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Development of methodology for calibrated simulation in single-family residential buildings using three-parameter change-point regression model

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ABSTRACT

This study developed a methodology for a calibrated simulation of single-family residential buildings using a three-parameter change-point regression model. This new method provides a reproducible systematic and consistent calibration procedure. The procedure consists of two parts: a sensitivity analysis that can analyze the characteristics of the building; and a calibration procedure that uses the results of the sensitivity analysis. In the first part, the characteristics of the case-study house were analyzed using a detailed sensitivity analysis with a three-parameter change-point regression model. In this procedure, the most to least influential parameters for each three-parameter coefficient for the house were identified. Next, the identified parameters for each three-parameter coefficient were adjusted to closely match the actual building energy use of the house. Using the procedure, the 36.9% global CV (RMSE) of the initial simulation was improved to 8.8% after calibrated simulation, which is within the accuracy criterion according to the ASHRAE Guideline 14-2014. This study was conducted using a case-study house in a hot and humid climate. However, the procedure developed should be useful for other climates as well. In addition, the results of calibrated simulation can help determining energy efficient measures that are appropriate for the house in the future.

1. Introduction

In general, the simulated energy use of an existing residential building modeled using a building energy simulation program have large differences when compared with actual energy use of the house. For this reason, the simulation of the building should be tuned or calibrated by adjusting the appropriate input values to more closely match the actual building energy use. This process is commonly called calibrated simulation. Calibrated simulation can more accurately predict energy savings for future energy efficiency retrofits of the building because the calibrated simulation reflects the current building condition such as the deterioration of the air conditioner efficiency, etc. In addition, the accuracy of a calibrated simulation can vary from one simulation user to another because it relies heavily on the users' level of skill and knowledge in both the use of the simulation, practical knowledge about building operation, and ability to calibrate the simulation model.

Several calibrated simulation methodologies has been studied since the 1970s, which were summarized by Reddy [1]. According to Reddy, the methodologies can be divided into four approaches, which include: (i) calibration based on manual, iterative, and pragmatic intervention; (ii) calibration based on a suite of informative graphical comparative displays; (iii) calibration based on special tests and analytical procedures; and (iv) analytical/mathematical methods of calibration. A number of studies in each approach have been reviewed, including: (i) the manual, iterative, and pragmatic intervention methods that were the most popular approach for the calibrated simulation. For example, Diamond and Hunn [2] conducted one of the first calibrated simulations by comparing the results of DOE-2 simulation with monthly utility data for an entire year in seven sets of commercial buildings in the late 1970s. A few years later, Kaplan et al. [3,4] calibrated small office building simulations using the monitored energy data for short periods in the heating and cooling seasons. They suggested that for the calibration procedure, one of the first step is to correct the obvious simulation errors such as unreasonable default values used by the simulation, then correct internal loads and other inputs. Hunn et al. [5] also calibrated a DOE-2.1d model for the Texas Capitol building

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Nomenclature

AFUE	annual fuel utilization efficiency
AMY	actual meteorological year
CV-RMSE	coefficient of variation of root mean squared error
CV-STD	coefficient of variation of standard deviation
EF	energy factor
IMT	inverse modeling toolkit
L&E	lighting and equipment
NCDC	national climatic data center
NMBE	normalized mean bias error
SEER	seasonal energy efficiency ratio
SHGC	solar heat gain coefficient
TMY3	typical meteorological year, version 3
WWR	window-to-wall ratio
3PC or 3PH	3-parameter cooling or heating

by generating normalized electricity use schedules for typical day types for the building. In addition, Haberl and Bou-Saada [6] studied the calibrated simulation for weather-dependent loads, which included space heating and cooling; (ii) in the second approach, informative graphical displays for calibrated simulation were used to show the differences between the simulated and measured energy use to help simulation users in deciding which parameters to calibrate for the next iteration. Bronson et al. [7] developed comparative three-dimensional graphics for a case-study building, Haberl et al. [8] developed the plots to help calibrated simulations such as the contoured density plots of energy use that can provide the users an improved perception of the central tendency of a cloud of data points, which included time-sequenced, surface density plots of energy use that added time sequencing of the contoured density plots of energy use; (iii) in the third approach, the special tests and analytical procedures using specialized approaches for calibrated simulation, including short-term energy monitoring test and signature analysis method were developed. Manke and Hittle [9] conducted short-term energy monitoring for small commercial buildings. In this study, they calibrated the simulation model using parameter sensitivity tests. They used the root mean squared error (RMSE) and total building energy use over the test period to compare the model to the energy use. In addition, Liu and Claridge [10] developed characteristic calibration signatures that are parametric sensitivity analysis plots that are helpful in the determination of which simulation input parameter needs to be adjusted and by what amount; (iv) in the fourth approach an analytical/mathematical method of calibration, Sun and Reddy [11] proposed a general analytic framework for calibrating an office building energy simulation through mathematical and statistical basis using DOE-2 program.

Although the methods in previous approaches help building energy simulation calibration process easily and accurately, they still require an advanced simulation users' knowledge in the simulation program and knowledge of building operation to calibrate the simulation. Therefore, the purpose of this study was to make the calibrated simulation process more effective by providing the users with a systematic and consistent procedure for more easily and accurately simulating single-family residential buildings. This methodology has another advantage of reducing time and effort of the users during the calibrated simulation process by separating the simulation parameters into weather-independent and weather-dependent groups using three-parameter coefficients that have physical meanings. In addition, the methodology enables the users to accelerate making decision which parameter to adjust next by providing the most significant parameter during the calibration process, which further saves time and effort of the users. These

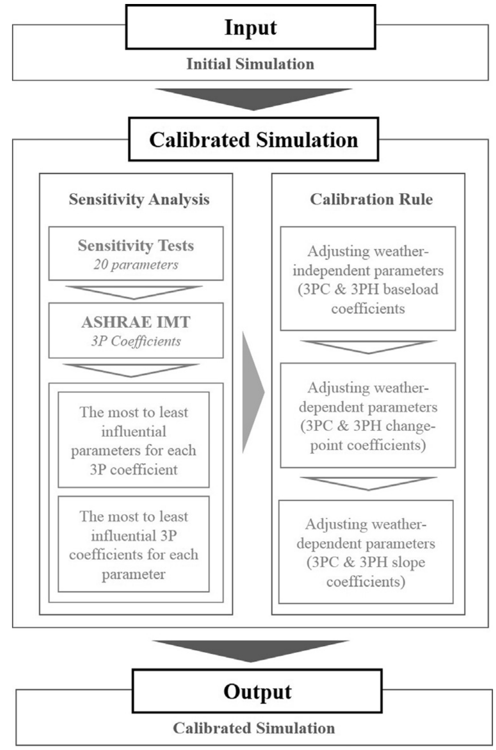


Fig. 1. The overall flow of calibrated simulation procedure.

features can be an advantage of this methodology against other existing methodologies.

This study is organized by the following five sections: (i) introduction and purpose of this study; (ii) calibrated simulation methodology; (iii) calibrated simulation for a first case-study house, including sensitivity analysis using a three-parameter change-point regression model; and (iv) calibrated simulation for a second case-study house; and (v) conclusion and discussions.

2. Methodology

The overall flow of the developed procedure of calibrated residential simulation is shown in Fig. 1. This methodology consists of two procedures, which include a sensitivity analysis that can analyze the characteristics of the building, and the calibrated simulation procedure that uses the results of the sensitivity analysis.

3. Calibrated simulation for a first case-study house

3.1. Sensitivity analysis using a three-parameter change-point regression model

3.1.1. Three-parameter change-point model

The ASHRAE inverse modeling toolkit (IMT) [12] was used for calculating the three-parameter change-point regression models in this study. The IMT is mostly used for building energy analysis for weather-normalization. The three-parameter change-point regression model is appropriate for analyzing single-family residential energy use that is strongly influenced by outside weather conditions due to heat gain or heat loss through walls and windows, and air infiltration through the building surfaces. Fig. 2 shows three-parameter change-point models for: (a) electric cooling and (b) natural gas heating as a function of outdoor air temperature.

Electricity use for a three-parameter change-point regression model of building can be calculated from Eq. (1). This equation describes the electricity use of a building as a constant (i.e.,

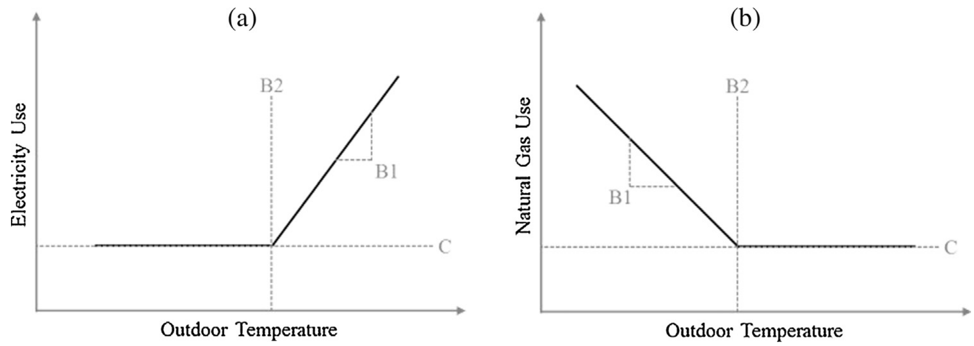


Fig. 2. Three-parameter change-point regression models for (a) electricity and (b) natural gas use.

baseload) until a certain outdoor temperature (i.e., the cooling change-point temperature) is reached. When outdoor temperatures are higher than the cooling change-point temperature, electricity use of a building increases linearly with outdoor temperature (i.e., the cooling slope) for the three-parameter cooling (3PC) change-point model. In a similar fashion to the 3PC change-point model of the electricity use, natural gas can be calculated using a three-parameter change-point regression model as shown in Eq. (2). This equation divides the natural gas use of a building into three regions, a constant (i.e., baseload) when the outdoor temperature is higher than a certain outdoor temperature (i.e., the heating change-point temperature), and when the outdoor temperature is lower than the heating change-point temperature, the natural gas use of a building increases linearly (i.e., the heating slope). This type of model is called a three-parameter heating (3PH) change-point model.

$$E = C + B1(T - B2)^{+} \tag{1}$$

where E is the electricity use in kW h; $B1$ is the cooling slope in kW h/°C; $B2$ is the cooling change-point temperature in °C; C is the baseload in kW h; T is the outdoor temperature in °C and $(.)^{+}$ is the positive values only inside the parenthesis.

$$E = C + B1(B2 - T)^{+} \tag{2}$$

where E is the natural gas use in MJ; $B1$ is the heating slope in MJ/°C; $B2$ is the heating change-point temperature in °C; C is the baseload in MJ; T is the outdoor temperature in °C, and $(.)^{+}$ is the positive values only inside the parenthesis.

One of the strengths of the three-parameter (3P) change-point regression model is that the 3P coefficients (i.e., $B1$, $B2$ and C in Eqs. (1) and (2)) characterize physical properties of the building envelope and the operation of cooling or heating systems. The 3P coefficient C represents the annual weather-independent energy use such as lighting and equipment for electricity use and the natural gas energy for hot water heating. The 3P coefficient $B1$ represents weather-dependent energy use that is used for cooling or heating the building. This coefficient is related to cooling or heating loads, plus the cooling or heating system efficiency of the building. Lastly, the 3P coefficient $B2$ is defined as the outdoor temperature when space cooling or heating begins. $B2$ is a function of the cooling thermostat set-point temperature; the sum of the internal loads from electricity use, solar heat gain and occupants of the building; and heat transfer coefficient of the building envelope [13].

3.1.2. Methodology for sensitivity analysis using three-parameter change-point regression model

In order to test the sensitivity of the 3P model, simulated building energy use was regressed against local outdoor temperatures using the IMT three-parameter change-point regression model. For the simulated building energy use, DOE-2.1e simulation data were used. In order to run the simulation, an actual weather file was created using an hourly actual meteorological year (AMY) format with coincident weather data obtained from the National Climatic Database Center (NCDC) and a solar test bench at the nearby Texas A&M University.

The purpose of the sensitivity analysis was to identify what building parameters affect the 3PC or 3PH coefficients as shown in Fig. 3. In order to identify the sensitivity of the simulation input parameters, 20 simulation input parameters were selected for analysis in this study. For the 20 simulation inputs, the previous literature regarding calibrated simulation, including Cho and Haberl [14], Haberl and Bou-Saada [6], Liu et al. [15] and Manke and Hittle [9] was reviewed. Architectural parameters such as the house size and orientation were excluded for the analysis in order to concentrate on other building or system characteristics. The selected 20 parameters are shown in Table 1.

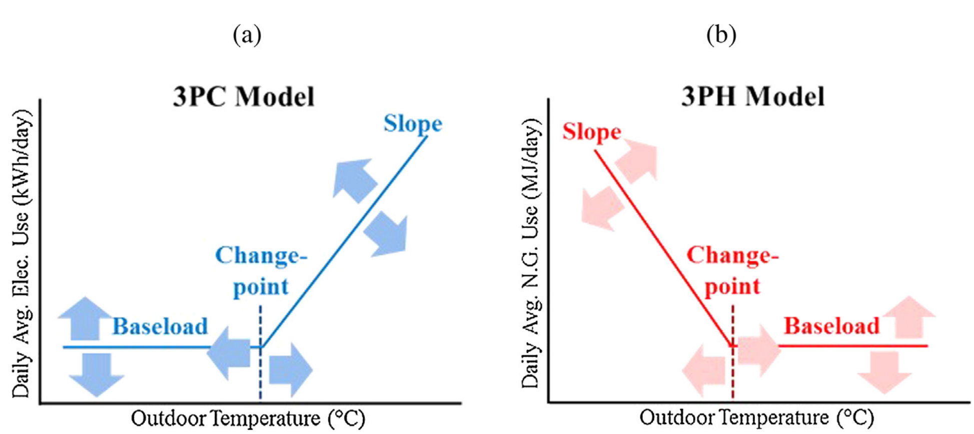


Fig. 3. Application of three-parameter change-point regrssion models to sensitivity analysis.

Table 1
The most to least influential parameters to 3PC (a) change-point temperature, (b) baseload, (c) slope, and 3PH (d) change-point temperature, (e) baseload and (f) slope coefficients.

(a) Electricity: Change-point [%]			(b) Electricity: Baseload [%]			(c) Electricity: Slope [%]		
Parameter	%	Acc. %	Parameter	%	Acc. %	Parameter	%	Acc. %
L&E	40.0	40.0	L&E	59.0	59.0	SEER	40.9	40.9
SHGC	40.0	80.0	Shading Devices	7.0	66.0	Ret. Duct Leak.	9.3	50.2
Window U-value	20.0	100.0	SEER	6.3	72.3	Roof Absorption	6.8	57.0
Wall R-value	0.0	100.0	SHGC	5.7	78.0	Sup. Duct R-value	5.3	62.3
Roof R-value	0.0	100.0	WWR for South	3.6	81.6	Roof R-value	5.1	67.4
Wall Absorption	0.0	100.0	Window U-value	3.1	84.7	Window U-value	4.9	72.3
Roof Absorption	0.0	100.0	Roof Absorption	3.1	87.8	Sup. Duct Leak.	3.4	75.7
Shading Devices	0.0	100.0	WWR for East	2.5	90.3	Shading Devices	3.0	78.7
Infiltration Rate	0.0	100.0	Wall Absorption	2.4	92.7	Infiltration Rate	3.0	81.7
SEER	0.0	100.0	Roof R-value	1.5	94.2	WWR for North	2.9	84.6
AFUE	0.0	100.0	Ret. Duct Leak.	1.4	95.6	L&E	2.7	87.3
EF	0.0	100.0	Infiltration Rate	1.4	97.0	WWR for West	2.4	89.7
Sup. Duct Leak.	0.0	100.0	Wall R-value	0.9	97.9	WWR for East	2.4	92.1
Ret. Duct Leak.	0.0	100.0	WWR for North	0.8	98.7	Wall Absorption	2.3	94.4
Sup. Duct R-value	0.0	100.0	Sup. Duct Leak.	0.8	99.5	Wall R-value	1.7	96.1
Ret. Duct R-value	0.0	100.0	WWR for West	0.5	100.0	WWR for South	1.6	97.7
WWR for South	0.0	100.0	Ret. Duct R-value	0.0	100.0	SHGC	1.5	99.2
WWR for East	0.0	100.0	Sup. Duct R-value	0.0	100.0	Ret. Duct R-value	0.8	100.0
WWR for West	0.0	100.0	AFUE	0.0	100.0	AFUE	0.0	100.0
WWR for North	0.0	100.0	EF	0.0	100.0	EF	0.0	100.0
(d) Natural Gas: Change-point [%]			(e) Natural Gas: Baseload [%]			(f) Natural Gas: Slope [%]		
Parameter	%	Acc. %	Parameter	%	Acc. %	Parameter	%	Acc. %
L&E	36.4	36.4	EF	89.3	89.3	AFUE	29.3	29.3
Window U-value	18.2	54.6	Wall R-value	1.4	90.7	Window U-value	15.0	44.3
Wall R-value	9.1	63.7	L&E	1.3	92.0	Infiltration Rate	9.1	53.4
Roof R-value	9.1	72.8	AFUE	1.3	93.3	Roof R-value	6.8	60.2
SHGC	9.1	81.9	Infiltration Rate	1.0	94.3	SHGC	6.2	66.4
AFUE	9.1	91.0	SHGC	0.9	95.2	L&E	5.2	71.6
EF	9.0	100.0	Wall Absorption	0.7	95.7	Shading Devices	4.2	75.8
Wall Absorption	0.0	100.0	WWR for North	0.7	96.4	WWR for North	3.5	79.3
Roof Absorption	0.0	100.0	WWR for West	0.7	97.1	WWR for West	3.4	82.7
Shading Devices	0.0	100.0	Roof R-value	0.6	97.7	Wall R-value	2.7	85.4
Infiltration Rate	0.0	100.0	WWR for East	0.5	98.2	Sup. Duct R-value	2.6	88.0
SEER	0.0	100.0	Shading Devices	0.4	98.6	Wall Absorption	2.3	90.3
Sup. Duct Leak.	0.0	100.0	Window U-value	0.4	99.0	Sup. Duct Leak.	2.2	92.5
Ret. Duct Leak.	0.0	100.0	Roof Absorption	0.3	99.3	Ret. Duct Leak.	2.1	94.6
Sup. Duct R-value	0.0	100.0	Ret. Duct Leak.	0.2	99.5	WWR for East	1.6	96.2
Ret. Duct R-value	0.0	100.0	Sup. Duct R-value	0.2	99.7	Roof Absorption	1.6	97.8
WWR for South	0.0	100.0	WWR for South	0.1	99.8	WWR for South	1.0	98.8
WWR for East	0.0	100.0	Sup. Duct Leak.	0.1	99.9	EF	0.6	99.4
WWR for West	0.0	100.0	Ret. Duct R-value	0.1	100.0	Ret. Duct R-value	0.4	99.8
WWR for North	0.0	100.0	SEER	0.0	100.0	SEER	0.2	100.0

The sensitivity analysis of the selected simulation parameters was performed by changing the parameter values one at a time from 50% to 150% in increments of 10% of their nominal values, which were obtained from the case-study house owner, while holding the other parameters constant. Each run was run using an hourly AMY weather file coincident with the utility data. Simulated hourly electricity and natural gas use were then extracted from the hourly-report for each case run. The simulation results were then regressed against the coincident outdoor temperature using the three-parameter change-point regression models. In this way, the 3PC and 3PH coefficients for each run were calculated. These simulations were run for all 20 selected simulation parameters.

3.1.3. *Results of sensitivity analysis using three-parameter change-point regression model*

An example of the sensitivity test result for window *U*-value changes is presented in Fig. 4. Fig. 4(a) shows the effect of the window *U*-value on electricity use and Fig. 4(b) shows the effect of the window *U*-value on the natural gas use. In both cases, the window *U*-value was varied from 2.5 W/m^2 K (0.44 Btu/h ft^2 °F) to 7.4 W/m^2 K (1.31 Btu/h ft^2 °F). These plots visually show how the window *U*-value changes affect the 3PC and 3PH coefficients. In a similar fashion to Fig. 4, the sensitivity tests for all other parameters (i.e., wall *R*-value [m^2 K/W], roof *R*-value [m^2 K/W], wall absorption [Fraction], roof absorption [Fraction], shading devices [m], SHGC [fraction], infiltration rate [ACH], lighting and equipment (L&E) [kW], seasonal energy efficiency ratio (SEER), annual fuel utilization efficiency (AFUE), energy factor (EF), supply duct leakage [Fraction], return duct leakage [Fraction], supply duct *R*-value [m^2 K/W], return duct *R*-value [m^2 K/W], Window-to-wall ratio (WWR) [%] for south, east, west, and north) were conducted [16]. The following observations were made from the example of window *U*-value changes from the sensitivity tests: In Fig. 4, the window *U*-value increase of 2.5 W/m^2 K (0.44 Btu/h ft^2 °F) to 7.4 W/m^2 K

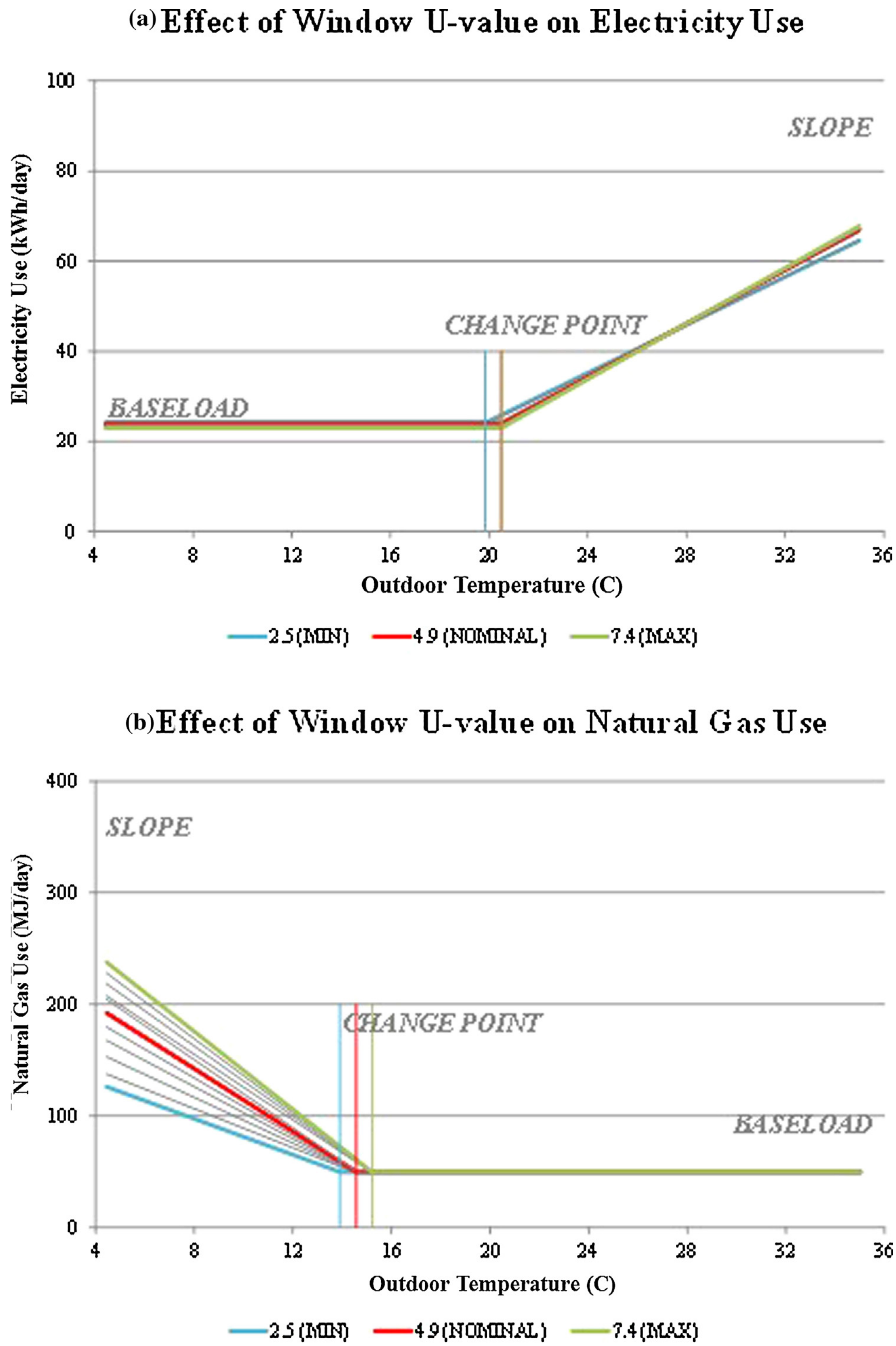


Fig. 4. An example of sensitivity test result: effect of window *U*-value changes on: (a) electricity and (b) natural gas use.

(1.31 Btu/h ft^2 °F) produced an increase of 0.7 °C (1.2 °F) in the 3PC change-point and a change of 0.7 kW h/°C (0.4 kW h/°F) in the 3PC slope. It also reduced the 3PC baseload by 1.2 kW h as the window *U*-value increased. In addition, the window *U*-value increase of 2.5 W/m^2 K (0.44 Btu/h ft^2 °F) to 7.4 W/m^2 K (1.31 Btu/h ft^2 °F) produced an increase of 1.3 °C (2.4 °F) in the 3PH change-point and a change of 18.6 MJ/°C (9.4 kBtu/°F) in the 3PH slope, as well as a reduction of 0.1 MJ (0.1 kBtu) in the 3PH baseload.

The next step was to identify which parameters affected each 3P coefficient. In order to do this, the 3P coefficients from the simulation runs of the sensitivity tests for each parameter were first calculated under varying conditions. After that, the percentage range from nominal value of each coefficient for a specific parameter was calculated using Eq. (3). This procedure was repeated for all 20 simulation parameters.

$$\%\ \text{Range from Nominal Value} = \frac{\text{Maximum Value} - \text{Minimum Value}}{\text{Nominal Value}} \tag{3}$$

Table 2
Building characteristics of case-study house..

Component			Case-study house
Envelope	Window-to-wall ratio	18.8%	
	Exterior wall	Wall color	Dark
		Gross area	145 m^2
		Average wall height	2.4 m
		Insulation *R*-value	*R*-13
		Stud spacing	40 cm
	Window	Gross area	27 m^2
		Glazing type	Clear double pane
		Frame type	Aluminum
		U-value	4.94
		SHGC	0.66
	Roof/attic	Roof color	Dark
		Ceiling type	Ceiling with attic above
		Gross area	145 m^2
		Insulation *R*-value	*R*-29.6 (20 cm insulation depth)
	Slab floor	Gross area	145 m^2
		Slab perimeter *R*-value	*R*-0
Infiltration	ACH	N/A	
Equipment	Heating system	Fuel	Natural gas
		System type	Furnace
		Efficiency (AFUE or HSPF)	66%
		Manufacturer	Lennox
		System location	Attic
	Cooling system	System type	Air conditioner, air cooled
		Efficiency (SEER)	10 (9.9–10.7)
		Manufacturer	Lennox
		System location	Unconditioned area
	Domestic hot water heater	NAECA-covered water heating equipment (yes, no)	Yes
		Fuel	Gas
		Capacity	190 L
		Energy factor	
		Type	Storage
		Tank location	Unconditioned area
		Manufacturer	Rheem

The next step was to identify which 3P coefficient was the most influential for each simulation parameter. This can be calculated by the following equation:

$$\%\ \text{of Coefficient for Each Parameter} = \frac{\text{Each}\ \%\ \text{Range from Nominal Value for Selected Parameter}}{\text{Sum of}\%\ \text{Range from Nominal Value for Selected Parameter}} \qquad (4)$$

After identifying the most to least influential parameters for each 3P coefficient, the parameters were applied to the calibration. The most to least influential parameters for the 3PC baseload coefficient were as follows: L&E (58.98%), shading devices (6.98%), SEER (6.30%), SHGC (5.74%), WWR for south (3.60%), window *U*-value (3.12%), roof absorption (3.06%), WWR for east wall (2.49%) (Table 1(b)). This rule was then applied for the other 3P coefficients as well.

However, not all the candidate parameters chosen previously for each 3P coefficient were used for the calibration; some of them were eliminated. The reason for this is better explained with the following example: as shown in Table 1(b), the parameter, *shading devices* was one of the most influential parameters for 3PC baseload, but it was also influential parameters for 3PC slope and 3PH slope coefficients. In this case, the result of the sensitivity analysis that showed the most influential 3P coefficients for each simulation parameter (i.e., 3PH slope (48.0%), 3PC baseload (28.4%), 3PC slope (22.0%), 3PH baseload (1.7%), 3PC and 3PH change-point (0.0%) for *shading devices*) was used. For example, if the parameter, *shading devices* was the most influential parameter affecting to 3PH slope, the *shading devices* would be used for calibration to adjust 3PH slope rather than other coefficients (i.e., 3PC baseload and slope). In this way, the process for the other parameters continued, and the parameters, as well as the order that the parameters used during the calibration were decided.

Following this, the calibrated simulation was begun using the parameters that corresponded to the 3PC baseload coefficient, and continued to the other parameters that correspond to 3PH baseload, 3PC change-point temperature, 3PH change-point temperature, 3PC slope and the 3PH slope in order for adjusting the corresponding 3P coefficients to match the actual energy use. There was one exception in which the parameters not used in the sensitivity analysis were used for the calibration. These were the cooling and heating thermostat set-point temperature parameters. To adjust the 3P change-point temperature coefficients, the cooling and heating thermostat set-point temperature parameters were used for the calibration based upon the characteristics of 3P model. Finally, through the sensitivity analyses, the significant parameters for each coefficient that would be used for calibrated simulation were determined as shown in Table 1 as orange highlighted parameters. These parameters were selected from the most influential parameters for each 3PC and 3PH coefficient, and were selected once more from the most of the influential 3PC and 3PH coefficients for each simulation parameter.

3.2. *Calibrated simulation using sensitivity analysis results*

3.2.1. *Description of a first case-study house*

The first case-study house is a single-family, single-story house located in College Station, Texas that uses electricity for cooling and natural gas for heating. The required building characteristics [17] and annual monthly utility bills for electricity and natural gas use during 2012 were obtained from the homeowner. The building characteristics are summarized in Table 2.

3.2.2. Methodology for calibrated simulation using sensitivity analysis results

3.2.2.1. Initial simulation. In order to run an hourly simulation, an hourly weather file needs to be used that contains the appropriate weather data for the same location. For example, Typical Meteorological Year 3 (TMY3) format weather files are recommended for use for selecting adequate HVAC systems or estimating energy use of the building for normal weather conditions since the TMY3 is annual averaged data composed of twelve typical meteorological months for a location over a thirty-year. On the other hand, AMY format weather files are recommended for use to represent the actual weather data that corresponds to a specific utility billing period. Therefore, an AMY weather file is recommended for use for calibrating a building energy simulation against actual energy use data for a particular year. In this study, an hourly AMY weather file was used for the simulation. Since the first case-study house in this study is located in College Station, Texas, the AMY weather file for College Station, Texas was used that corresponded to the 2012 billing period. After that, an initial simulation was run by DOE-2.1e based on the building characteristics information shown in Table 2 and the produced AMY weather file. In the simulation, the occupancy, lighting and equipment, and HVAC operating schedules were set to run 24 h per a day for a year, and the building geometry was simplified to a square. The occupancy and equipment operations were scheduled and the building geometry was simplified in this manner because there were no information of them as the most other cases of residential simulation.

3.2.2.2. Application of three-parameter change-point regression model. In order to calibrate the simulation, the three-parameter change-point regression model was applied to the output from the simulation program and the measured utility data from the first case-study house. The coefficients from the two three-parameter change-point regression models were then compared.

3.2.2.2.1. Application of three-parameter change-point regression model to initial simulation. The hourly-reports for electricity and natural gas use were obtained from the output file of the DOE-2.1e program. In order to obtain a three-parameter change-point regression model of the annual, simulated energy use for electricity and natural gas use against the local outdoor temperature using the IMT, a day-adjusted model of three-parameter change-point regression model was applied. The day-adjusted model was used where the energy use per period is divided by the days in the billing period before the regression is performed. The final coefficient of the model is therefore expressed as an energy use per day, which is then multiplied by the number of days in the billing period to adjust for variations in the utility billing cycle.

To begin, the simulated hourly energy use was converted to monthly average daily electricity and natural gas use divided by the days in the month. At the same time, the local hourly outdoor temperature from the simulation's weather file was also converted to a monthly average daily outdoor temperature corresponding to each month. Using the converted monthly average daily electricity and natural gas use, and monthly average daily outdoor temperature, a 3PC model for the simulated electricity use and 3PH model for the simulated natural gas use were calculated using the corresponding local outdoor temperature with the IMT to determine the coefficients for the simulated electricity and natural gas use (i.e., 3PC and 3PH baseload, change-point temperature and slope).

3.2.2.2.2. Application of three-parameter change-point regression model to measured energy use. In order to obtain the three-parameter change-point regression model of the monthly utility billing data against the local outdoor temperature using the IMT, the day-adjusted model of three-parameter change-point regression model was applied in a similar fashion as was applied to the initial simulation.

In the first step of the regression process, the monthly utility billing data was converted to monthly average daily electricity and natural gas use by dividing the monthly amount by the days in the respective billing cycles. At the same time, the coincident hourly outdoor temperature was also converted to monthly average daily outdoor temperature corresponding to the respective monthly billing periods. Using the monthly average daily electricity and natural gas use, and the monthly average daily outdoor temperature, the 3PC model for electricity use and 3PH model for natural gas were calculated using the corresponding local outdoor temperature with the IMT. In such a fashion, the monthly 3P coefficients (i.e., 3PC and 3PH baseload, change-point temperature and slope) for electricity and natural gas use were obtained for the actual utility billing data.

3.2.2.3. Identifying abnormal energy use from monthly utility billing data. Unfortunately, the monthly utility billing data may not always be used directly for the calibrated simulation because the actual energy use of the house may include abnormal energy use that can create an inaccurate calibration. For example, a long term vacation may be shown as an extremely low energy use for a certain month, and therefore this data would need to be adjusted for the calibration. In this case, the 3P coefficients obtained from the utility billing data for the electricity and natural gas use were used. For example, in Fig. 5(a), when the natural gas use was determined to be extremely low during the summer, the homeowner was contacted to determine if this was a vacation period. Once this was confirmed, the data was replaced by the data from the regression model as shown in Fig. 5(b). The decision for the abnormal energy use data could also be conducted by setting upper and lower limits for each coefficient to identify outliers that could be indicating abnormal energy use data. In this example, the upper and lower limits were determined by calculating the coefficient of variation of the root mean square error (CV (RMSE)) of 3P regression models shown in Fig. 5 as the dotted lines.

3.2.2.4. Calibrated simulation using sensitivity analysis results. The overall procedure for the calibrated simulation is as following: First, the parameter for calibration was varied from approximately 50% to 150% of its nominal value, in 2% increments, while the other parameters were held constant in order shown in Table 3. The indicator that was used to find the best fit of the parameter, the

Table 3
Calibration procedure resulted from sensitivity analysis results..

Calibration run no.	3P coefficient	Parameter	
1	Baseload	Electricity	L&E
2		Natural gas	EF
3	Change-point	Electricity	Cooling thermostat
4	Temperature	Natural gas	Heating thermostat
5	Slope	Electricity	SEER
6			Return duct leakage
7			Roof absorption
8			Supply duct *R*-value
9			Supply duct leakage
10			Return duct *R*-value
11		Natural gas	AFUE
12			Window *U*-value
13			Infiltration rate
14			Roof *R*-value
15			SHGC
16			Shading devices
17			WWR for north
18			WWR for west
19			Wall *R*-value
20			Wall absorption
21			WWR for east
22			WWR for south

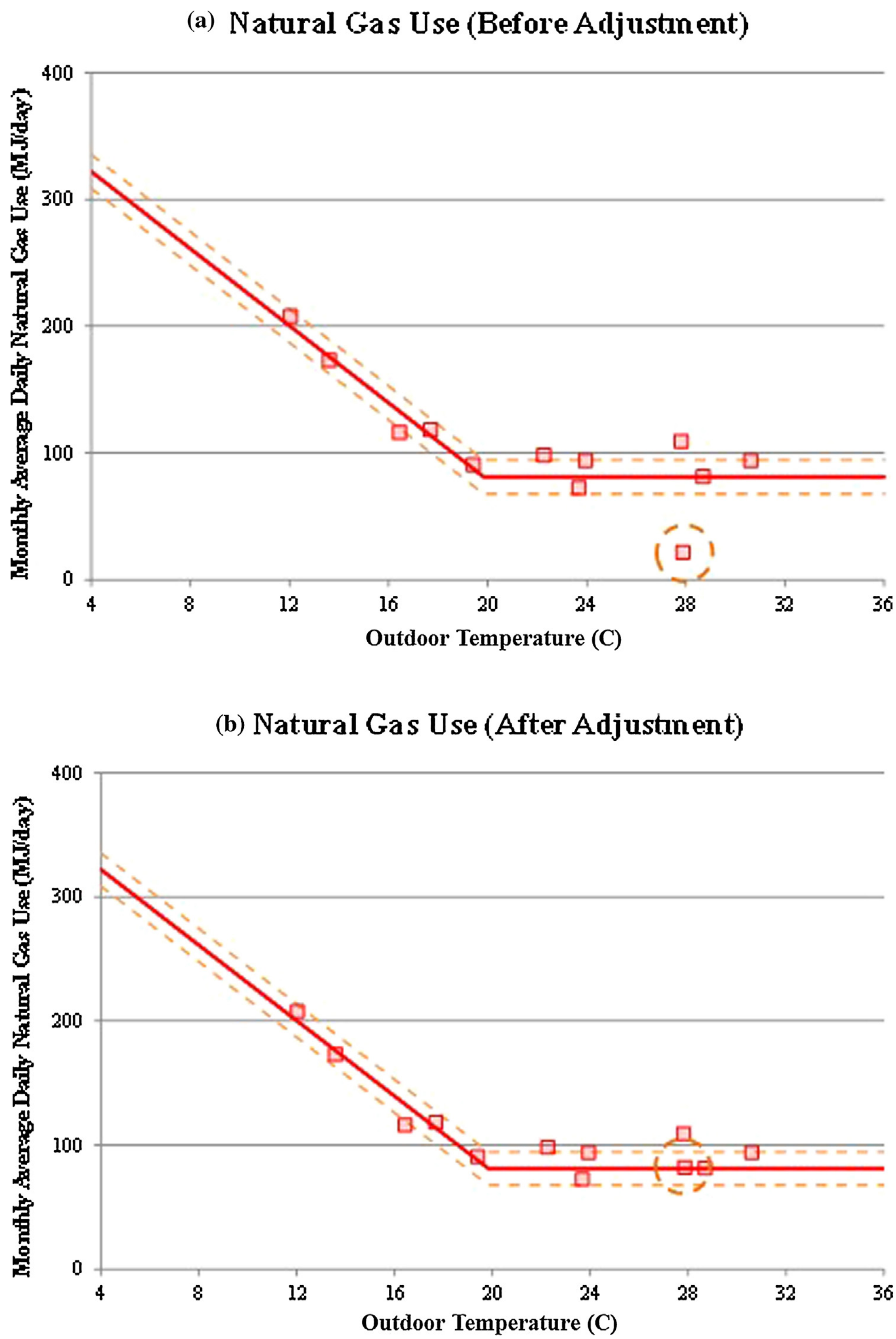


Fig. 5. Monthly utility billing data for first case-study house: (a) before and (b) after adjustment of abnormal natural gas use.

global CV (RMSE) which includes electricity and natural gas was used. There are three indicators used for evaluating the accuracy of calibrated simulation according to ASHRAE Guideline 14-2014 [18], which are the coefficient of variation of the standard deviation (CV (STD)), the CV (RSME), and the normalized mean bias error (NMBE). Among the indicators, CV (RMSE) was used in this study because it is the most widely used calibrated simulation indicator. The global CV (RMSE) were calculated by comparing the energy use obtained by the simulation model versus the utility billing data. The equations for the electricity, natural gas and global CV (RMSE) are shown in Eqs. (5)–(7), respectively. Second, after finding the minimum global CV (RMSE) using the simulations, the next parameters were selected and the same procedure was used to find the minimum global CV (RMSE), while holding the parameter value constant that was already decided from the previous step. This procedure for the calibration was carried out for all 22 parameters, including the cooling and heating thermostat set-point temperature parameters until reaching the required accuracy criterion, which was 15% of monthly global CV (RMSE). This tolerance value was chosen based on the ASHRAE Guideline 14-2014 recommendation [18]. In this

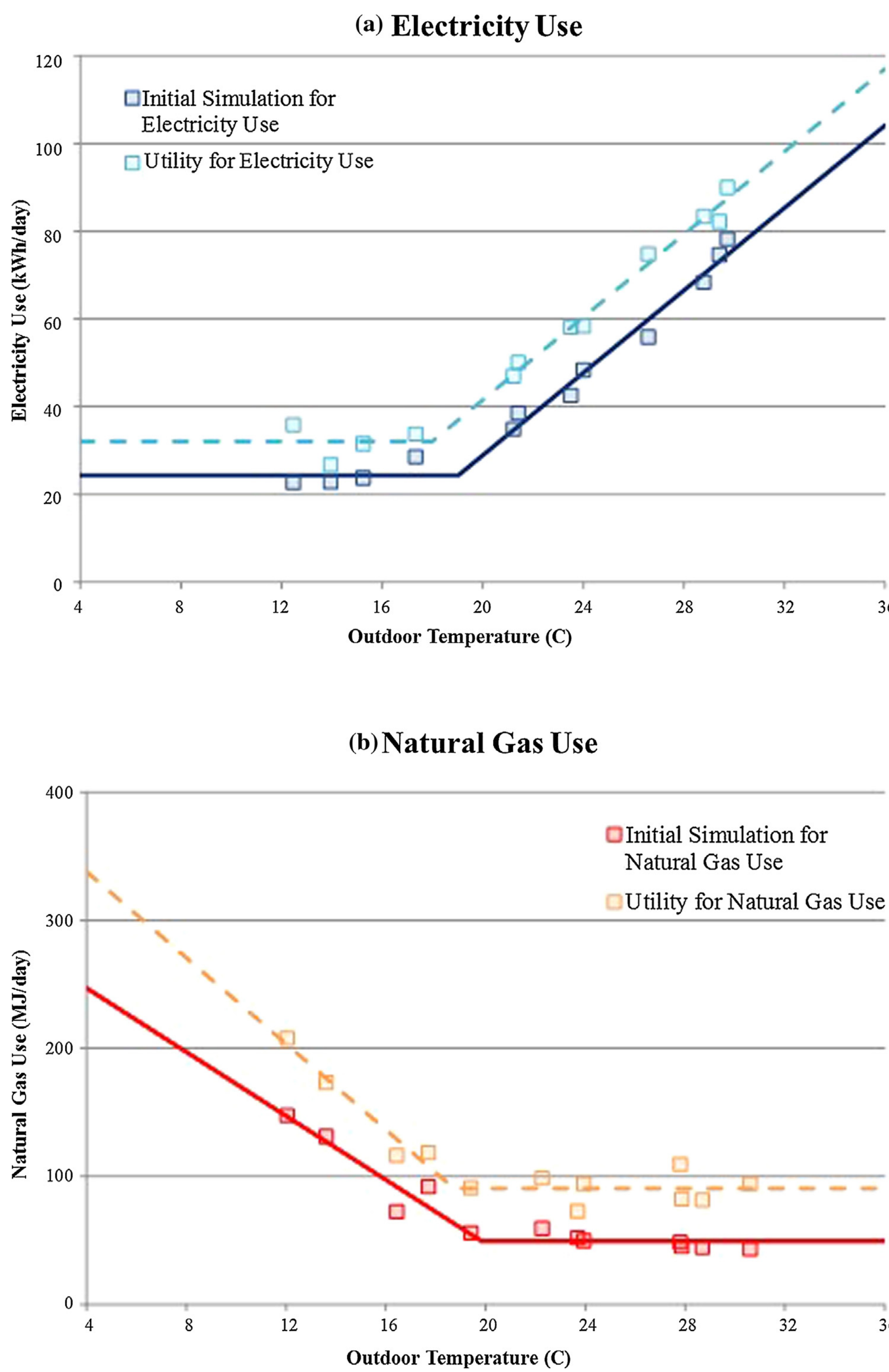


Fig. 6. Initial simulation results for: (a) electricity and (b) natural gas use with corresponding three-parameter models for the first case-study house.

way, the simulation model was calibrated using all the parameter values that were determined by adjusting each parameter until the minimum global CV (RMSE) was obtained.

$$\mathrm{CV(RMSE)}_{\mathrm{Electricity}} = \frac{\sqrt{\left(\sum_{n}^{i=1}\left(y_{\mathrm{simulated,i}} - y_{\mathrm{data},i}\right)^2/n-1\right)}}{\bar{y}_{\mathrm{data}}} \times 100 \tag{5}$$

$$\mathrm{CV(RMSE)}_{\mathrm{NaturalGas}} = \frac{\sqrt{\left(\sum_{n}^{i=1}\left(y_{\mathrm{simulated},i} - y_{\mathrm{data},i}\right)^2/n-1\right)}}{\bar{y}_{\mathrm{data}}} \times 100 \tag{6}$$

$$\mathrm{CV(RMSE)}_{\mathrm{Global}} = \frac{\sqrt{\left(\sum_{n}^{i=1}\left(y_{\mathrm{simulated},i} - y_{\mathrm{data},i}\right)^2/n-1\right)}}{\bar{y}_{\mathrm{data}}} \times 100 \tag{7}$$

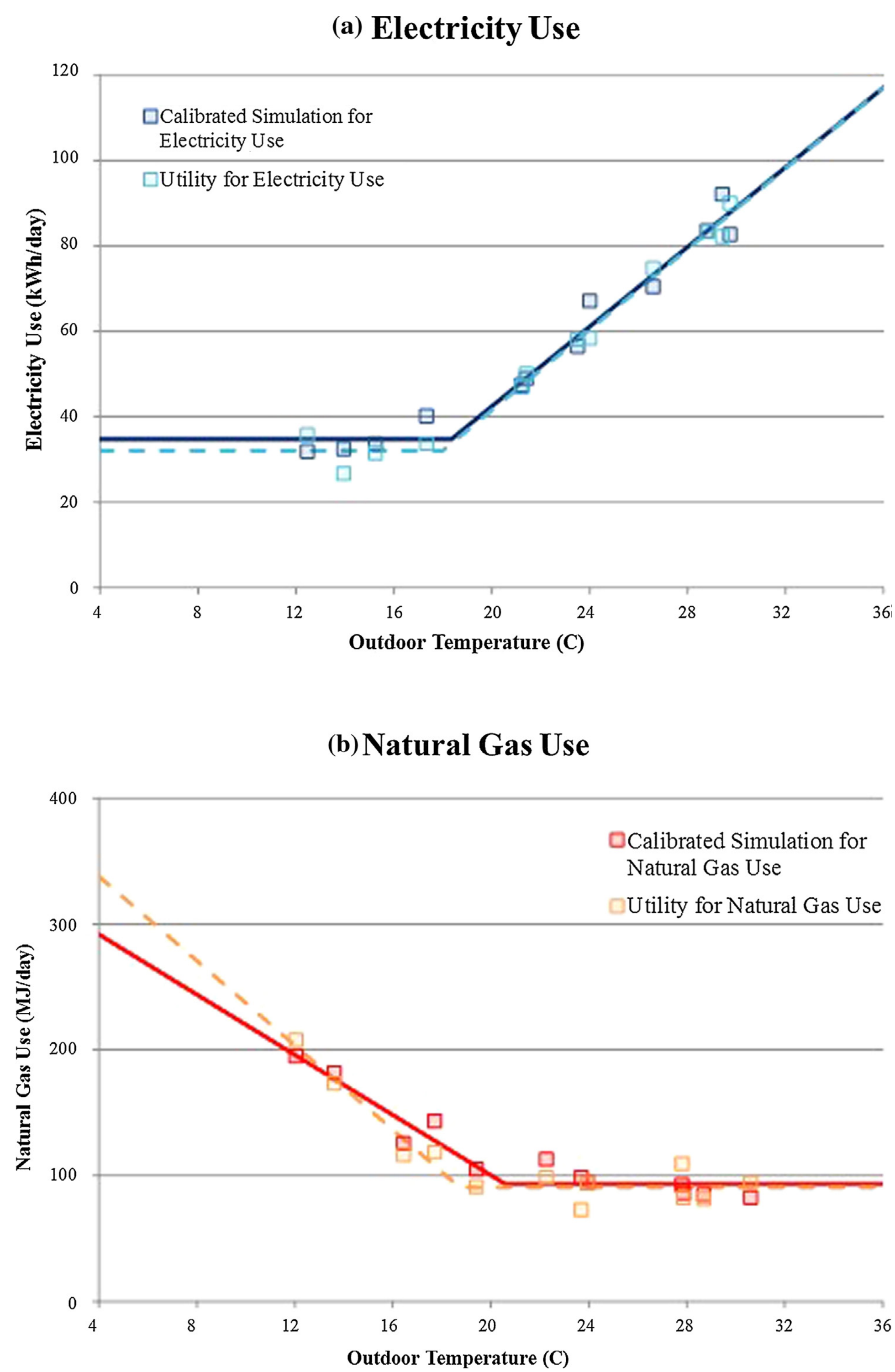


Fig. 7. Calibrated simulation results for: (a) electricity and (b) natural gas use with corresponding three-parameter models for the first case-study house.

where $y_{\text{simulated},i}$ is a simulated dependent variable value corresponding to a particular set of values of the independent variables, $y_{\text{data},i}$ is the data value of the dependent variable for the same set of independent variables above, $\bar{y}_{\text{data}}$ is the mean value of the dependent variable of the data set, and n is the number of data points in the data set.

3.2.2.5. Results of calibrated simulation using sensitivity analysis results. Fig. 6 shows the monthly average daily simulated and measured electricity and natural gas use versus outdoor temperature and the respective 3PC and 3PH regression models from the IMT. The monthly CV (RMSE) for the initial simulation was calculated to assess the goodness-of-fit, which yielded 27.3% for the electricity use, 61.6% for the natural gas use and 36.9% for global, respectively.

The first case-study house simulation was calibrated using the adjusted electricity and natural gas utility bills and the coincident weather data. Each parameter was varied from approximately 50%

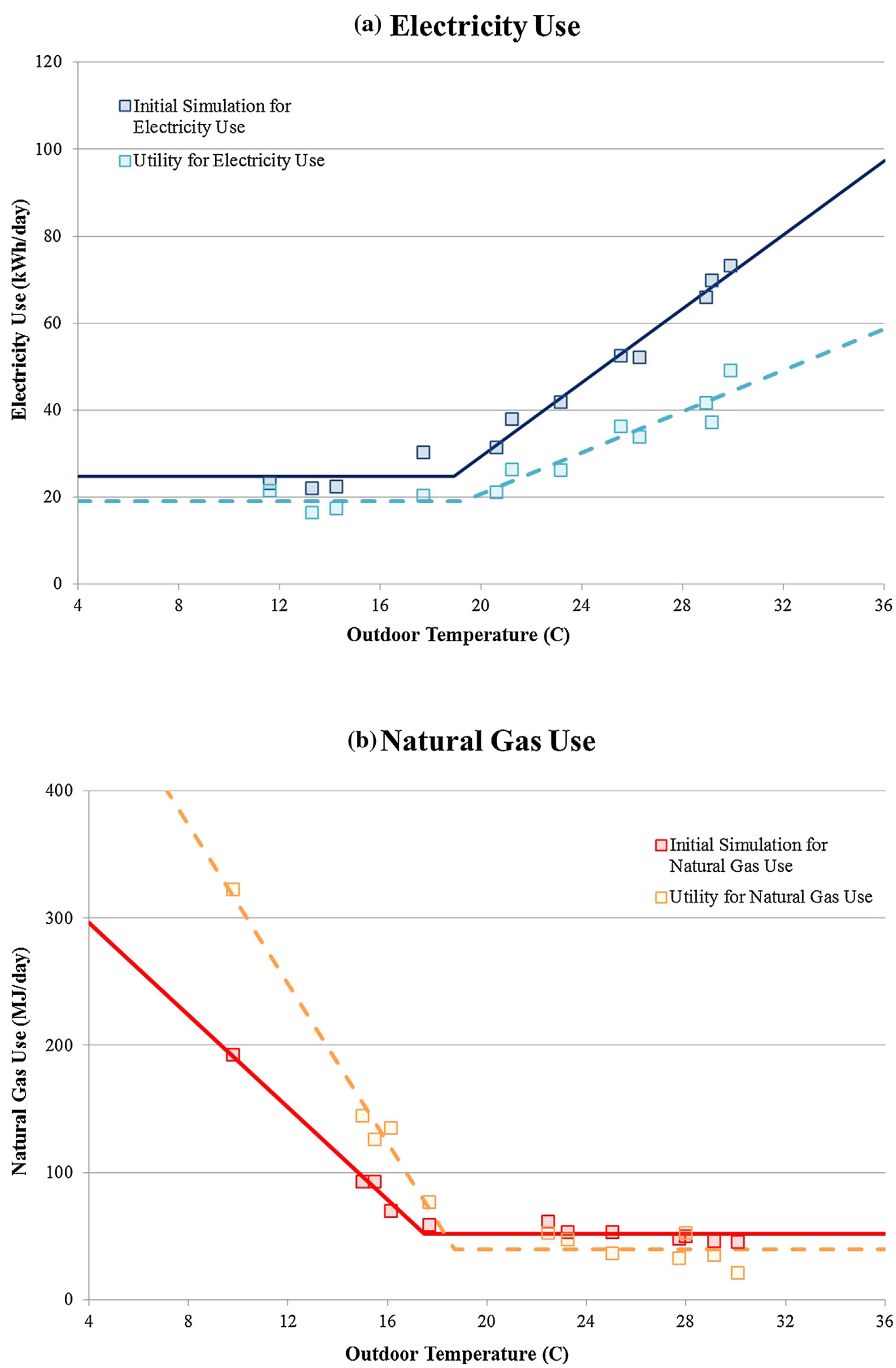
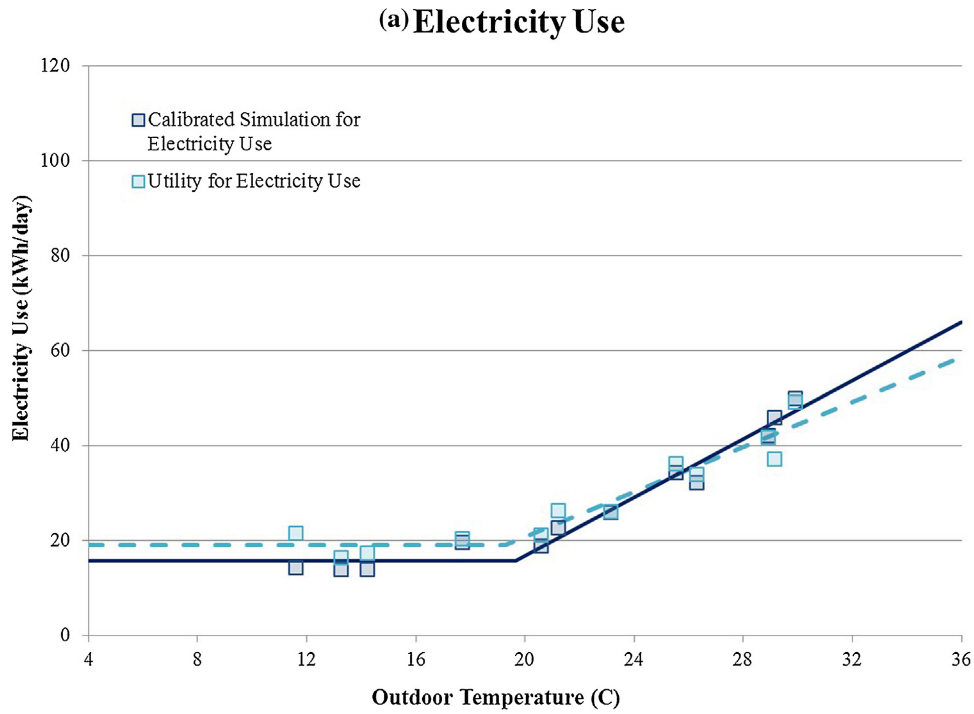


Fig. 8. Initial simulation results for: (a) electricity and (b) natural gas use with corresponding three-parameter models for the second case-study house.

to 150% of its nominal value, in roughly 2% increments, while the other parameters were held constant until the parameter value reaching to the minimum global CV (RMSE) had been found. In this process, the calibrated simulation was begun by adjusting L&E values. When the global CV (RMSE) reached its minimum, which was 0.59 of the L&E, the adjusted L&E value was then used for next step. For the next parameter, the EF values were varied until the minimum global CV (RMSE) was reached. This procedure was continued for all 22 parameters. Fig. 7 shows the calibrated energy use of the case-study house simulation model against outdoor temperature. The final minimum global CV (RMSE) was 8.8% for the first calibrated case-study house simulation, which is within the accuracy criterion that was previously established.

4. Calibrated simulation for a second case-study house

In a similar fashion to the first case-study house, a second case-study house was also simulated and calibrated by the same



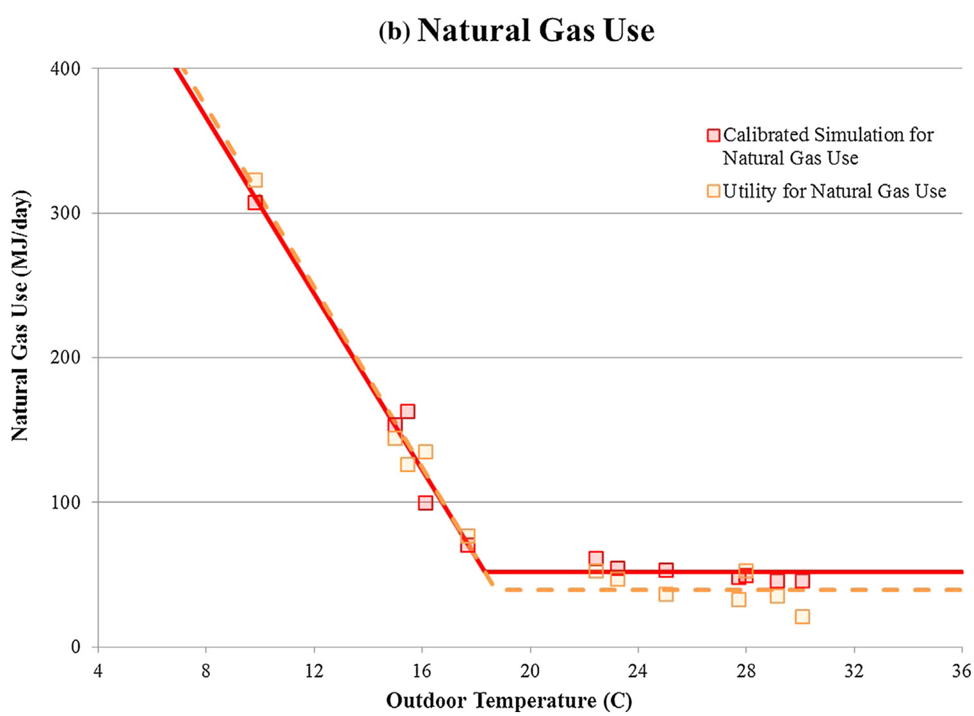


Fig. 9. Calibrated simulation results for: (a) electricity and (b) natural gas use with corresponding three-parameter models for the second case-study house.

procedure. The second case-study house is a single-family, single-story house located in College Station, Texas that uses electricity for cooling and natural gas for heating as well. The required building characteristics and annual monthly utility bills for electricity and natural gas use during 2012 were obtained from the homeowner. Fig. 8 shows the monthly average daily simulated and measured electricity and natural gas use versus outdoor temperature and the respective 3PC and 3PH regression models from the IMT. The monthly CV (RMSE) for the initial simulation was calculated to assess the goodness-of-fit, which yielded 40.7% for the electricity use, 47.8% for the natural gas use and 47.8% for global, respectively.

The second case-study house simulation was calibrated using the adjusted electricity and natural gas utility bills and the coincident weather data. Fig. 9 shows the calibrated energy use of the second case-study house simulation model against outdoor temperature. The final minimum global CV (RMSE) was 17.21% for the second calibrated case-study house simulation which is acceptable for the accuracy criterion previously established.

5. Conclusion and discussions

This study presents a methodology for calibrating whole-building energy simulations in single-family residential buildings using a three-parameter change-point regression model. This methodology provides a systematic and consistent calibrated simulation approach, as well as cost savings from reduced time and effort of users. The procedure consists of two phases, which are the sensitivity analysis procedure that can analyze a characteristics of the building, and the calibrated simulation procedure that uses the results of the sensitivity analysis. The findings from this study are summarized as follows:

(1) A characteristics of the first case-study house was analyzed with the methodology using a detailed sensitivity analysis with a three-parameter change-point regression model. In this procedure, the most to least influential parameters for each three-parameter coefficient for the first case-study house were identified. For the first case-study house, the L&E was selected as the most influential parameter for 3PC baseload, next, SEER, return duct leakage, roof absorption, supply duct *R*-value, supply duct leakage, return duct *R*-value parameters were selected for 3PC slope, EF was selected for 3PH baseload, and the AFUE, window *U*-value, infiltration rate, roof *R*-value, SHGC, shading devices, WWR for North and west walls, wall *R*-value, wall absorption, WWR for east and south walls were selected for 3PH slope.

(2) The parameters identified for each three-parameter coefficient were then used to determine the rules for calibrated simulation procedure. First, the parameters corresponding to 3PC and 3PH baseload (i.e., weather-independent) were adjusted, next, the parameters corresponding to 3PC and 3PH change-point, and 3PC and 3PH slope (i.e., weather-dependent) were adjusted. These parameters in the order described in (1) were adjusted to closely match the actual building energy use, which was the annual monthly utility billing data in this study. Finally, the goodness-of-fit of 36.9% for the global CV (RMSE) was improved to 8.8% for the first case-study house, which are within the accuracy criterion previously established by the ASHRAE Guideline 14-2014.

(3) In a similar fashion to the first case-study house, a second case-study house was also simulated and calibrated by the same procedure. The goodness-of-fit of 47.8% for the global CV (RSME) was improved to 17.2% for the second case-study house, which is acceptable for the accuracy criterion previously established.

(4) The case-study houses in this study are single-family houses in a hot and humid climate, which use electricity for cooling and natural gas for heating. Therefore, future studies will need to focus on expanding this methodology to various other types of buildings such as multi-family residential buildings, small offices and retails.

References

[1] T. Reddy, Literature review on calibration of building energy simulation programs: uses, problems, procedures, uncertainty, and tools, ASHRAE Trans. 112 (1) (2005) 226–240.
[2] S. Diamond, B. Hunn, Comparison of DOE-2 computer program simulations to metered data for seven commercial buildings, ASHRAE Trans. 87 (1) (1981) 1222–1231.
[3] M. Kaplan, J. McFerran, J. Jansen, R. Pratt, Reconciliation of a DOE2.1C model with monitored end-use data for a small office building, ASHRAE Trans. 96 (1) (1990) 981–993.
[4] M. Kaplan, B. Jones, J. Jansen, DOE-2.1C model calibration with monitored end-use data, Am. Counc. Energy-Efficient Econ. 10 (1990) 115–125.
[5] B. Hunn, J. Banks, S. Reddy, Energy analysis of the Texas capital restoration, in: Proceedings of the Eighth Symposium on Improving Building Systems in Hot and Humid Climates, Dallas, TX, 1992.
[6] J. Haberl, T. Bou-Saada, Procedures for calibrating hourly simulation models to measured building energy and environmental data, ASME J. Sol. Energy Eng. 120 (1998) 193–204.
[7] D. Bronson, S. Hinchey, J. Haberl, D. O'Neal, A procedure for calibrating the DOE-2 simulation program to non-weather-dependent measured loads, ASHRAE Trans. 98 (1) (1992) 636–652.
[8] J. Haberl, R. Sparks, C. Culp, Exploring new techniques for displaying complex building energy consumption data, Energy Build. 24 (1996) 27–38.
[9] J. Manke, D. Hittle, Calibrating building energy analysis models using short term test data, in: Proceedings of the ASME International Solar Engineering Conference, 1996, pp. 369–378.
[10] M. Liu, D. Claridge, Use of calibrated HVAC system models to optimize system operation, ASME J. Sol. Energy Eng. 120 (1998) 131–138.
[11] J. Sun, A. Reddy, Calibration of building energy simulation program using the analytic optimization approach (RP-1051), HVAC&R Res. 12 (2006) 177–196.
[12] K. Kissock, J. Haberl, D. Claridge, Development of a toolkit for calculating linear, change-point linear and multiple-linear inverse building energy analysis models, in: ASHRAE Research Project 1050-RP, 2002.
[13] F. Sever, K. Kissock, D. Brown, S. Mulqueen, Estimating industrial building energy savings using inverse simulation, ASHRAE Trans. 117 (1) (2011) 348–355.
[14] S. Cho, J. Haberl, Development of a Simulation Toolkit for the Selection of High Performance Systems for Office Building in Hot and Humid Climates, in: Poceedings of the Third National Conference of International Building Performance Simulation Association-USA, Berkeley, CA, 2008.
[15] M. Liu, D. Claridge, N. Bensouda, K. Heinemeier, S. Lee, G. Wei, High Performance Commercial Building Systems: Manual of Procedures for Calibrating Simulations of Building Systems, Energy Systems Laboratory, College Station, TX, 2003.
[16] K. Kim, Development of an Improved Methodology for Analyzing Existing Single-family Residential Energy Use, Doctoral Dissertation, Texas A&M University, College Station, TX, 2014.
[17] P. Im, A Methodology to Evaluate Energy Savings and NO_x Emissions Reductions from the Adoption of the 2000 International Energy Conservation Code (IECC) to New Residential in Non-attainment and Affected Counties in Texas, Texas A&M University, College Station, TX, 2003 (M.S. Thesis).
[18] American Society of Heating, Refrigerating, and Air-Conditioning Engineers, ASHRAE Guideline 14-2014, Measurement of Energy and Demand Savings, ASHRAE, Atlanta, GA, 2014.