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A Methodology to Create Prototypical Building Energy Models for Existing Buildings: A Case Study on U.S. Religious Worship Buildings

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Abstract

Prototypical building energy models are of great significance because they are the starting point in conducting analyses for various applications, such as building energy saving potential analysis, building design, building energy market evaluation, and building energy policy-making. However, current prototypical building energy models only represent limited types of buildings in certain countries. To fill the gap, this paper proposes a methodology to systematically create prototypical building energy models. First, a six-step methodology is introduced: model input identification, data collection, data cleaning, data conversion, model simulation, and model calibration. Then, the methodology is demonstrated by a case study of creating 30 prototypical energy models for U.S. religious worship buildings, representing buildings in 15 climate zones and 2 vintages (pre- and post-1980). Finally, to show the applications of the models, the building energy saving potentials from six efficiency measures are analyzed for pre-1980 U.S. religious worship buildings in three ASHRAE Climate Zones. The results show that the maximum energy saving potentials are approximately 30% for the religious worship buildings in all three climate zones investigated, indicating significant opportunities for energy savings in these buildings through their prototypical building model development.

Key words: Prototypical Building Energy Models, Religious Worship Building, Energy Saving Potential

1. Introduction

Both commercial and residential buildings consume large amount of energy, and the International Energy Agency (IEA) stated that the global buildings sector was responsible for approximately 30% of primary energy consumption in 2017 [1-3]. Moreover, energy consumption of buildings all over the world is still rapidly growing. Conducting building energy analyses provides a quantitative understanding of building energy performance, which assists building owners and managers to avoid using energy inefficiently and to reduce energy consumption of buildings. Prototypical building energy models are the starting point in conducting these analyses for both existing and new buildings. The prototypical building energy models for existing buildings need to contain typical building features; meanwhile, the models for new buildings need to meet the requirements of building energy standards. Previous research has applied some current prototypical building energy models for various purposes. Field, et al. [4] provided a variety of application examples of prototypical building energy models, such as evaluation of building energy standards and comparison of energy performance for buildings of different vintages. Glazer [5] analyzed the maximum technically achievable energy targets for commercial buildings by using prototypical building energy models as baselines. Similarly, Thornton, et al. [6] evaluated the performance of energy and cost savings of the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 90.1-2010 based on prototypical building energy models.

Building energy simulation programs are frequently used to create prototypical building energy models and conduct building energy analyses. Brackney, et al. [7] provided a history of building energy simulation program development. DOE-2 and EnergyPlus are two of the most popular building energy simulation programs [8, 9]. They can analyze the hourly energy consumption year-round for individual energy sources and end-uses. To simplify the model creation and perform detailed analyses for the buildings with complex characteristics and operations, graphical user interfaces eQUEST and OpenStudio were developed based on DOE-2 and EnergyPlus, respectively [10, 11]. Because of the various calculation methods, different building energy simulation programs have their own requirements for model inputs and varying accuracy of simulating results for building energy consumption. To compare the abilities and performance of popular building energy simulation programs, Crawley, et al. [12] contrasted the capabilities of 20 simulation programs, which provides a valuable reference for energy modelers.

To facilitate building energy-related analyses, the U.S. Department of Energy (US DOE) published several sets of prototypical building energy models. For example, to improve energy efficiency of commercial buildings, it is crucial to have a set of building energy models, which can represent the majority of U.S. commercial building types. Thus, the US DOE created DOE Commercial Reference Building Models with EnergyPlus [13]. The models represent new and existing commercial buildings in the U.S. and can be used for various applications, including assessing new technologies, optimizing designs, and conducting studies of building components. The building models include three vintage categories: pre-1980, post-1980, and new construction. With these prototypical models, the US DOE quantified the potential energy savings of U.S. commercial buildings with improving energy codes, such as ASHRAE Standard 90.1 [14-17] and the International Energy Conservation Code (IECC) [18-21]. Accordingly, the US DOE has been continuously updating the building models based on different editions of ASHRAE Standard 90.1 and IECC. The updated building energy models were then called the DOE Commercial Prototype Building Models [22]. Recently, the US DOE developed a library called OpenStudio-Standards gem, which includes OpenStudio's version of the DOE Commercial Reference Building Models and the DOE Commercial Prototype Building Models [23, 24].

Although there is a rich set of existing prototypical building energy models in the U.S., there are still some building types missing, such as religious worship buildings, mechanic shops, and college or university buildings. Those missing building types still account for over 20% of the total energy consumption in the U.S. commercial building sector and approximately 20% of the floor space [6, 25]. Some researchers are currently working to create models of these missing building types, but overall, this work is not receiving sufficient attention [26, 27]. For example, religious worship buildings are approximately 25% of the total floor area and 13% of the total site energy use among the U.S. commercial building sector [28, 29]. Despite these relatively significant percentages, existing U.S. religious worship buildings have received minimal energy analysis attention, and there is a lack of prototypical building energy models [30-32]. Therefore, creating appropriate models for U.S. religious worship buildings is essential.

Thornton, et al. [6] developed a detailed methodology to create energy models based on ASHRAE Standards, which model developers can use as a reference to create prototypical building energy models for new construction types. However, there is no comprehensive guideline to create prototypical energy models for existing buildings. To accomplish this, model developers need to collect and summarize the information from building energy surveys, measured databases, and related literature. Because these data sources contain their own special formats, it is challenging to convert the disparate data sources into forms that can be used for model inputs representing the typical buildings. Thus, it is necessary to provide a systematic methodology to create prototypical building energy models for existing buildings.

To fill the gap, this paper proposes a general methodology to systematically create prototypical building energy models for existing buildings, which consists of six steps: (1) identifying the model inputs; (2) collecting related data from different data sources; (3) cleaning the data; (4) converting the data into model inputs; (5) conducting simulations; and (6) calibrating building energy models by using meta-models. Then, the methodology is demonstrated by a case study, where 30 prototypical energy models are created for U.S. religious worship buildings, representing buildings in 15 climate zones and 2 vintages (pre- and post-1980). The modeled energy results are evaluated by using the energy data from existing religious worship building samples in the 2003 CBECS. Finally, to introduce the possible applications of prototypical building energy models, we analyzed the building energy saving potentials from six efficiency measures for pre-1980 U.S. religious worship building models in ASHRAE Climate Zones 2A, 5A, and 8.

2. Methodology of Prototypical Building Energy Model Creation

Prototypical building energy models of existing buildings should contain the typical building characteristics, include relevant operating schedules, and reflect the typical energy performance of that building type for a certain vintage at a given climate zone. This section proposes a methodology to systematically create prototypical building energy models to meet the above requirements. To create prototypical building energy models, data analytics is applied to a rich set of building energy data sources. Figure 1 illustrates the six key steps of the proposed methodology for determining model inputs and calibrating the building energy models with the available data sources. The first step is to identify the requirements for model inputs based on the selected building energy simulation program. In order to determine the model input values, Step 2 is to collect data for the specific building type, location, and vintage from several data sources. Step 3 is to clean the data to exclude atypical and erroneous data. Because some data cannot directly be used as model inputs, Step 4 converts the data into model inputs. After that, Step 5 generates the model input files and predicts the energy results of the prototypical building energy models. Finally, Step 6 calibrates the prototypical building energy models to obtain the energy results that represent the energy performance of typical buildings.

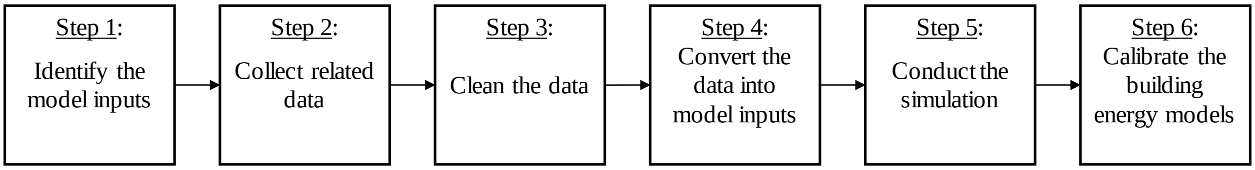


Figure 1. Workflow of the proposed methodology in creating prototypical building energy models

2.1. Step 1: Identify the Model Inputs

Figure 2 summarizes the possible model inputs of prototypical building energy models from high level frameworks to low level frameworks. The top level of the model inputs can be divided into the following six categories: *Weather Condition*, *Geometry*, *Envelope*, *Schedule*, *Internal Load*, and *System*. First, the *Weather Condition* consists of the ambient parameters, such as ambient temperature and wet bulb temperature. The hourly ambient parameters are needed if model developers plan to simulate hourly energy consumption of the buildings. Second, the *Geometry* contains dimensional and shape parameters, including total floor area and window location. Next, the *Envelope* is composed of two sublevels; the upper sublevel contains the types of envelopes and the construction layers for specific envelope types, while the lower sublevel contains the detailed envelope parameters, including the thickness of each layer and R-value of insulation layers. Then, the *Schedule* is needed for occupants, lighting, plug loads, and building systems. To obtain the hourly energy consumption of the buildings, energy modelers need to provide the hourly schedules for model input files. Although the schedules of system operations and the occupants are related, they are not the same. For example, the HVAC system usually operates before the first person enters a building and stops after the last person leaves the building. After schedules, the *Internal Loads* are required as model inputs, which are comprised of power and occupant densities. Finally, the *System* category consists of the HVAC system, domestic hot water system, and refrigeration system. After determining the specific type of each system for an individual building, energy modelers then need to identify the parameters of all the components in each system.

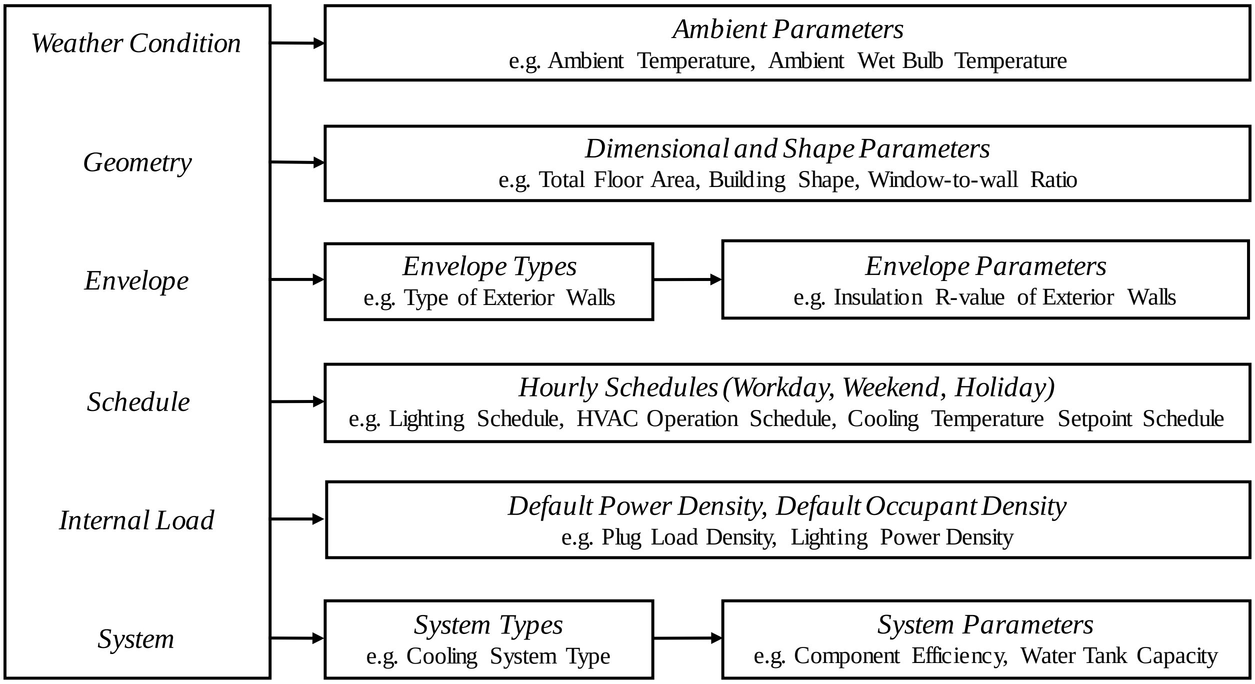


Figure 2. Inputs of prototypical building energy models from high level frameworks (left) to low level frameworks (right)

2.2. Step 2: Collect Related Data

Based on the required model inputs identified in Step 1, the related data can be collected from building energy databases, literature, and current building energy models of other building types. First, building energy databases provide building characteristics, operating schedules, and energy data of existing buildings. There are several commonly used databases for U.S. commercial buildings, such as CBECS, Building Performance Database (BPD), and California Commercial End-Use Survey (CEUS) [33-36]. The data in these databases is mainly collected from surveys and field measurements. However, the data availability varies depending on the databases. For example, CBECS, a national in-depth sample survey for the stock of U.S. commercial buildings, provides the building characteristics, operating schedules, and detailed energy data for individual building samples [33, 36]. On the other side, BPD gives the distributions of characteristics and energy data for different categories of commercial buildings [34]. Based on the extent that data is available, we can evaluate the possibility of obtaining relevant data for model inputs from the databases. Table 1 summaries the possibility of related data for model inputs provided by the above-mentioned U.S. commercial building energy databases.

The sites and total floor areas of buildings are often readily obtained from the databases, while the details of envelopes, systems, and hourly operating schedules are sometimes either not available or require significant processing. For example, CBECS provides building characteristics, operating schedules, and energy data for individual building samples [33]. CBECS also provides detailed information on weather conditions, building geometries, and energy consumption for individual energy sources and end-uses. However, it is challenging to record the hourly schedules for thousands of building samples. Instead, CBECS provides information on total weekly work hours and whether the building is operated on weekdays and weekends. The general types of envelopes and building systems are also collected in CBECS; however, their details – such as insulation R-values, exterior wall thicknesses, and cooling and heating system efficiencies – are not included. Even if geometry information is included in detail, it is still difficult to obtain all the required data for model inputs, such as window-to-wall ratio and window location. Measured data collected from sensors can relieve this problem. However, using measured data for prototypical building energy models is not always feasible, since data from many similar buildings are required, and including many buildings can be prohibitive in terms of cost and time.

Table 1. Possibility of related data for model inputs provided by commonly used U.S. commercial building energy databases

		Category of Model Inputs					
		Weather Condition	**Geometry**	**Envelope**	**Schedule**	**Internal Load**	**System**
Possibility of Data Provided by Building Energy Databases	**Strong**	• Climate Zone/Typical City/Typical HDD and CDD	• Total Floor Area				
	Moderate		• Number of Floors • Building Shape	• Exterior Wall Type • Roof Type • Windows Type • Floors Type	• General Total Weekly Work Hours • Whether Work on Workday and Weekend		• HVAC System Type • Water Heating Equipment Type
	Weak or Unavailable		• Window-to-Wall Ratio • Aspect Ratio • Window Location • Floor Height • Orientation • Shading • Spaces or Thermal Zones	• Exterior Wall Insulation R-value • Roof Insulation R-value • Floors Insulation R-value • Window U-value • Windows SHGC • Interior Petitions • Internal Mass • Infiltration	• Lighting Schedule • Electric and Natural Gas Equipment Schedules • Occupant Schedule • HVAC Schedule • Heating and Cooling Temperature Setpoints • Service Hot Water Schedule • Water Heater Setpoint • Daylighting Control	• Occupant Density • Lighting Power Density • Electric Equipment Power Density • Natural Gas Equipment Power Density	• HVAC System Detailed Components • HVAC System Component Efficiency • HVAC System Control • Water Heating Equipment Efficiency

One solution to address the missing data in databases is to consult other sources, such as building energy-related papers, reports, building energy standards, and existing energy models for other building types. For example, the DOE Commercial Reference Building Models used some data from building energy-related papers, reports, and standards to implement the data related to the envelopes and equipment [25]. In addition, Griffith, et al. [37] determined the values of model inputs by collecting data from various building energy-related papers and reports.

2.3. Step 3: Clean the Data

Before using the data collected in Step 2 to create building energy models, it is necessary to clean the data that is not suitable for model inputs and contains errors. Figure 3 displays the workflow to clean the related data, which begins with checking whether the data is representative for the typical buildings. Five aspects need to be inspected: (1) Are there atypical building characteristics in the data set? The data set usually provides either categories or numerical values for different building characteristics. If the building characteristics are categorical, then building samples with features that fall under those categories are assumed to be typical. If the building characteristics are numerical, then the building samples with characteristics between the 25th and 75th percentiles for the given building type are assumed to be typical. For atypical building characteristics, engineering judgement or on-site survey should be used to clean the data, such as special building shapes, extremely high total floor areas, and extremely high window-to-wall ratios. Building samples with atypical characteristics are deleted from the data sets directly. (2) Do the locations of the building samples and the prototypical building energy models have similar weather conditions? Climates impact the values of some data, such as insulation of the envelopes. Thus, if the building samples have different weather conditions from the models, the data that is easily influenced by the climate must be cleaned. In these building samples, the climate-sensitive data is changed into the data from other building samples, which have required weather conditions and have similar building features. (3) Are there typical building assets of building samples in the dataset, and are the assets from representative building models? The typical building assets have the same definition as the typical building characteristics. For example, high energy-efficient equipment should not be selected for models of old buildings, where the technology did not yet exist. In these building samples, the assets are changed into the data from other building samples, which have qualified assets and have similar building features. (4) Are there atypical operating schedules present? For instance, the data is cleaned for the building samples with extremely low operating time. In these building samples, the schedules are changed into the data from other building samples, which have qualified schedules and have similar building features. (5) Is the energy consumption per area much higher or lower than the median value? If so, the data will be cleaned. For the unchanged building samples, the samples are deleted if the values are 3 standard deviations away from the median value; for the building samples being modified based on aspects 2~4, the energy consumption is adjusted based on the rules. If the values are still 3 standard deviations away from the median value, the samples are deleted.

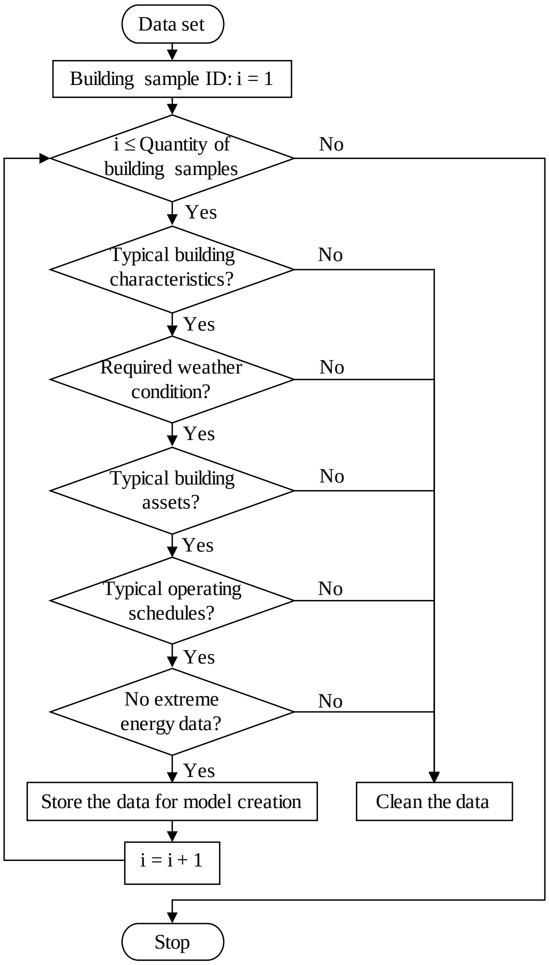


Figure 3. Workflow of data cleaning

If the building energy databases provide the data for individual building samples, we need to check whether there are missing data or errors. The recommended sequence to check data is: (1) energy data, (2) weather conditions, (3) geometries, (4) schedules, and (5) others. The erroneous data should be deleted. On the other hand, if a building sample is only missing a few data points, the remaining data can still be used for identifying the model inputs after the data adjustment based on expert knowledge. For example, even if the data of operating schedules for one building sample is not provided by the database, the geometry and envelope data are still useful to create the prototypical building energy models and can be used to determine model inputs in the subsequent steps.

2.4. Step 4: Convert the Data into Model Inputs

Not all the collected data can be directly used as model inputs; as such, this step converts the collected data into model inputs. The data are classified into four categories based on their sources and situations. Table 2 lists the methods to convert data into model inputs for each category.

Table 2. Methods to convert related data into model inputs

Index	Data Source	Data Type	Method
M1	Building Energy Databases	Data can be directly used as model inputs	Numerical data: median value Categories: highest frequent category

Index	Data Source	Data Type	Method
M2		Data cannot be directly used as model inputs	Convert data into model inputs
M3	Literature	-	Use the data as model inputs
M4	Existing Building Energy Models	-	Adjust inputs of existing building energy models to better represent prototypical building

Building energy databases provide the data for individual building samples or analysis data. If the data can be directly used as model inputs, we select median values for numerical data and the most frequent category for categories as model inputs, which is described in method M1 of Table 2. For example, the 2003 CBECS provides the total floor areas for individual building samples; the median total floor area will be used as the model input.

If the data cannot be directly used as model inputs, procedures need to be designed to convert data into model inputs based on existing methods in literature as method M2. For instance, Winiarski, et al. [38] and Winiarski, et al. [39] determined the model inputs of envelopes and HVAC systems based on the 2003 CBECS. Further, the 2003 CBECS provides the building shapes for individual building samples instead of aspect ratios. However, the aspect ratio is required for model inputs. Thus, Winiarski, et al. [38] identified the building shape category with the highest frequency and determined the aspect ratio based on the building shape. In addition, Griffith, et al. [37] created over 4,000 building energy models to simulate the energy performance of individual building samples in the 2003 CBECS and introduced several methods to convert the survey data into model inputs. For instance, because the 2003 CBECS data only contains limited information on schedules (such as the total weekly operating hours or general workday/weekend operation), Griffith, et al. [37] designed a workflow to identify the work hours every day, which is needed for the model.

In addition to building energy databases, the data in Step 2 may also be collected from literature and existing model sources. Literature provides summaries of measured data or simulation data, which can be directly used as model inputs. Data in literature should be recorded from existing buildings when the prototypical building energy models represent the energy performance of existing buildings as described in method M3. For instance, Persily [40] provided the data for infiltration rate, which can be used for existing building models.

Furthermore, inputs of existing building energy models for other building types, such as office and primary school models in the DOE Commercial Reference Building Models, can be use as reference, which is named as method M4. For example, the types of envelopes can be collected from the CBECS. The types of envelopes in the new models are usually used in some existing building energy models for other building types. Thus, the envelope details, such as insulation R-values, can be obtained from these existing building energy models.

2.5. Step 5: Conduct the Simulation

After creating the building energy model input files, whole building energy simulation programs generate the building energy results. The prototypical building energy models are sometimes used to analyze the energy performance of existing buildings in many different locations and vintages. Therefore, it is required for many variants of the prototype building models featuring characteristics of different locations and vintages. Because the input files of DOE-2 and EnergyPlus are both text files, they can be seamlessly modified for batch processing.

2.6. Step 6: Calibrate the Building Energy Models

The building characteristics and operating schedules identified through this workflow represent typical existing buildings; however, it is possible that the modeled energy use intensity (EUI) obtained in Step 5 does not align with the median level of the typical existing building obtained through empirical energy data. There are three possible causes for the EUI difference between prototypical building energy models and empirical data: (1) different weather conditions and characteristics between the models and existing buildings, (2) lack of information on existing building operating schedules, and (3) uncertainties in the model inputs. While the first two causes are caused by limitations in the available databases, the model can be calibrated based on the third cause; as such, we adjust the model inputs in the range of the uncertainties present. Figure 4 summarizes the workflow to calibrate building energy models to modify the prototypical building energy models consuming extremely high or low energy.

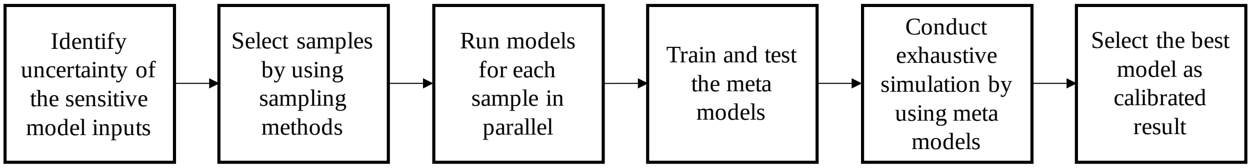


Figure 4. Workflow of model calibration

Figure 4 lists the six steps to adjust sensitive model inputs based on their uncertainties. First, sensitive model inputs that have the greatest impact on energy consumption are identified. Tian [41] reviewed common sensitivity analysis methods used in building energy applications, which can be applied to identify sensitive model inputs. Second, building samples are selected that lie in uncertainty ranges of sensitive model inputs. Third, the new building energy models for individual building samples are generated and simulated. Fourth, the sensitive model inputs and energy outputs of building energy models for building samples are used to train and test the meta-models. Eisenhower, et al. [42] introduced the methodology to optimize the building energy models based on meta-models. Fifth, to reduce computing time and obtain the global best calibrated building energy models, meta-models are used to conduct exhaustive simulation. Finally, based on the mathematical and physical criteria for specific cases, the best calibrated models can be selected.

3. Building Energy Models for Existing U.S. Religious Worship Buildings

To implement the methodology detailed in the Section 2, prototypical building energy models for existing U.S. religious worship buildings are created. The DOE Commercial Reference Building Models encompass representative cities from the 15 ASHRAE Standard 90.1-2004 Climate Zones. The models are classified as existing buildings in two vintages: pre-1980 and post-1980 buildings. By following the settings of the climate zones and vintages in the DOE Commercial Reference Building Models, this paper creates 30 prototypical building energy models for existing U.S. religious worship buildings. The energy performance of the building energy models is evaluated by the empirical site EUIs from building samples in the 2003 CBECS.

3.1. Description of Building Energy Models

The 30 prototypical building energy models are created by using SketchUp for the geometries and OpenStudio for the envelopes, schedules, internal loads, and systems. Based on the methodology introduced in the Section 2, the model inputs are determined by using the 2003 CBECS data, the data provided by building energy-related papers and reports, and model inputs of DOE Commercial Reference Building Models [13, 28, 30-32, 37-39]. We collect these data into a data set. Then the data set needs to be cleaned.

For example, approximately 50% religious worship building samples have wide-rectangle shape while lower than 1% samples have 'E' shape. Thus, we should delete the samples with 'E' shapes. Further, only 25% religious worship building samples are smaller than 235 m^2, and only 25% samples are bigger than 4,000 m^2. Thus, the samples smaller than 235 m^2 or bigger than 4,000 m^2 are deleted. Since the 2003 CBECS data only provides 311 samples for religious worship buildings, which is insufficient to develop the building models, some building samples are implemented by selecting from other survey data sources, such as the 2012 CBECS data [29]. The buildings constructed after 2003 are not selected. Ultimately, the initial sample size is approximately 550 buildings, and after cleaning, we are left with approximately 300 samples. Over 200 samples were modified based on the rules introduced in Section 2.3. Since most of the building samples come from the 2003 CBECS data set, we uniformly refer to the survey building samples by this name. After cleaning the related data, the data is classified into four categories and converted into model inputs by using various methods identified in Table 2. For example, through method M1, the median total floor area of the religious worship building samples is used as the modeled total floor area. Because the total floor area is not impacted by the climate, the same settings are applied to all models regardless of the climate zone, which avoids the problem of insufficient building samples. Next, by using methods M2 and M4, operating schedules in the models are determined. Just as with total floor area, the models have the same profiles for operating schedules in all the climate zones. Table 3 lists the four variables in the 2003 CBECS that are used to determine the operating schedules for the models, and Figure 5 shows the workflow to determine the modeled operating hours every day based on the 2003 CBECS data.

Table 3. Variables in the 2003 CBECS used to determine operating schedules for models[1]

No.	Variable Name	Variable Description	Variable Type
1	WKHRS8	Total weekly operating hours	Numerical Data *(0~168)*
2	OPEN248	Open 24 hours-a-day	Category *(Yes/No)*
3	OPNMF8	Open during the week	Category *(Open all five days/Open some of these days/Not open at all)*
4	OPNWE8	Open on weekends	Category *(Yes/No)*

[1] *The information is provided by the document of All Layout Files and Format Codes in the 2003 CBECS [43].*

In Figure 5, the numbers shown above boxes and ovals are the quantities of remaining building samples in the 2003 CBECS after being classified. Based on the workflow, the models should operate 2~15 hours each weekend and all five workdays as evenly as possible. After that, the operating schedules are adjusted by using DOE Commercial Building Models and engineering judgement. Then by using method M3, the models' infiltration rate is identified [37]. Finally, the 2003 CBECS provides the general types of exterior walls and roofs for individual building samples, but it does not give the details of the envelopes; thus, the method M4 is used to identify the details of the envelopes in the models. Winiarski, et al. [38] provided the matchup of envelope types between the 2003 CBECS and ASHRAE Standard. Since the classification of envelope types in DOE Commercial Reference Building Models follows ASHRAE Standard, the insulation R-values of exterior walls and roof in DOE Commercial Reference Building Models can be used as references to create the prototypical building energy models of existing U.S. religious worship buildings [13]. Figure 6 shows the geometry of the building energy models.

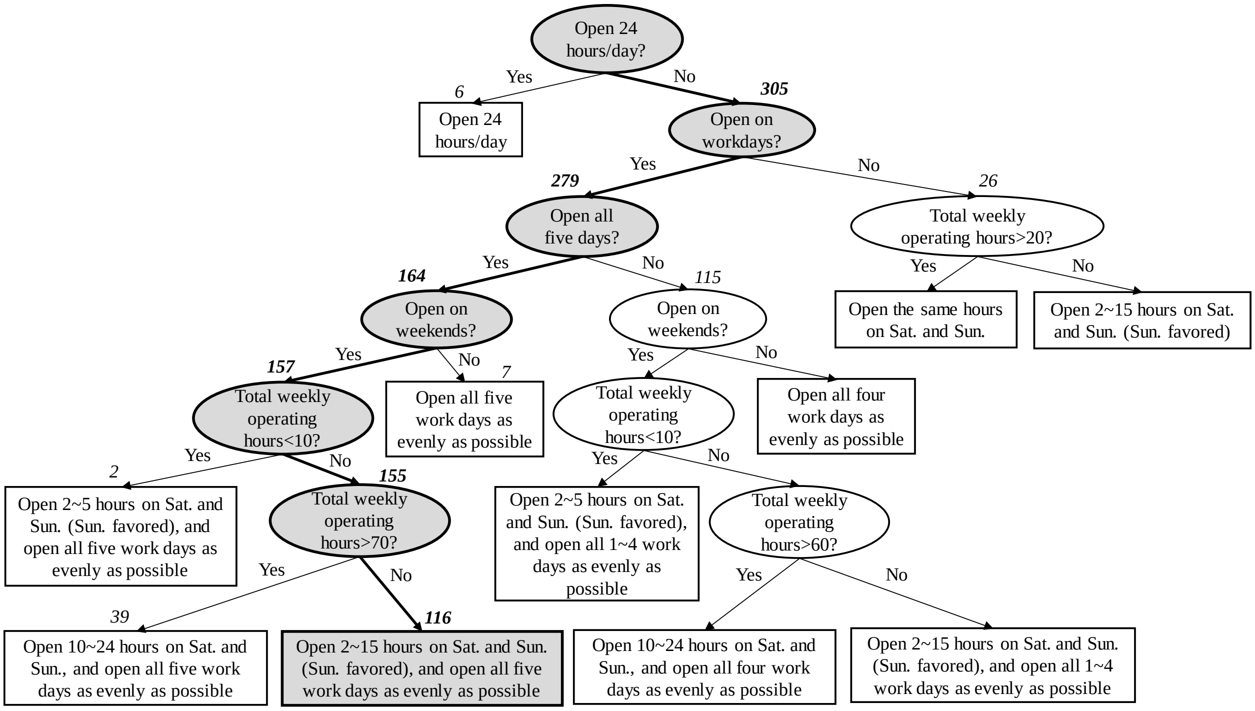


Figure 5. Workflow to determine operating hours for models

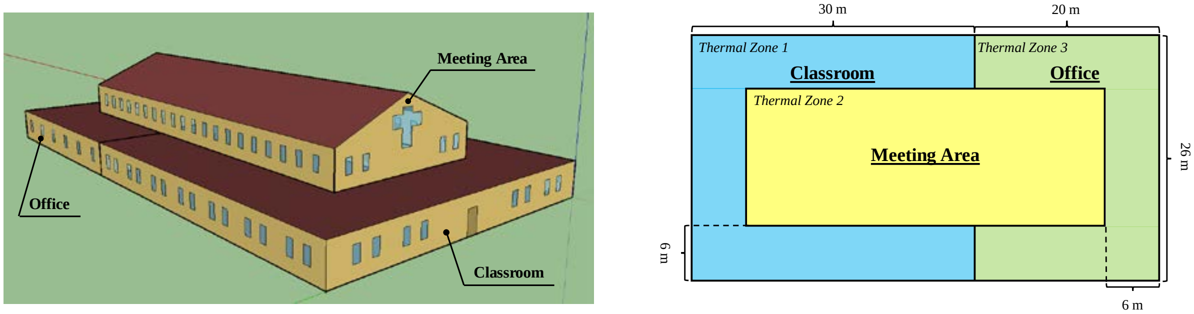


Figure 6. Geometry of the building energy models

To perform the energy analysis of religious worship building, the geometry is created based on the information provided by the 2003 CBECS and several relevant papers [28, 30-32]. The total floor area of the building energy model is 1,300 m^2 with a wide rectangular shape and 1.93 aspect ratio. It contains three space types and three thermal zones. The perimeters are offices and classrooms, and the core is a meeting area. The window-to-wall ratio is 11.5%, and windows are distributed with equal percentages on all four sides. The front of religious worship model faces to west. The floor-to-ceiling heights of offices and classrooms are both 3 m, while the height of meeting area is 6~9 m.

Based on reviewing the existing prototypical building model sets [13, 22, 23], this paper selects one typical city for each ASHRAE Climate Zone. The existing prototypical building model sets for existing buildings, such as DOE Commercial Reference Building Models and OpenStudio-Standards gem [13, 23], use the ASHRAE Standard 90.1-2004 Climate Zones [44, 45]. To be consistent with their settings, the same version of ASHRAE Climate Zones is used in this paper, and 15 typical cities are selected for the 15 climate zones based on the typical cities selected in the existing data sets and engineering judgements. Because empirical energy data is used to evaluate the modeled energy results, 2003 historical weather files of the typical cities are used for the prototypical building energy models. Based on the methodology described in the Section

2, model input files are created for the 30 models and the uncertainties of sensitive model inputs are identified.

Then, the models are calibrated in the ranges of uncertainties of envelopes, schedules, and internal loads. By calibrating the building models, we select the 10 sensitive model inputs, such as electrical equipment power density, lighting power density, insulation R-value of envelopes, and rated COP for cooling system. The ranges of the sensitive model inputs for prototypical building models are decided based on the CBECS data, literature, DOE Commercial Reference Building Models, and engineering judgement [13, 25, 28, 30-32, 37]. The building models with different vintages in various climate zones have their own specific ranges for individual inputs, and we assume normal distributions for all inputs. Next, the Latin Hypercube Sampling (LHS) method is used to select the building samples. The simulations are conducted for all the samples. The values of sensitive model inputs and site EUIs for individual building samples are used to train and test the Support Vector Regression (SVR) meta-models. Then we conduct exhaustive simulations by using meta-models. In total, we consider approximately 10^7 possible combinations for each prototypical building model. Finally, based on the mathematical and physical criteria, we select the best combinations as the prototypical building models with the two vintages in the 15 climate zones. By comparing the simulation results with the survey data, the average difference between the modeled site EUIs and the 2003 CBECS median site EUIs is reduced by approximately 10%. However, there are still differences between the modeled site EUIs and the 2003 CBECS median site EUIs. The reason will be analyzed in Section 3.2. Table 4 lists the inputs of prototypical building energy models for existing U.S. religious worship buildings after model calibration. The Method column shows the relevant method index corresponding to those listed in Table 2.

Table 4. Model inputs of existing U.S. religious worship buildings

Input	Value	Method[1]
Location	1A, Miami, FL 2A, Houston, TX 2B, Phoenix, AR 3A, Atlanta, GA 3B, El Paso, TX 3C, San Francisco, CA 4A, Baltimore, MD 4B, Albuquerque, NM 4C, Seattle, WA 5A, Chicago, IL 5B, Denver, CO 6A, Minneapolis, MN 6B, Helena, MT 7, Duluth, MN 8, Fairbanks, AK	M4
Vintage	Pre-1980 Post-1980	M4
Geometry	Total floor area: 1,300 m^2 Building shape: Wide rectangle Aspect ratio: 1.93 Window fraction: 11.5% Window locations: Equal percentages on all sides Number of floors: 1 Shading: No	M1, M2, M3

Input	Value	Method[1]
	Floor-to-ceiling height: • Meeting area: 6~9 m • All other areas: 3 m	
Schedules	Calculated based on Figure 5 and engineering judgement	M2, M4
Envelope	Exterior walls: mass walls • Insulation R-value of exterior walls (m^2-K/W): o Pre-1980: [0.35, 0.99] o Post-1980: [0.10, 3.32] Roof: Insulation Entirely Above Deck (IEAD) • Insulation R-value of roof (m^2-K/W): o Pre-1980: [1.56, 2.74] o Post-1980: [2.18, 5.48] Windows: hypothetical window • U-value of glazing (W/m^2-K): o Pre-1980: [3.53, 5.84] o Post-1980: [2.96, 5.84] • SHGC of glazing (unitless): o Pre-1980: [0.41, 0.54] o Post-1980: [0.25, 0.62]	M2, M4
Plug and process loads	2.5 W/m^2 for the whole building	M2
Occupant density	7.00 m^2/person for meeting area 23.22 m^2/person for other area	M2
Lighting power density	10.00 W/m^2 for meeting area 15.10 W/m^2 for other area	M3
Infiltration rate	0.00027 m/s for the whole building (Flow per exterior surface area)	M3
Ventilation requirement	0.0094 m^3/s-person for the whole building	M4
HVAC system	Cooling: packaged A/C units (Rated COP: 3.27) Heating: furnaces (Efficiency: pre-1980: 0.78, post-1980: 0.8)	M1, M4
Water heating equipment	Natural gas centralized water heater	M1, M4

[1] *The main data sources consist of:*
M1: EIA [28];
M2: EIA [28], Griffith, et al. [37], Winiarski, et al. [38];
M3: Griffith, et al. [37], Winiarski, et al. [38], Deru, et al. [25], Terrill, et al. [30], Terrill and Rasmussen [32];
M4: DOE [13], NREL [23].

3.2. Evaluation

It is essential to evaluate the performance of prototypical building energy models by using the energy data of building samples with the similar weather conditions. ASHRAE classifies the U.S. into 15 climate zones [44, 45], which are used to select the 15 typical cities; however, since the 2003 CBECS divides the U.S. into 5 climate zones [46], a method is required correlate these different zone identifications. To accomplish this, the 15 typical cities are put into the 2003 CBECS Climate Zones based on the cooling degree day 65°F

(CDD65) and heating degree day 65ºF (HDD65). Equations (1) and (2) express the method to calculate CDD65 and HDD65:

$$CDD65 = \sum_{Day=1}^{365} \left(\frac{1}{24} \sum_{hr=1}^{24} T_{hr} - 65 \right)^{+} \tag{1}$$

where T_{hr} is the ambient temperature in ºF at a given hour in a day, and the $^{+}$ means that only the days with positive values for $\left(\sum_{hr=1}^{24} T_{hr} - 65\right)$ are included in the annual summation.

$$HDD65 = \sum_{Day=1}^{365} \left(65 - \frac{1}{24} \sum_{hr=1}^{24} T_{hr} \right)^{+} \tag{2}$$

where, similarly to CCD65, the $^{+}$ means that only the days with positive values for $\left(65 - \sum_{hr=1}^{24} T_{hr}\right)$ are included in the annual summation.

To allocate the 15 typical cities across the 5 climate zones available in the 2003 CBECS dataset, the 2003 historical weather files of the typical cities are used to identify CDD65 and HDD65. Figure 7 shows the location distribution of typical cities and building samples in the 2003 CBECS.

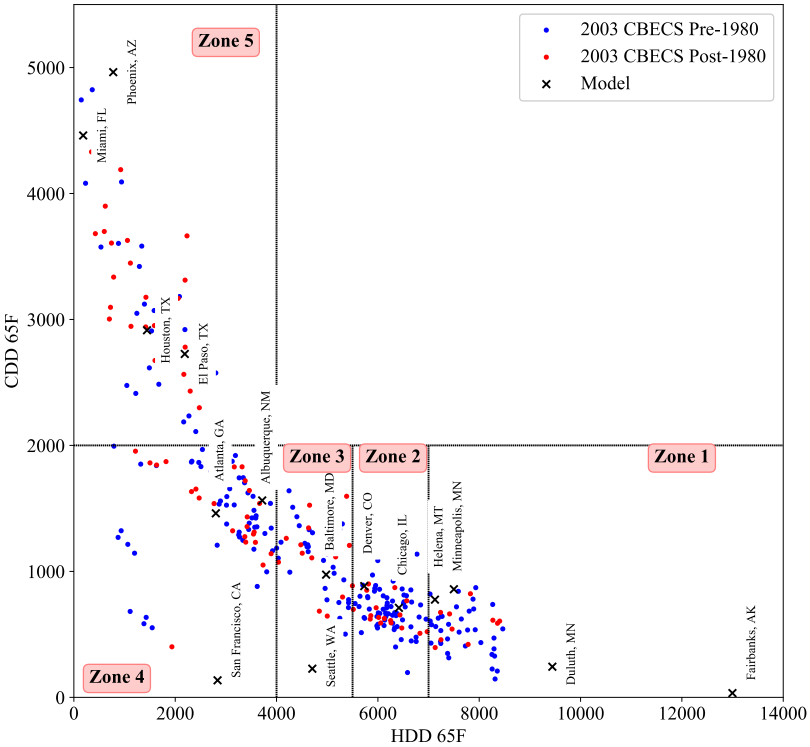


Figure 7. Location distribution of building samples in CBECS climate zones and prototypical building energy models

Due to limitations in available survey data, the survey values available do not always accurately represent the required model cities. Figure 7 shows that the most building samples in the 2003 CBECS are located in areas with HDD65 less than 9,000, and there is a lack of building samples in locations over 9,000 HDD65. However, two model cities, Duluth, MN and Fairbank, AK, have HDD65 over 9,000. Thus, we can expect that the building energy models in 2003 CBECS Climate Zone 1 will have higher energy consumption for heating than the building samples. Similarly, the CDD65 of San Francisco, CA is far lower than the median value of building samples in the 2003 CBECS Climate Zone 4, and the CDD65 of Seattle, WA is lower than median value in the 2003 CBECS Climate Zone 3. Because of this, the models in the San Francisco, CA and Seattle, WA probably consume less energy per area for cooling compared to the building sample data. After calibrating the building energy models, the site EUIs of models are compared with the EUIs of building samples for each climate zone. Figure 8 shows the site EUIs of the prototypical building energy models and the building samples in the 2003 CBECS.

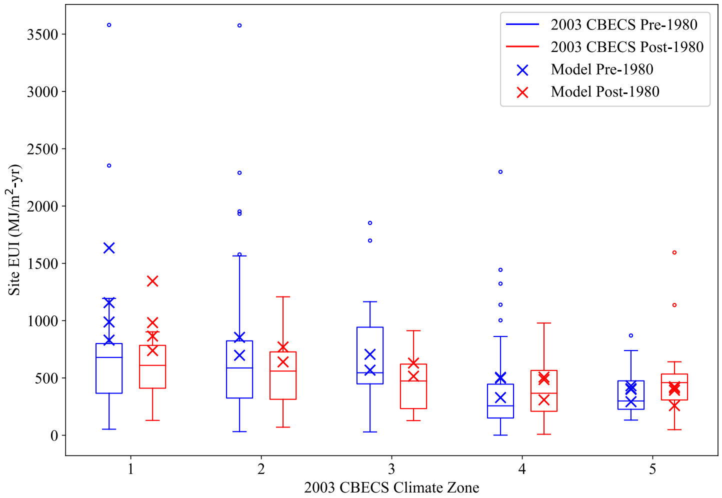


Figure 8. Site EUIs of building samples and prototypical building energy models

While the site EUIs of the prototypical building energy models are mainly in the 25th~75th percentiles of building samples' site EUIs (Figure 8), some discrepancies between model and sample EUIs exist due to misalignment in locations available and low sample sizes in some categories. Typical cities in the 2003 CBECS Climate Zone 1 have higher HDD65 than the locations of most building samples; as a result, the models in these cities consume more energy per area for heating, and the site EUIs of these models will also be higher than the building samples in this climate zone. In addition to misalignments such as this, some discrepancies between the model and building sample EUIs are caused by low sample sizes. The total number of both pre-1980 and post-1980 building samples in the 2003 CBECS is around 300; however, the number of building samples is insufficient for some climate zones and vintages. For example, only 14 post-1980 building samples are in 2003 CBECS Climate Zone 3. The median site EUI is easily affected by individual building samples when there are insufficient samples. To address these limitations and avoid overfitting, we compare the energy performance of prototypical building energy models to the building samples from the CBECS data using engineering judgements.

Table 5 summarizes the performance metrics for select cities to exemplify how we use engineering judgement to evaluate the calibrated typical building models. These selected cities demonstrate median and extreme cases when comparing the typical models and CBECS sample buildings. As can be seen in Figure 7, Houston has average CDD65 and HDD65 among the building samples in the 2003 CBECS Climate Zone 5. As such, pre-1980 and post-1980 religious worship building models in Houston have similar EUIs for cooling and heating compared to the survey median data, as shown in Table 5. Conversely, Phoenix has higher cooling EUIs compared to the survey data. This difference is due to the higher CDD65 in Phoenix than the median level of building samples in the 2003 CBECS Climate Zone 5. Thus, the Phoenix prototypical building energy model is qualified after being calibrated. Another example is that the models in Fairbanks have higher HDD65 than the survey buildings, as can be seen in Figure 7; both pre-1980 and post-1980 models have higher EUIs for heating compared to the corresponding median empirical EUIs.

Repeating this process for all 15 typical cities, we confirm that the calibrated building energy models meet the criteria based on engineering judgement. Therefore, the developed models of existing U.S. religious worship buildings are good representations of prototypical building energy models. However, we note that due to the limited number of building samples, we need to avoid overfitting and accept large variation between the survey and simulation data.

Table 5. Performance evaluation of prototypical building energy models for select cities

Typical City	**2003 CBECS Climate Zone**	**Vintage (Pre/Post)**	**Criteria[1]**	**Model [2] (MJ/m^2-yr)**		**Survey[2,3] (MJ/m^2-yr)**			**Meet the Criteria (Y/N)**
				Cooling	**Heating**	**Cooling**	**Heating**	**# Samples**	
Houston	5	Pre	Both	70.82	27.12	69.99	20.21	25	Y
Phoenix	5	Pre	Cooling	132.98*		69.99		25	Y
San Francisco	4	Pre	Cooling	4.52		39.11*		56	Y
Seattle	3	Pre	Cooling	6.81		12.35*		34	Y
Denver	2	Pre	Both	30.81	186.41	4.70	294.39	40	Y
Duluth	1	Pre	Heating		845.95*		158.48	37	Y
Fairbanks	1	Pre	Heating		1291.55*		158.48	37	Y
Houston	5	Post	Both	67.04	28.73	88.84	16.21	31	Y
Phoenix	5	Post	Cooling	131.27*		88.84		31	Y
San Francisco	4	Post	Cooling	3.39		34.45*		22	Y
Seattle	3	Post	Cooling	4.96		27.82*		14	Y
Denver	2	Post	Both	26.03	168.14	11.80	378.87	33	Y
Duluth	1	Post	Heating		698.50*		426.88	10	Y
Fairbanks	1	Post	Heating		1051.45*		426.88	10	Y

[1] *The criteria listed indicates which EUI is being compared (Cooling or Heating).*

[2] *The asterisks indicate which EUI is larger between the Model and Survey.*

[3] *EUIs in the survey columns are the median empirical EUIs for cooling and heating.*

4. Case Study for Applications: Energy Saving Potential Analysis

The prototypical building energy models have various applications such as building energy saving potential analysis, building design goal setting, building energy market evaluation, and building energy policy evaluation. This section uses the models of pre-1980 U.S. religious worship buildings in ASHRAE Climate Zone 2A, 5A, and 8 to illustrate how to conduct building energy-related analyses by using the prototypical building energy models. Six energy efficiency measures (EEMs) are selected to analysis building energy saving potentials of the three models.

4.1. Selection of EEMs

Glazer [47] described 30 EEMs that were used in the analysis of maximum technically achievable energy targets for commercial buildings. Based on the EEMs identified by Glazer [47], six EEMs are selected to analyze the energy saving potentials of existing U.S. religious worship buildings. The data in several papers, reports, and standards like Glazer [5] and ASHRAE [17] is used to determine the values of EEMs. Table 6 lists the values of six EEMs.

The first three EEMs optimize the envelopes of the building energy models. ASHRAE Standard 90.1-2013 provides the minimum requirements for insulation R-values of exterior walls and roof, and the requirements for window U-values and SHGCs for each ASHRAE Climate Zone [17]. With these requirements, the energy performance of the models is improved. Moreover, two additional options for higher insulation R-values are adopted for exterior walls (EEM1) and roof (EEM2). In EEM4, the lighting fixtures are replaced by high-efficacy LED fixtures, resulting in a lower lighting power density. Lastly, EEM5 and EEM6 substitute the existing HVAC system for a new HVAC system with a high-efficiency cooling coil and a natural gas burner.

Table 6. Descriptions of selected energy efficiency measures

No.	Selected EEM	Description
EEM1	Optimal Exterior Walls Insulation Level	1. Minimum requirements in ASHRAE Standard 90.1-2013 2. 20% more insulation than minimum requirements 3. 50% more insulation than minimum requirements
EEM2	Optimal Roof Insulation Level	1. Minimum requirements in ASHRAE Standard 90.1-2013 2. 20% more insulation than minimum requirements 3. 50% more insulation than minimum requirements
EEM3	Optimal Choice of Vertical Fenestration Construction	Requirements in ASHRAE Standard 90.1-2013
EEM4	High Performance Lighting (LED)	Lighting power density is 8.6 W/m^2
EEM5	High-Efficiency Cooling Coil	The rated COP is 4.4
EEM6	High-Efficiency Burner	The efficiency of burner is 0.82

4.2. Results Analysis

Based on the selected prototypical building energy models and EEMs, energy saving potentials are analyzed. The analysis consists of three aspects – energy savings of individual EEMs, the interactive impacts of two EEMs, and the energy saving potentials by using different number of EEMs. First, to analyze the impact of individual EEMs on the energy consumption, only one EEM is applied in each time. Figure 9 shows the site EUIs of new models and the energy saving with respect to baseline models. More specifically, the upper plot shows the site EUIs of the building energy models with individual EEMs, the middle plot displays the site energy savings compared with the baseline models, and the lower plot exhibits the percentages of energy savings based on the baseline models.

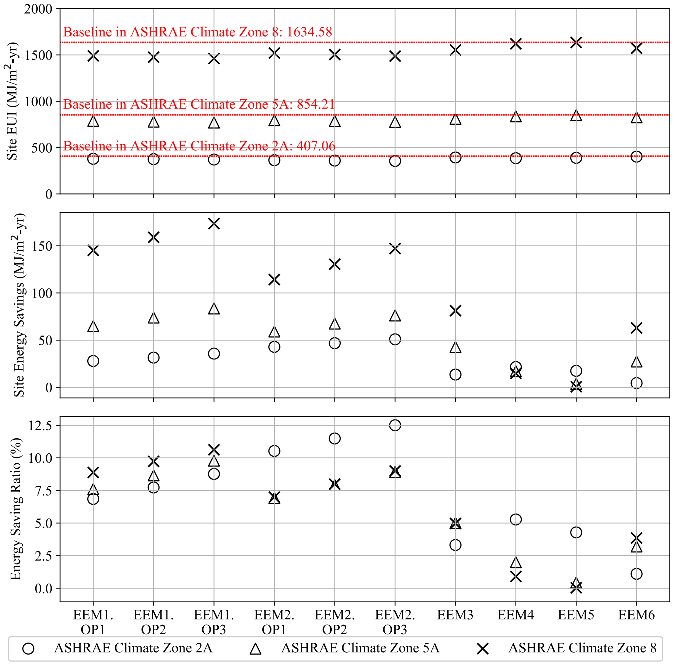


Figure 9. Energy saving potentials for individual EEMs

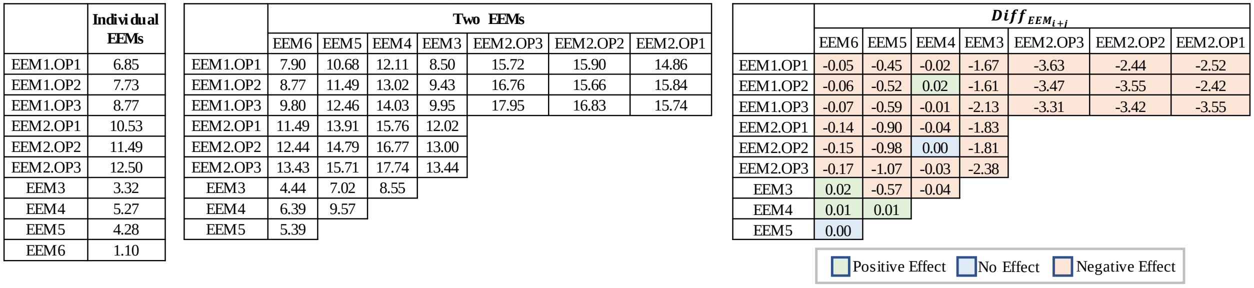
Figure 9 indicates that the site EUIs of baseline models in ASHRAE Climate Zone 2A, 5A, and 8 are 407.06 MJ/m^2-yr, 854.21 MJ/m^2-yr, and 1,634.58 MJ/m^2-yr, respectively. All six EEMs reduce energy consumption of pre-1980 U.S. religious worship buildings in the three climate zones. The maximum energy savings for individual EEMs are around 50 MJ/m^2-yr, 80 MJ/m^2-yr, and 175 MJ/m^2-yr, respectively, in ASHRAE Climate Zone 2A, 5A, and 8. Increasing the insulation R-value of walls and roofs is the first option to reduce the energy consumption in all the three climate zones. In Climate Zone 2A, improving roof insulation saves more energy than increasing the insulation R-value of exterior walls. In Climate Zone 5A, EEM1 and EEM2 have similar contributions to the energy saving. In Climate Zone 8, improving the insulation R-value of exterior walls is most useful to save energy consumption. Besides adding insulation to exterior walls and roof, optimal choice of vertical fenestration construction can also reduce around 4% energy consumption. Moreover, some EEMs perform differently in hot and cold locations. For example, high-performance LED lighting and high-efficiency cooling coils save more energy in hot locations while high-efficiency burners save more energy in cold locations.

EEM combinations often have interactive effects impacting energy savings. If it is a positive effect, it is beneficial to apply both EEMs in a building and total energy saved will be more than the sum of the savings due to each EEM individually. If it is a negative effect, users need to be careful to use the two EEMs in the same building. Figure 10 shows interactive effects of two EEMs. The three prototypical building energy models are used as baseline models. In each subfigure, the data in the left table is the percentage of energy saving by using individual EEMs. The data in the middle table is the percentage of energy saving by using two EEMs. The data in the right table is the difference between the combined effects of two EEMs and the sum of the effects of individual EEMs, which is calculated by:

$$Diff_{EEM_{i+j}} = EEM_{i+j} - EEM_i - EEM_j, i \neq j \text{ and } i, j = 1,2, \dots ,11 \quad (3)$$

where i and j are the number of the EEM for each option; EEM is the percentage of energy saving. Thus, EEM_{i+j} is the percentage of energy saving by using ith and jth EEMs, and EEM_i or EEM_j is the percentage of energy saving by only using ith or jth EEM. If the $Diff_{EEM_{i+j}}$ is positive, it means that the two EEMs have a positive effect on energy saving; a negative value means a negative effect; and zero is no interactive effect.

(a) Percentage of Energy Saving (%) in ASHRAE Climate Zone 2A



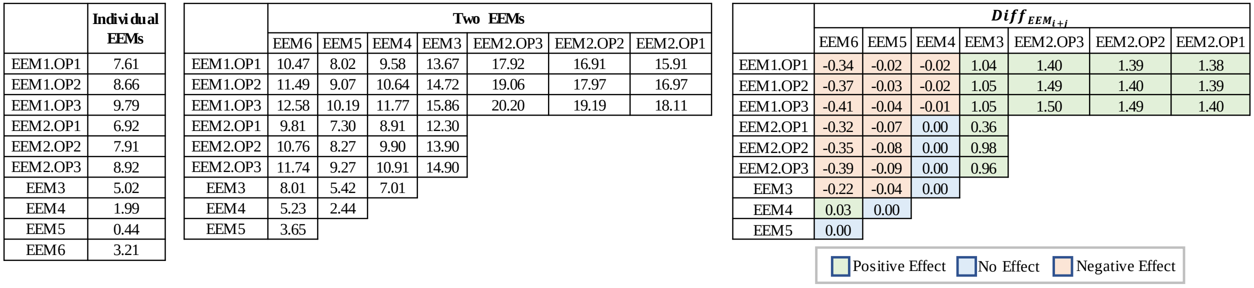
	Individual EEMs
EEM1.OP1	6.85
EEM1.OP2	7.73
EEM1.OP3	8.77
EEM2.OP1	10.53
EEM2.OP2	11.49
EEM2.OP3	12.50
EEM3	3.32
EEM4	5.27
EEM5	4.28
EEM6	1.10

	Two EEMs						
	EEM6	EEM5	EEM4	EEM3	EEM2.OP3	EEM2.OP2	EEM2.OP1
EEM1.OP1	7.90	10.68	12.11	8.50	15.72	15.90	14.86
EEM1.OP2	8.77	11.49	13.02	9.43	16.76	15.66	15.84
EEM1.OP3	9.80	12.46	14.03	9.95	17.95	16.83	15.74
EEM2.OP1	11.49	13.91	15.76	12.02			
EEM2.OP2	12.44	14.79	16.77	13.00			
EEM2.OP3	13.43	15.71	17.74	13.44			
EEM3	4.44	7.02	8.55				
EEM4	6.39	9.57					
EEM5	5.39						

	$Diff_{EEM_{i+j}}$						
	EEM6	EEM5	EEM4	EEM3	EEM2.OP3	EEM2.OP2	EEM2.OP1
EEM1.OP1	-0.05	-0.45	-0.02	-1.67	-3.63	-2.44	-2.52
EEM1.OP2	-0.06	-0.52	0.02	-1.61	-3.47	-3.55	-2.42
EEM1.OP3	-0.07	-0.59	-0.01	-2.13	-3.31	-3.42	-3.55
EEM2.OP1	-0.14	-0.90	-0.04	-1.83			
EEM2.OP2	-0.15	-0.98	0.00	-1.81			
EEM2.OP3	-0.17	-1.07	-0.03	-2.38			
EEM3	0.02	-0.57	-0.04				
EEM4	0.01	0.01					
EEM5	0.00						

🟩 Positive Effect 🟦 No Effect 🟧 Negative Effect

(b) Percentage of Energy Saving (%) in ASHRAE Climate Zone 5A



	Individual EEMs
EEM1.OP1	7.61
EEM1.OP2	8.66
EEM1.OP3	9.79
EEM2.OP1	6.92
EEM2.OP2	7.91
EEM2.OP3	8.92
EEM3	5.02
EEM4	1.99
EEM5	0.44
EEM6	3.21

	Two EEMs						
	EEM6	EEM5	EEM4	EEM3	EEM2.OP3	EEM2.OP2	EEM2.OP1
EEM1.OP1	10.47	8.02	9.58	13.67	17.92	16.91	15.91
EEM1.OP2	11.49	9.07	10.64	14.72	19.06	17.97	16.97
EEM1.OP3	12.58	10.19	11.77	15.86	20.20	19.19	18.11
EEM2.OP1	9.81	7.30	8.91	12.30			
EEM2.OP2	10.76	8.27	9.90	13.90			
EEM2.OP3	11.74	9.27	10.91	14.90			
EEM3	8.01	5.42	7.01				
EEM4	5.23	2.44					
EEM5	3.65						

	$Diff_{EEM_{i+j}}$						
	EEM6	EEM5	EEM4	EEM3	EEM2.OP3	EEM2.OP2	EEM2.OP1
EEM1.OP1	-0.34	-0.02	-0.02	1.04	1.40	1.39	1.38
EEM1.OP2	-0.37	-0.03	-0.02	1.05	1.49	1.40	1.39
EEM1.OP3	-0.41	-0.04	-0.01	1.05	1.50	1.49	1.40
EEM2.OP1	-0.32	-0.07	0.00	0.36			
EEM2.OP2	-0.35	-0.08	0.00	0.98			
EEM2.OP3	-0.39	-0.09	0.00	0.96			
EEM3	-0.22	-0.04	0.00				
EEM4	0.03	0.00					
EEM5	0.00						

🟩 Positive Effect 🟦 No Effect 🟧 Negative Effect

(c) Percentage of Energy Saving (%) in ASHRAE Climate Zone 8

	Individual EEMs
EEM1.OP1	8.88
EEM1.OP2	9.73
EEM1.OP3	10.62
EEM2.OP1	6.99
EEM2.OP2	7.98
EEM2.OP3	9.00
EEM3	4.97
EEM4	0.90
EEM5	0.03
EEM6	3.85

	Two EEMs						
	EEM6	EEM5	EEM4	EEM3	EEM2.OP3	EEM2.OP2	EEM2.OP1
EEM1.OP1	12.39	8.91	9.76	13.93	17.99	16.97	15.95
EEM1.OP2	13.20	9.75	10.61	14.79	18.85	17.82	16.81
EEM1.OP3	14.05	10.64	11.50	15.69	19.71	18.72	17.71
EEM2.OP1	10.56	7.01	7.88	12.00			
EEM2.OP2	11.52	8.01	8.87	13.01			
EEM2.OP3	12.50	9.02	9.88	14.02			
EEM3	8.62	5.00	5.86				
EEM4	4.78	0.94					
EEM5	3.89						

	$Diff_{EEM_{i+j}}$						
	EEM6	EEM5	EEM4	EEM3	EEM2.OP3	EEM2.OP2	EEM2.OP1
EEM1.OP1	-0.35	-0.01	-0.02	0.08	0.11	0.10	0.09
EEM1.OP2	-0.38	-0.01	-0.02	0.09	0.12	0.11	0.10
EEM1.OP3	-0.42	-0.01	-0.02	0.10	0.10	0.12	0.11
EEM2.OP1	-0.28	-0.01	-0.01	0.05			
EEM2.OP2	-0.32	-0.01	-0.02	0.05			
EEM2.OP3	-0.36	-0.01	-0.02	0.06			
EEM3	-0.20	0.00	-0.01				
EEM4	0.02	0.00					
EEM5	0.00						

🟩 Positive Effect 🟦 No Effect 🟧 Negative Effect

Figure 10. Interactive effects of two EEMs on energy savings

Figure 10 shows that the energy savings of pre-1980 religious worship buildings could have positive or negative interactive effects by using two EEMs. For instance, improving insulation of opaque envelopes will counteract part of energy savings gained by using higher-efficiency cooling and heating systems, while the high-performance lighting and high-efficiency burner assist each other to save more energy. Further, the interactive effects could be different in various climates. For example, improving the insulation R-values of exterior walls and roof has a positive effect in cold areas (zone 5A and 8) while it has a negative effect in hot areas. Moreover, some EEMs have no interactive effects on energy savings, such as heating and cooling systems in both hot (zone 2A) and cold areas (zone 5A and 8).

Generally, when various EEMs are used in one building, the energy consumption will be reduced even if the energy savings are usually lower than the sum of energy savings by using individual EEMs. The ranges of energy savings by using different numbers of EEMs are discussed. Figure 11 shows the ranges of energy saving ratios with different number of EEMs. The upper horizontal line of each violin plot means the maximum value; the lower line is the minimum value; the middle one is the median value. The outer shape represents all possible results, with thickness indicating how common.

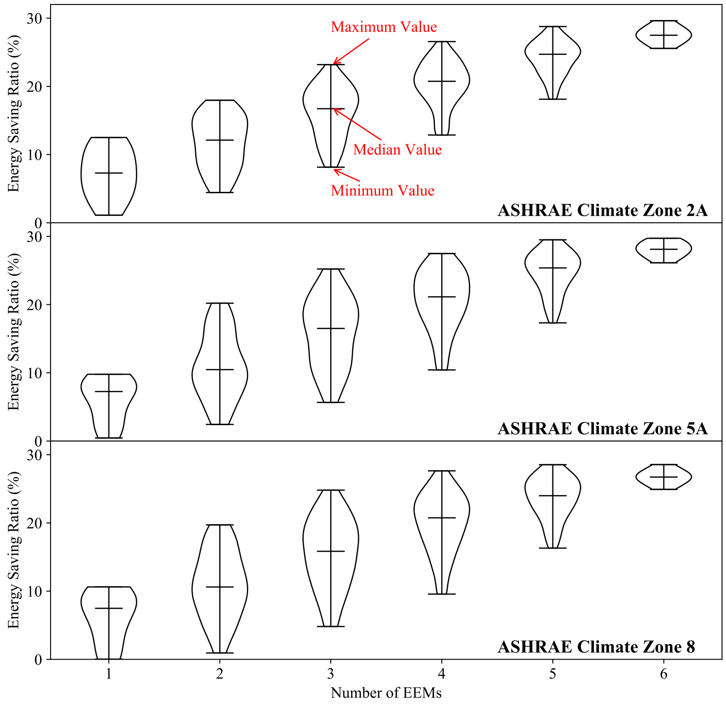


Figure 11. Energy saving potentials with different number of EEMs

Figure 11 indicates that when the number of EEMs is increased, the maximum, median, and minimum values of energy saving ratios become higher. The maximum value for each violin plot is the most important index, which provides the energy saving potentials by using a certain number of EEMs. Based on Figure 11, the energy saving potentials by using the six EEMs in the three climate zones are all closed to 30%. Moreover, the maximum values of energy saving ratio by using five EEMs are similar to the values by using all the six EEMs in the three climate zones. Thus, it is recommended to use five EEMs to reach approximately 30% energy savings.

5. Conclusion

The prototypical building energy models provide a starting point for various building energy-related analyses. This paper proposes a systematic methodology to create the prototypical building energy models for existing buildings, which is applicable for most building types in various locations. In this methodology, six steps are required: identify the model inputs, collect the related data, clean the data, convert the data into model inputs, conduct simulation, and calibrate the building models. The data is collected from databases, literature, and existing building energy models for other building types. Then the data can be systematically cleaned and converted into model inputs. It is necessary to calibrate the models based on survey or measured energy data. This paper introduces model calibration by using meta-models, which provides means to calibrate results much faster than using building energy simulation programs.

Then, to implement the methodology proposed in this paper, 30 prototypical building energy models of existing U.S. religious worship buildings are created. Energy data in the 2003 CBECS is used to evaluate the performance of the prototypical building energy models of existing U.S. religious worship buildings. The models are qualified to be used as prototypical building energy models. To illustrate how to apply the models, three pre-1980 models of religious worship buildings and six EEMs are selected to analyze their energy saving potentials. Three aspects are analyzed – energy savings of individual EEMs, the interactive impacts of two EEMs, and the energy saving potentials by using different number of EEMs. The results indicated that the interactions between multiple EEMs can have both positive and negative contributions towards building energy consumption; thus, users need to consider these interactive effects when selecting different EEMs to save building energy. Furthermore, the results of this case study indicated that pre-1980 U.S. religious worship buildings can save approximately 30% energy saving potentials by using the six EEMs in both hot and cold climates. By developing prototypical building models for missing building types such as this, important energy savings can be evaluated and realized.

Acknowledgment

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