of Models

| System-related Parameter | Model Level | Base | Min | Max | Range | Factor | Reference |
|---|---|---|---|---|---|---|---|
| Outdoor airflow per person ($m^3/s \cdot m^2$) | 1, 2 | 0.00204 | 0.00024 | 0.00501 | – | – | Persily and Gorfain 2004 |
| | 3 | 0.00054 | 0.00048 | 0.00059 | 10.0% | Tolerance | Kim 2011 (Table 6.7) |
| Fan efficiency | 1 | 0.66 | 0.36 | 0.85 | 0.55–0.88 | Efficiency (as-new) | Radgen et al. 2008 (Table 3) |
| | | | | | 0.1–1.0% | Degradation | Griffith et al. 2008 |
| | 2, 3 | 0.49 | 0.38 | 0.55 | 6.0% | Tolerance | AMCA Standard 211-05, 2012 |
| | | | | | 0.1–1.0% | Degradation | Griffith et al. 2008 |
| Pressure rise (Pa) | 1 | 462.00 | 77.40 | 1,211.25 | 2.00–3.00 | Specific fan power (SFP) (W/l • s) | Radgen et al. 2008 (Table 19) |
| | 2 | 356.64 | 104.05 | 668.72 | 2.00–3.00 | SFP (W/ • s) | Radgen et al. 2008 (Table 19) |
| | 3 | 622.00 | 603.34 | 640.66 | 3.0% | Tolerance | Kim 2011 (Table B.5) |
| Fan motor efficiency | 1 | 0.70 | 0.43 | 0.95 | 0.65–0.98 | Efficiency (as-new) | Radgen et al. 2008 (page 84) |
| | | | | | 0.1–1.0% | Degradation | Griffith et al. 2008 |
| | 2, 3 | 0.73 | 0.55 | 0.81 | 0.5% | Tolerance | IEC Standard 60034-2-1, 2007 |
| | | | | | 0.1–1.0% | Degradation | Griffith et al. 2008 |
| Cooling system rated coefficient of performance (COP) | 1 | 3.10 | 1.69 | 4.46 | 2.56–4.62 | Efficiency (as-new) | Southern California Edison 2005 |
| | 2, 3 | 2.92 | 2.23 | 3.26 | 5.0% | Tolerance | ANSI/AHRI Standard 210/240, 2008 (page 22) |
| | | | | | 0.1–1.0% | Degradation | Griffith et al. 2008 |
| Degradation coefficient for partial-load performance curve | 1 | 0.25 | 0.06 | 0.26 | – | – | Hu 2009 (Table 4.14) |
| | 2, 3 | 0.25 | 0.24 | 0.26 | 5.0% | Tolerance | ANSI/AHRI Standard 210/240, 2008 (page 22) |
| Gas burner efficiency | 1 | 0.72 | 0.51 | 0.85 | 0.78–0.88 | Efficiency (as-new) | Kemna et al. 2007 (page 247) |
| | | | | | 0.1–1.0% | Degradation | Griffith et al. 2008 |
| | 2,3 | 0.67 | 0.51 | 0.75 | 2.0% | Tolerance | Kemna et al. 2007 (page 30) |
| | | | | | 0.1–1.0% | Degradation | Griffith et al. 2008 |
| DHW pump motor efficiency | 1 | 0.70 | 0.43 | 0.95 | 0.65–0.98 | Efficiency (as-new) | Radgen et al. 2008 (page 84) |
| | | | | | 0.1–1.0% | Degradation | Griffith et al. 2008 |
| | 2,3 | 0.73 | 0.56 | 0.82 | 0.5% | Tolerance | IEC Standard 60034-2-1, 2007 |
| | | | | | 0.1–1.0% | Degradation | Griffith et al. 2008 |
| DHW thermal efficiency | 1 | 0.72 | 0.51 | 0.85 | 0.78–0.88 | Efficiency (as-new) | Kemna et al. 2007 (page 247) |
| | | | | | 0.1–1.0% | Degradation | Griffith et al. 2008 |
| | 2, 3 | 0.69 | 0.53 | 0.77 | 2.0% | Tolerance | Kemna et al. 2007 (page 30) |
| | | | | | 0.1–1.0% | Degradation | Griffith et al. 2008 |
| Water heater setpoint temperature | 1, 2 | 60.00 | 40.50 | 82.22 | – | – | ASHRAE 2011 (Table 50.3) |
| | 3 | 60.00 | 58.20 | 61.80 | 3.0% | Tolerance | Kim 2011 (Table 6.7) |

## C.2 Parameter Screening

Table C.4 shows the ranking of uncertain parameters with respect to their effect on energy use for the three levels of large office building models. The rankings of the most dominant parameters for large office buildings were quite similar to those for medium and small office buildings. At Level 3, with the most accurate model, infiltration rate was the most influential parameter, followed by heating system efficiency, heating setpoint temperature during occupied hours, and infiltration rate reduction while mechanical system is on. At Level 2, outside airflow, appliance power density, and infiltration rate were outstandingly the dominant parameters, followed by heating system efficiency and pump head. Unlike the other office buildings, pump head becomes dominant since heat is circulated to tall office buildings by pumps. At Level 1, appliance power density is the most dominant parameter, followed by outside airflow, lighting power density, and infiltration rate.

Table C.4: Ranking of Uncertain Parameters for Each Model

| | Model Level 1 | | Model Level 2 | | Model Level 3 | |
|---|---|---|---|---|---|---|
| Rank | Model Parameter | Main Effect | Model Parameter | Main Effect | Model Parameter | Main Effect |
| 1 | Appliance power density | $29{,}461 \times 10^9$ | Outside airflow | $19{,}291 \times 10^9$ | Infiltration rate | $15{,}840 \times 10^9$ |
| 2 | Outside airflow | $18{,}388 \times 10^9$ | Appliance power density | $18{,}932 \times 10^9$ | Heating system efficiency | $4{,}495 \times 10^9$ |
| 3 | Lighting power density | $17{,}706 \times 10^9$ | Infiltration rate | $13{,}583 \times 10^9$ | Heating setpoint T – occupied | $2{,}330 \times 10^9$ |
| 4 | Infiltration rate | $15{,}341 \times 10^9$ | Heating system efficiency | $8{,}452 \times 10^9$ | Infiltration rate reduction | $1{,}980 \times 10^9$ |
| 5 | Pump head | $12{,}026 \times 10^9$ | Pump head | $8{,}145 \times 10^9$ | Cooling setpoint T – occupied | $1{,}735 \times 10^9$ |
| 6 | Heating system efficiency | $10{,}661 \times 10^9$ | Lighting power density | $2{,}765 \times 10^9$ | Appliance power density | $350 \times 10^9$ |
| 7 | Heating setpoint T – occupied | $4{,}770 \times 10^9$ | Cooling setpoint T – occupied | $2{,}436 \times 10^9$ | Fan system efficiency | $350 \times 10^9$ |
| 8 | Pump motor efficiency | $3{,}831 \times 10^9$ | Pump motor efficiency | $1{,}767 \times 10^9$ | Pump motor efficiency | $300 \times 10^9$ |

## C.3 Calibration Results

Figure C.1 shows the posterior distributions (blue) updated from the prior distributions (black) compared with the true values (red color). The trend of updating the prior distributions at each level was quite similar among the three office building types. At Level 3, only the posterior distribution for infiltration rate significantly narrowed the uncertainty range; the posterior distributions for the rest of the parameters, however, did not change much from the prior distributions. At Level 2, in addition to infiltration rate, the posterior distributions for outside airflow and appliance power density greatly reduced uncertainty while shifting toward the true value. At Level 3, for all the calibration parameters, the posterior distributions were greatly updated to move toward the true value and greatly reduce uncertainty.

## C.4 Model Predictions

Figure C.2 shows energy consumptions predicted by the calibrated model (red) and the uncalibrated model (blue) compared with actual utility bills (black). Overall, calibration improved the reliability of model predictions by updating the model to replicate utility bills and reducing uncertainty in the model. At Level 3, the uncalibrated model computed probabilistic outcomes with quite narrow confidence intervals for electricity use but computed a wider range of outcomes for gas use, which was noticeably reduced by calibration. At the other levels, energy consumptions predicted by the uncalibrated models were far off the utility bills. However, after calibration, predicted energy use was in good alignment with actual energy use, although there was some discrepancy for electricity consumptions.

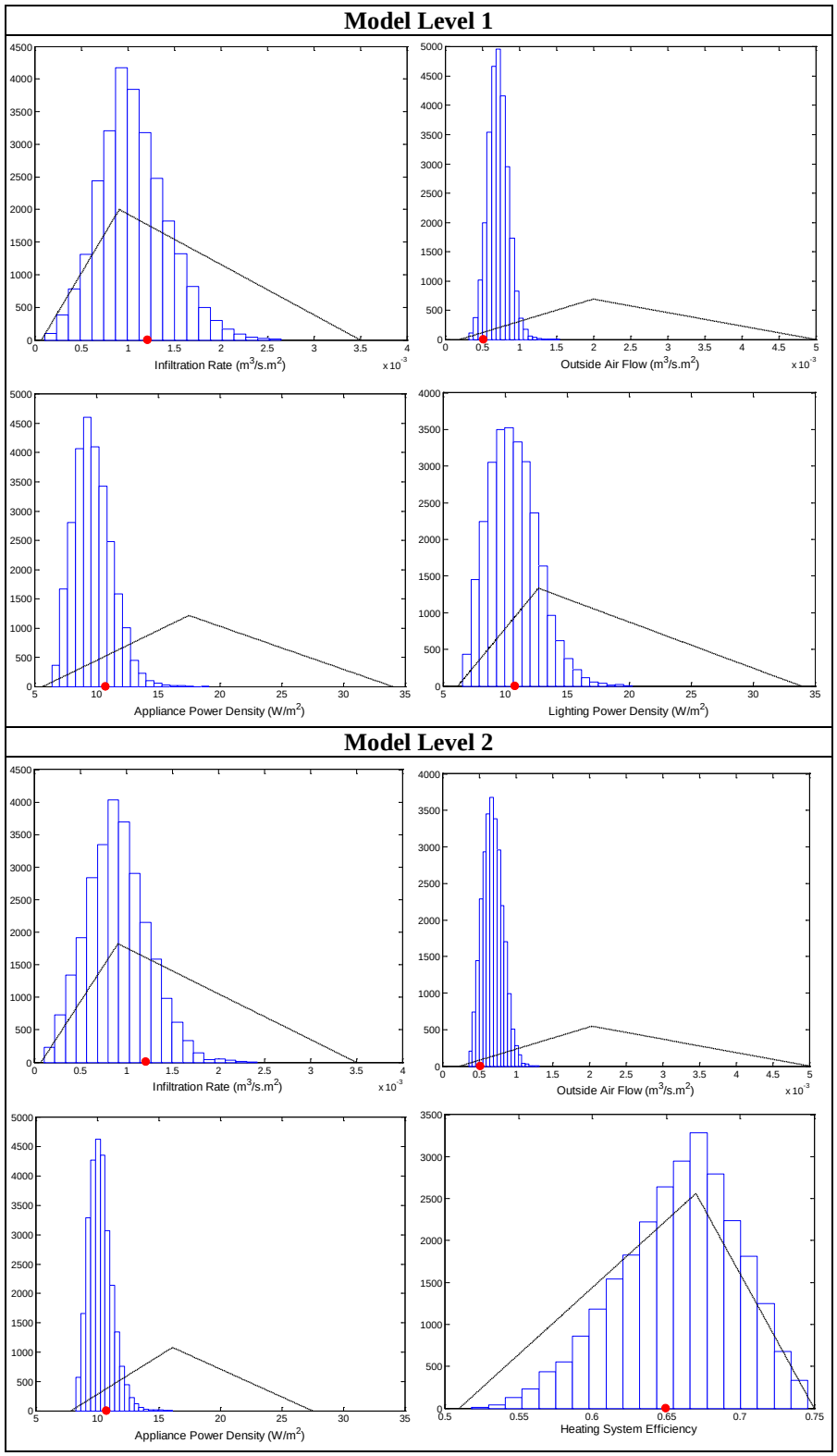



Figure C.1: Bayesian Calibration Results for Three Levels of Models

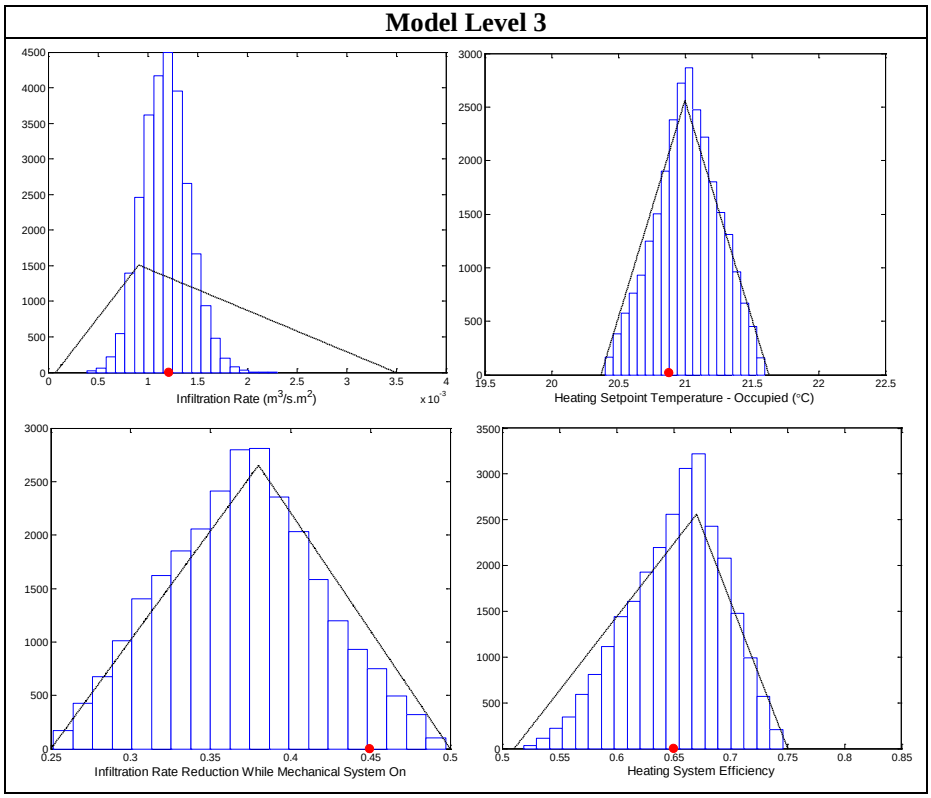



Figure C.1: Bayesian Calibration Results for Three Levels of Models (Cont.)

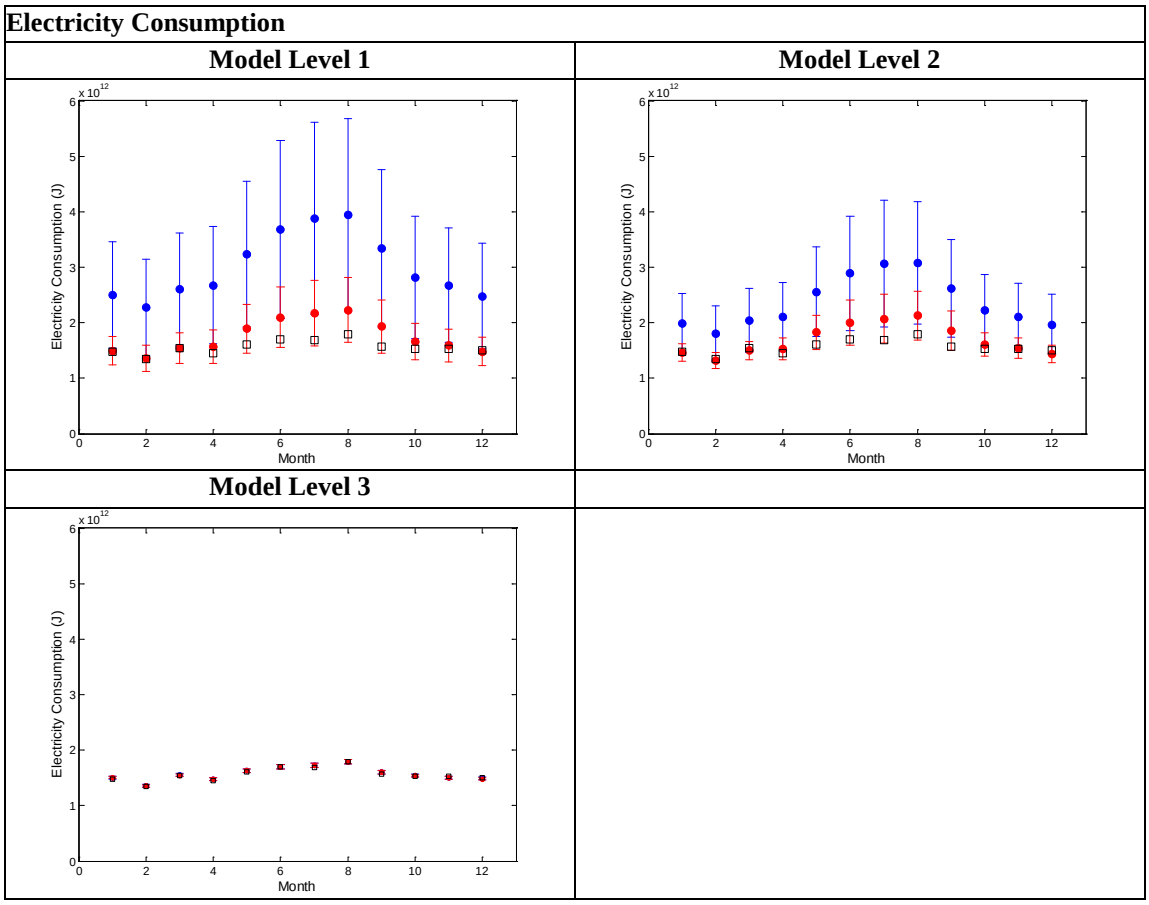
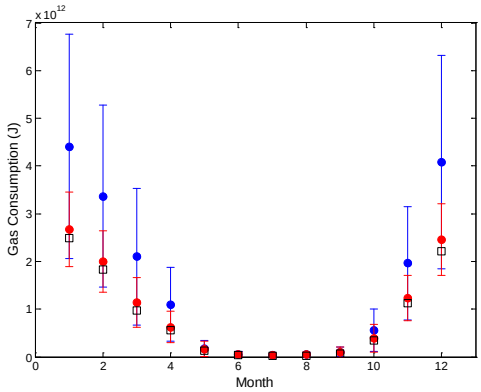


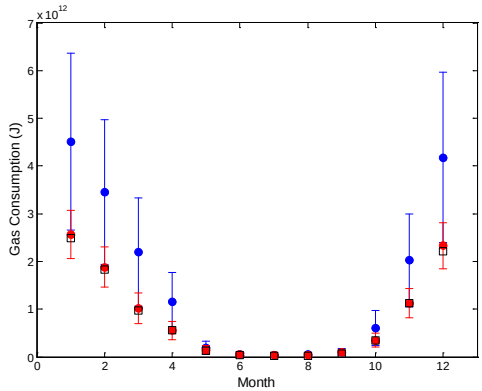

Figure C.2: Predicted Electricity and Gas Consumption Compared with Measured Data

**Gas Consumption**

**Model Level 1**




**Model Level 2**




**Model Level 3**

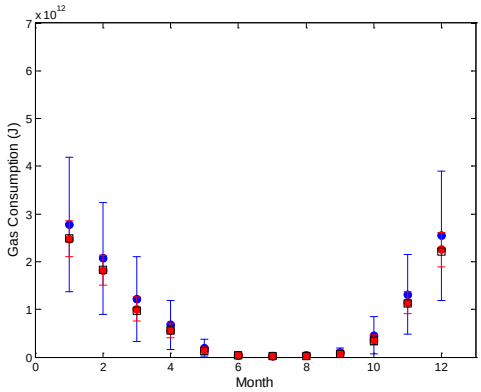



Figure C.2: Predicted Electricity and Gas Consumption Compared with Measured Data (Cont.)

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