Chapter 2
Building Envelope Specification

2.1 Building Envelope

The most basic definition of a building is a man-made structure that isolates the interior from the outdoor environment. The portions of the building that separate the building's interior from the outdoor environment (e.g. walls, roofs, floors) are often referred to as the building envelope. The envelope protects the interior from rain, snow, wind, and excessive heat or cold; helping to make the interior a safe, comfortable, and productive environment for its occupants. Often, a building's interior is conditioned with Heating, Ventilation and Air Conditioning (HVAC) to maximize occupant comfort. There are many important considerations when designing a building envelope. The envelope must be sufficiently strong to support itself. It must effectively keep water or other unwanted environmental materials from damaging the building or its contents. It must be secure enough to keep unwanted pests (or people) out of it. It must be visually appealing. These aspects are all very important and there are numerous texts devoted to each of them. As this book is devoted to building energy modeling our focus will be on the transfer of energy through the building envelope.

2.2 Weather

As noted weather personality Willard Scott once said, "Everyone complains about the weather, but nobody ever seems to do anything about it." It should come as no surprise that weather drives a significant portion of energy transfer into and out of

a building. An office building in Alaska will be subject to very different environmental conditions than an office building in Florida. It is also well known that, while the actual weather conditions occurring at any given time are difficult to predict, a location's general climate may be described in a meaningful way.

Because weather varies from year to year, a methodology for combining measured weather data from multiple years into what is referred to as a "Typical" Meteorological Year (TMY) has been developed.[1] TMY data attempts to represent both the annual average weather as well as a range of weather extremes that a given location experiences. This makes TMY data more useful in predicting future energy use than Actual Meteorological Year (AMY) data for a particular year. TMY data for many locations may be downloaded in EnergyPlus Weather (EPW) format from https://energyplus.net/weather. EPW files are a key input for any OpenStudio Model, representing the ambient conditions a building is exposed to.

The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) categorizes a location's climate into one of several climate zones based on TMY data for that location.[2] ASHRAE climate zones are codified with a climate zone number ranging from 0 for extremely hot through 8 for sub-arctic along with a sub-type letter: **A** for Moist, **B** for Dry, and **C** for Marine. Each location's climate zone number is a function of Heating Degree Days (HDD) and Cooling Degree Days (CDD) calculated from TMY data for that location.

HDD are calculated by summing the difference between a base temperature (typically 65 °F) and the average hourly outdoor air temperature over an entire year, discarding any hours for which the outdoor air temperature is greater than the base temperature. Assuming that a typical building requires no mechanical heating when outdoor air temperatures are above the base temperature this gives a rough metric related to how much heating energy will be required. CDD are calculated in a similar manner with a different base temperature for cooling (typically 50 °F).

$$HDD = \sum_{i=1}^{8760} \frac{MAX\left(T_{base\ heating} - T_i, 0\right)}{24}$$

$$CDD = \sum_{i=1}^{8760} \frac{MAX\left(T_i - T_{base\ cooling}, 0\right)}{24}$$

The climate zone subtype is related to the location's humidity and is a function of the average annual rainfall as well as the outdoor air temperatures. Using these definitions, the climate zone designation for all locations in the US is illustrated in Fig. 2.1. A representative city has been chosen for each climate zone, and it is often assumed that TMY data for these cities are representative of the entire climate zone when performing large-scale analyses involving prototypical buildings.

A location's climate zone designation is useful for understanding the temperatures that a building experiences. However, there are many more aspects to a loca-
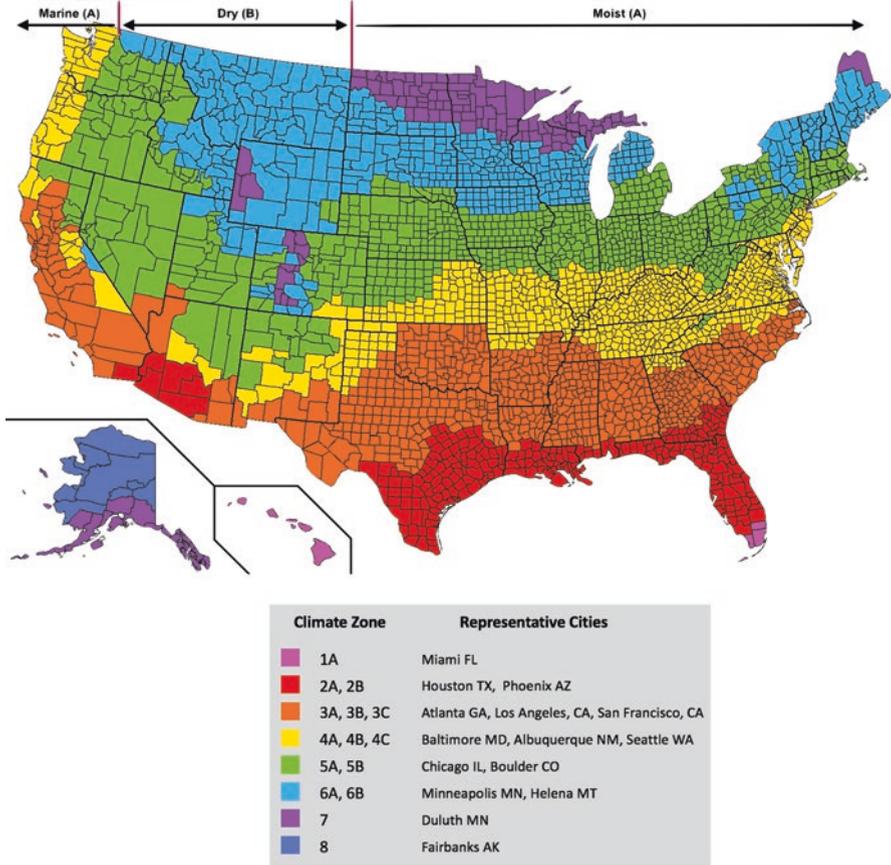
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[1] Wilcox and Marion (2008).

[2] ANSI/ASHRAE (2013).

Climate Zone		Representative Cities
	1A	Miami FL
	2A, 2B	Houston TX, Phoenix AZ
	3A, 3B, 3C	Atlanta GA, Los Angeles, CA, San Francisco, CA
	4A, 4B, 4C	Baltimore MD, Albuquerque NM, Seattle WA
	5A, 5B	Chicago IL, Boulder CO
	6A, 6B	Minneapolis MN, Helena MT
	7	Duluth MN
	8	Fairbanks AK

Fig. 2.1 Climate zone locations in U.S

tion's environment including altitude, wind speed and direction, psychrometric conditions, and solar radiation incident on the surface of the Earth (solar insolation) that are often captured in weather data files. Tools like DView (included with OpenStudio), Climate Consultant from UCLA (Fig. 2.2), Elements from Big Ladder Software, or Ladybug for Grasshopper are useful for exploring TMY data for a particular location in detail.

Additional weather information useful for energy modeling is also found in Design Day (DDY) files, which are freely available for many locations at https://energyplus.net/weather. Data in DDY files describe extreme climate conditions expected for a particular location. DDY files are frequently used when sizing HVAC systems since they must be capable of keeping the building comfortable during extreme heating, cooling, humidification, and dehumidification conditions. We shall revisit the topic of design days and HVAC sizing in Chap. 4.
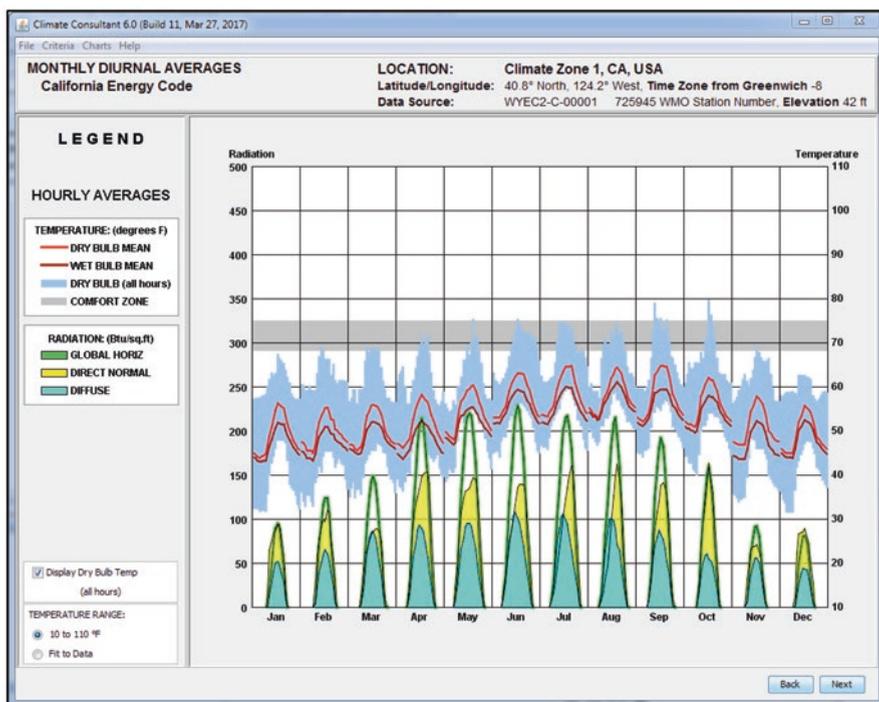
Fig. 2.2 TMY data inspected using climate consultant

2.3   Envelope Geometry and Building Spaces

There are number of ways to develop envelope and interior geometry for an OpenStudio Model. The floor plan editor integrated within the OpenStudio Application may be used to develop a two-dimensional floor plan for each building story (Fig. 2.3). The OpenStudio Plug-In for Trimble SketchUp can also be used to modify detailed building geometry in three dimensions (Fig. 2.4). Third party Computer Aided Drafting (CAD) tools capable of exporting geometry in Green Building Extensible Markup Language (gbXML) format may also be used since OpenStudio can import gbXML files. Finally, the OpenStudio API, discussed in Chap. 9, may be used to procedurally create geometry for an OpenStudio Model. While this book focuses primarily on the free and open source floor plan editor integrated with the OpenStudio Application, the general concepts discussed in this Chapter apply to the geometry of any OpenStudio Model, regardless of the source.

The interior geometry of an OpenStudio Model is composed of distinct (non-overlapping), three-dimensional volumes called Spaces. It is important to note that Spaces are an OpenStudio abstraction not presently shared with EnergyPlus. OpenStudio Spaces are useful for specifying programmatic activities within a building (e.g. Office, Classroom, etc.) and their corresponding energy loads. A shared
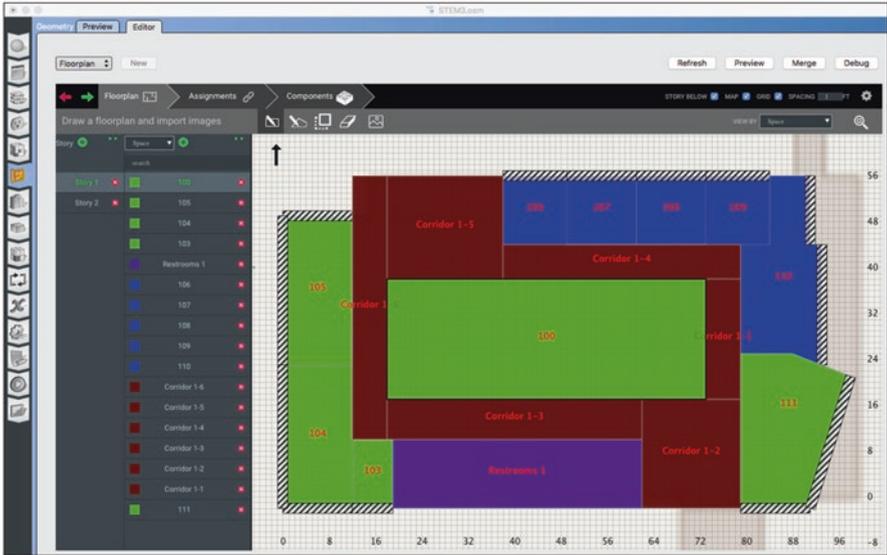
Fig. 2.3 Building envelope drawn with the OpenStudio Application floor plan editor
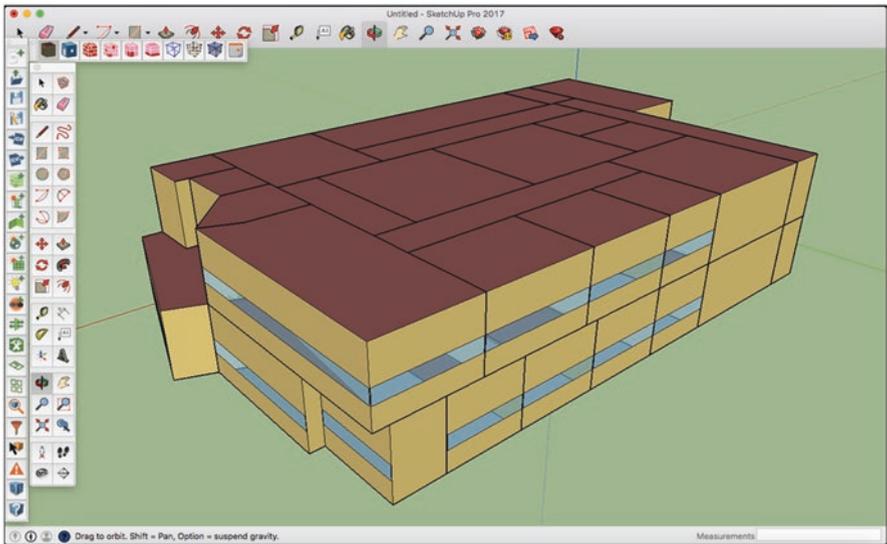

Fig. 2.4 Building envelope drawn using the OpenStudio Plug-In for Trimble SketchUp
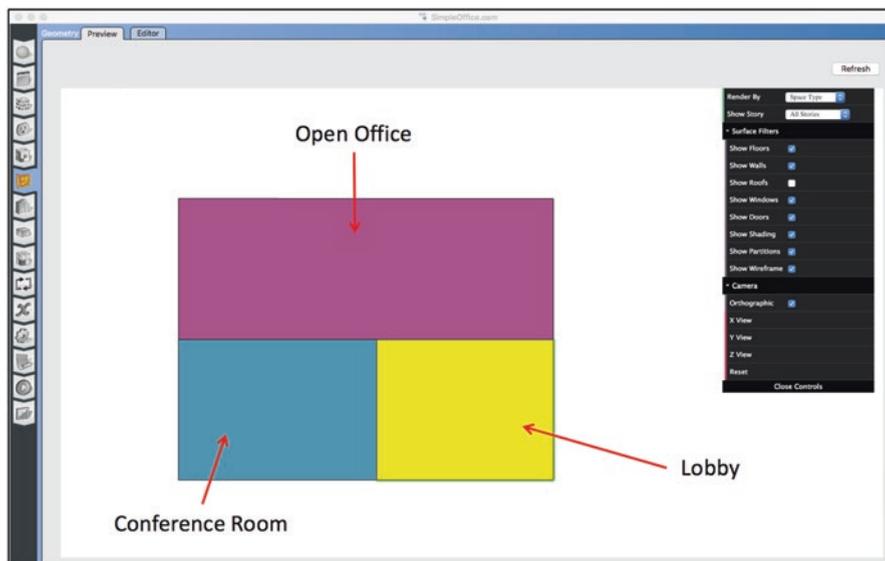
Fig. 2.5 Simple office building with three Spaces and two Space Types on second floor

definition of typical loads and schedules for a specific activity is referred to as an OpenStudio Space Type.[3] Each Space can be assigned a single Space Type. Figure 2.5 illustrates the second floor of a small office building divided into three Spaces which reference two Space Types. Space Types will be discussed in greater detail in Chap. 3.

One or more OpenStudio Spaces may be grouped together to form an OpenStudio Thermal Zone (Fig. 2.6). Thermal Zones are the primary object of simulation in EnergyPlus and will be discussed in Chap. 4. Because Thermal Zones are comprised of Spaces, Space geometry defines the geometry of a Thermal Zone. In the simplest case, an entire building could be treated as a single Thermal Zone consisting of a single Space.

In practice, the division of Spaces and Space Types within a building is generally prescribed by intended use of a given space. On the other hand, selecting building zoning is a far trickier task in terms of both building and energy Model performance. Furthermore, simulation time increases with the number of Thermal Zones and space boundaries so excessive geometry becomes computationally expensive. It is recommended to make Spaces only as small as required to capture the different activities within a building while also supporting proper thermal zoning. Thermal Zones will be revisited in Chap. 4.

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[3] It is worth noting that standards like ASHRAE 90.1 and California Title 24 specify assumptions and minimum performance requirements in the context of prescribed space types. The standardized definition of space types is not simply a useful concept, it is fundamental to the development of building codes and the projects that reference them.
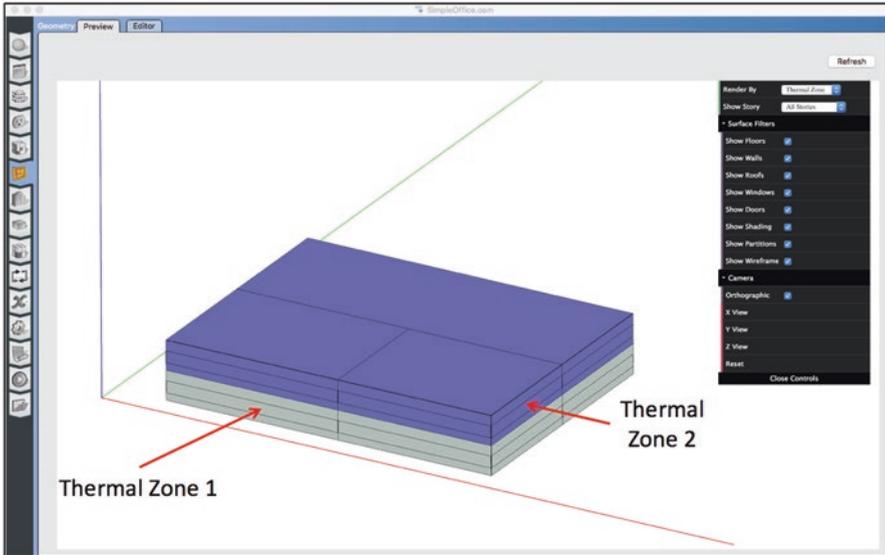
Fig. 2.6 Simple office building with first and second floors zoned separately

2.4 Surfaces

Each Space in an OpenStudio Model is bounded on all sides by a Surface. Each Surface is an infinitely thin, two-dimensional polygon that separates the volume inside a Space from the region outside the Space. The normal vector of a Surface (calculated by tracing the vertices using the right-hand rule) always points out of a Space. The collection of Surfaces associated with a Space defines the total volume of the Space. Omitting a Surface from a Space's boundary (e.g. not fully enclosing a Space) results in incorrect volume and area calculations and should be avoided.

Surfaces play a large role in defining the heat transfer into and out of Spaces and their related Thermal Zones (Fig. 2.7). Modes of heat transfer through a surface are shown in Fig. 2.8. Note that sunlight does not pass directly through the surface into the space. Transparent openings such as windows and skylights must be modeled separately as Sub-Surfaces, which are discussed later in this Chapter. Heat and mass transfer via (unintentional) infiltration is described in Chap. 3 and mechanical ventilation is introduced in Chap. 4.

Because Surfaces are infinitely thin, new modellers commonly wonder how they should describe actual building surfaces, which have non-zero thickness. The authors recommend placing Surfaces on the exterior face of all building surfaces exposed to outdoor or ground boundary conditions as shown in Fig. 2.9. Surfaces should be placed on the centreline of interior building surfaces as shown in Fig. 2.10. This technique ensures that the exterior area exposed to the outdoor environment is fully captured. Assuming that the envelope surface area is a more significant driver
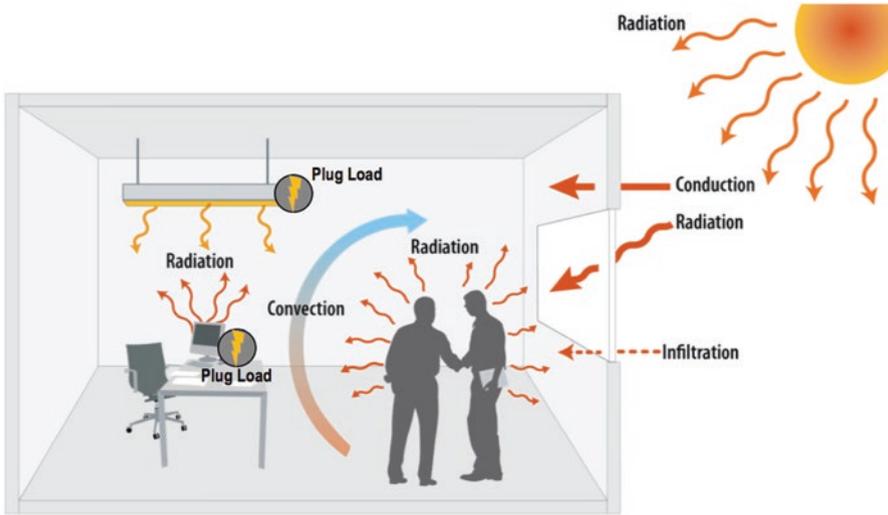
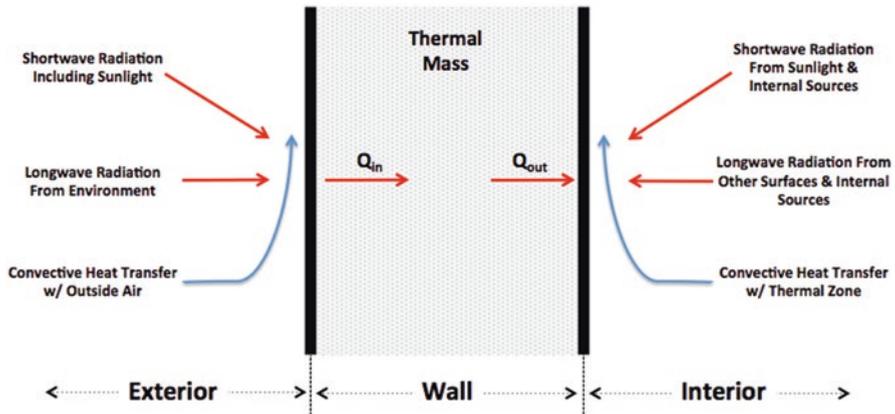**Fig. 2.7** Heat transfer mechanisms within a space. (Credit Marjorie Schott)

Fig. 2.8 Interior and exterior surface heat transfer

of building thermal performance than interior heat transfer effect, this can improve thermal model fidelity. It should be noted that this approach does artificially extend floor Surfaces into wall cavities, yielding a floor area that is somewhat larger than the usable area. Additionally, the calculated air volume derived from the bounding Surfaces will include the volume of air inside the wall and ceiling cavities. For larger buildings, these effects will be minimal.

Each individual Surface may be classified as a wall, floor, or roof/ceiling. These classifications allow for calculations such as the floor area of a Space or total exterior wall area. Each Surface also specifies the outside boundary condition that is
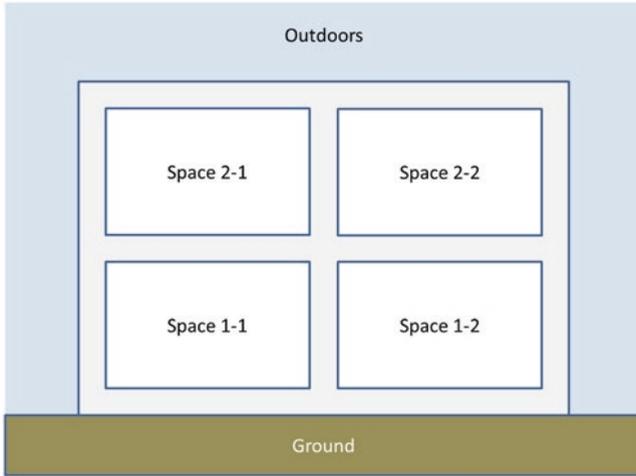
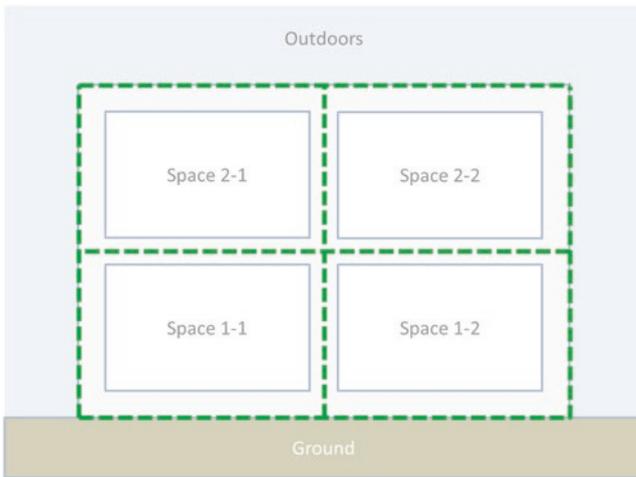**Fig. 2.9** Two story building with building surface thickness shown

Fig. 2.10 Recommended placement of OpenStudio surfaces to define Spaces

applied to that Surface. Outdoor Surfaces are exposed to the exterior environment typically including outdoor air temperature and solar radiation. Ground Surfaces are in contact with the ground domain and are not typically exposed to the outdoor air temperature or solar radiation. Interior Surfaces are in contact with a Surface in another space and are exposed to the indoor conditions of the other Space instead of the outdoor environment. A special Adiabatic Surface type does not allow any heat transfer by conduction into a Space and can be useful in some advanced applications.
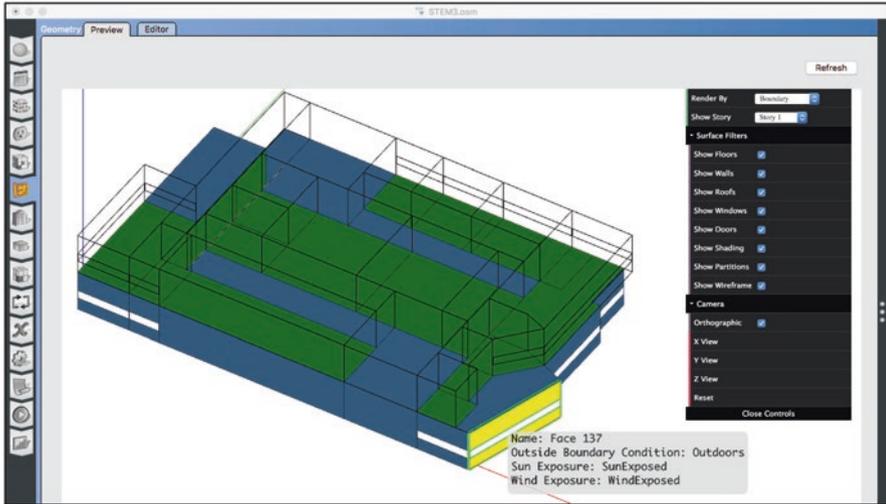
Fig. 2.11 Inspecting geometry boundary conditions in the OpenStudio Application

It is important to check that all Surfaces have the proper boundary conditions. The Geometry (▣) Tab in the Application shown in Fig. 2.11 may be used for this purpose. It is recommended to check for correct boundary conditions on all exterior surfaces first before hiding roof geometry and proceeding story by story to check that all interior surfaces have the correct boundary conditions. A Surface's boundary condition –not its location- dictates how it will treated by the simulation engine. Matched interior Surfaces should show up in green, whereas exteriors will appear blue and ground contact Surfaces render in light brown. Incorrect assignments will fail to simulate or produce unexpected results.

2.5 Constructions

Each Surface has an associated Construction. A Construction is comprised of layers of Materials as shown in Fig. 2.12. Materials are ordered from the exterior to interior Surface. Each Material layer has properties related to its heat transfer characteristics. Composite layers, such as a wood stud wall with batt insulation, are modelled with the Material properties of the overall assembly. Libraries of common construction material and assembly properties are distributed with OpenStudio. Additional Materials can also be found in the Building Component Library. Accessing materials from these sources will be discussed further in this Chapter's tutorial section. During simulation, the temperature on both sides of each Material layer is computed. Heat transfer through each Material is a function of the temperature difference across the Material, the Material's thermal resistance, and the Material's capacity to store thermal energy. This is commonly represented as an equivalent RC circuit model as shown in Fig. 2.13.
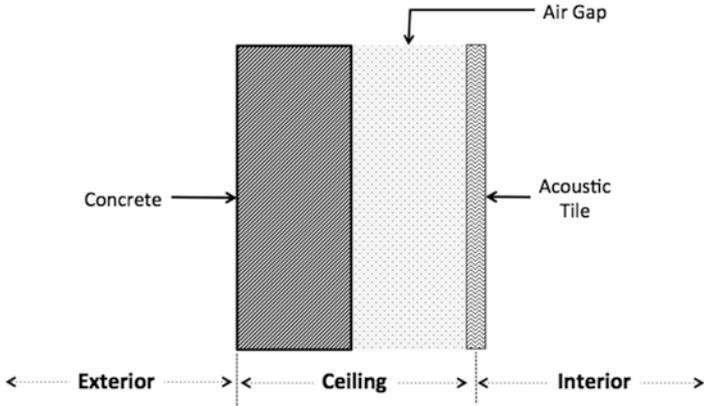
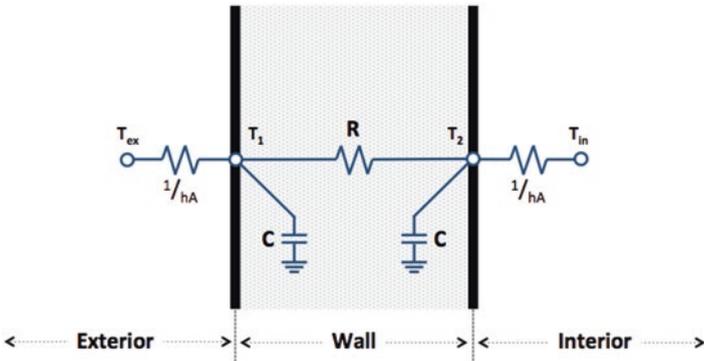**Fig. 2.12** Material layers in a ceiling construction

Fig. 2.13 Equivalent RC network for a construction

Interior Surfaces between adjacent Spaces are represented by Surfaces in each Space that reference one another. By design, these adjacent Surfaces each have Constructions which mirror each other, that is their Material layers are identical but in reverse order. If a Construction is symmetric (e.g. a layer of drywall followed by wood stud wall and another layer of drywall) then both Surfaces may reference the same Construction. This concept is shown in Fig. 2.14.

2.6 Sub-Surfaces

Surfaces may have openings such as doors, windows, and skylights. These Sub-Surfaces are linked to a parent Surface. The Sub-Surface overlaps the parent Surface, and its area is subtracted from the parent's gross area for the purpose of heat
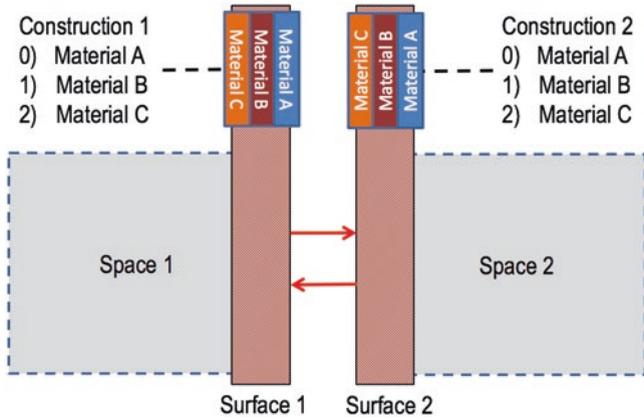
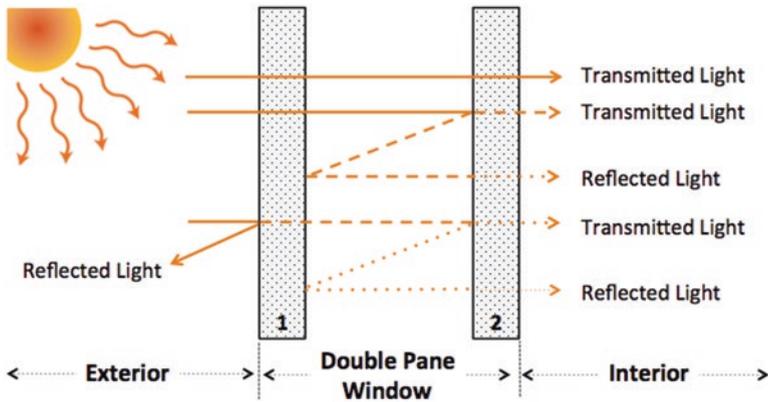**Fig. 2.14** Mirrored constructions for adjacent surfaces

Fig. 2.15 Heat transfer through transparent constructions

transfer. Like Surfaces, Sub-Surfaces also reference related Constructions. Constructions for opaque Sub-Surfaces such as doors may use the same opaque Materials as Surfaces. All Sub-Surfaces must be explicitly modeled. Cutting a hole in a surface or leaving a gap in the space boundary does not result in simulation of air transfer or allow light into the space. Note that solar radiation only passes through transparent Sub-Surfaces like windows or skylights.

Constructions for transparent Sub-Surfaces such as windows or skylights must be made of window Materials such as glass, gas filled voids, or window shading such as blinds or screens. Like opaque Materials, transparent Materials allow heat transfer through conduction as well as heat storage. However, transparent Materials also allow solar radiation to pass through or be reflected back at each layer (Fig. 2.15). Transparent properties are often provided separately for the entire solar radiation spectrum and for the spectrum of visible light.

2.7   Introduction to Data Inheritance in OpenStudio

At this point, many readers may be reeling at the prospect of properly assigning Space Types, Constructions, and Materials subject to the rules and constraints described in previous sections. In truth, creating correct EnergyPlus input files requires significant attention to detail, but fortunately OpenStudio comes to our rescue with a concept known as "data inheritance." Data inheritance is a key feature of object oriented software paradigms, allowing child objects to inherit data from their parents without explicit specification. For example, defining a building type allows OpenStudio to inherit a standard Space Type that is automatically applied to all Spaces within that building. For example, Spaces within a school building automatically inherit a "classroom" Space Type, the most common in schools. Explicit assignment of Space Type to any given Space becomes the exception rather than the rule, saving time and reducing the opportunity for error.

The concept of data inheritance also applies to Constructions and Materials. With OpenStudio, users may specify a top-level Construction Set that will be applied to an entire building. Each Construction Set specifies a standard Construction for a particular type of Surface or Sub-Surface (e.g. walls, roofs, windows, doors). When a Surface or Sub-Surface is queried for its Construction, the Surface first checks if a Construction has been explicitly assigned to it. If not, the Surface or Sub-Surface checks if its associated Space has a Construction set which defines a construction for it. If not, the Space's Building Story Construction Set is checked and finally the Construction Set assigned to the whole building will be checked.

The inheritance process, shown in Fig. 2.16, allows for constructions to be quickly assigned to all surfaces in the Model while also allowing explicit Construction specification for Surfaces, Spaces, or building Stories as needed.

Fig. 2.16 Construction inheritance hierarchy
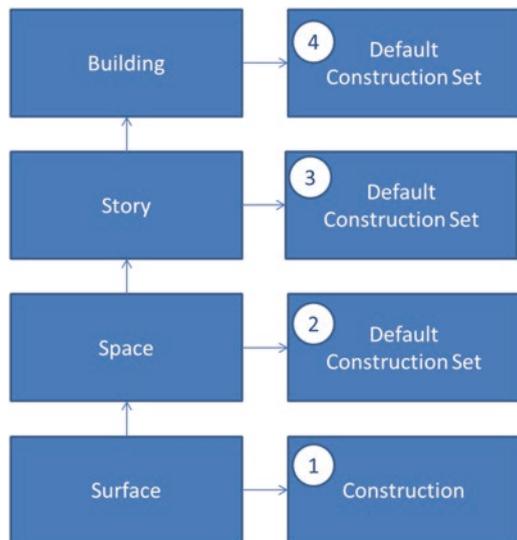
Numbers in this figure represent the relative priority of Construction or Material data that may have been explicitly assigned at any level. For example, a Construction Set that may have been explicitly assigned in a Space will take precedence over any Construction Sets that may have been assigned for the Story or Building. Of course, if the modeler has defined a specific Surface or Sub-Surface construction in a Space that will always be respected.

Typically, Construction Sets contain definitions for all types of Surfaces or Sub-Surfaces. However, Construction Sets may also include partial definitions – e.g. window Constructions, but not wall Constructions. In such cases, the inheritance search process halts as soon as it finds appropriate data. This allows, for example, a Construction Set to specify a particular window Construction to use for one Story of the building while all other Constructions would be inherited from the Building Construction Set.

Data inheritance is a key feature of OpenStudio, and understanding how it works is important for maximizing a modeler's productivity. We will reinforce this concept in Chap. 3 where Space Type inheritance will be discussed in greater detail, but inheritence applies throughout the SDK and we cannot overstate the value of understanding how it works.

2.8 Checkpoint One: Creating an Energy Model with an Unconditioned Envelope

In this first exercise, we will create a simple Model with a single Space and Thermal Zone. The geometry for our first Model shown in Fig. 2.17 comes from ASHRAE Standard 140 test case 600. ASHRAE Standard 140 is used to evaluate energy simulation programs, and is designed around BESTEST, a suite of building modeling test cases.[4] For this first exercise, we will only specify our simple building's envelope geometry and Constructions. This will allow us to simulate the envelope's unconditioned response to weather conditions. In Chap. 3 we will add internal heat gains related to Space use. We will revisit this Model once more in Chap. 4, adding an HVAC system for Space conditioning.

2.8.1 Adding Weather to a Model

To begin, we must first identify the location and weather file for our Model. We recommend that you seek out weather files associated with your own city. Weather files in EPW format are freely available at https://energyplus.net/weather. Download weather data for a location of interest. Once downloaded, examine the data using the

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[4] https://yeungus.com/ashrae-standards-analysis-free-related-pdf.html.
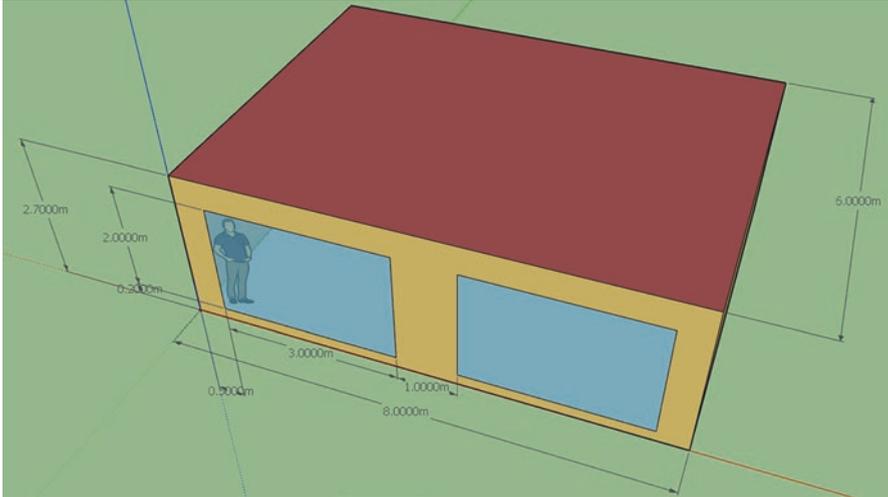
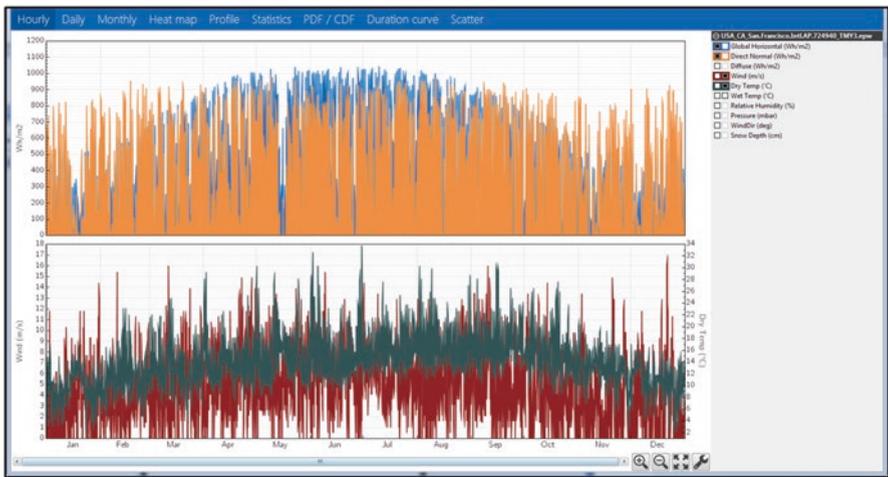**Fig. 2.17**   ASHRAE Standard 140 BESTEST Case 600 Building

Fig. 2.18   TMY data inspected with DView

DView Application packaged with OpenStudio (Fig. 2.18) to become acquainted with the type of information it contains. With weather files in hand, it is time to create our first OpenStudio Model.

Locate the OpenStudio Application on your computer and launch it. As the program begins running, the user is presented with a startup dialog shown in Fig. 2.19, while a new, empty Model is created. After a brief pause, the dialog is replaced with the main OpenStudio Application window shown in Fig. 2.20.

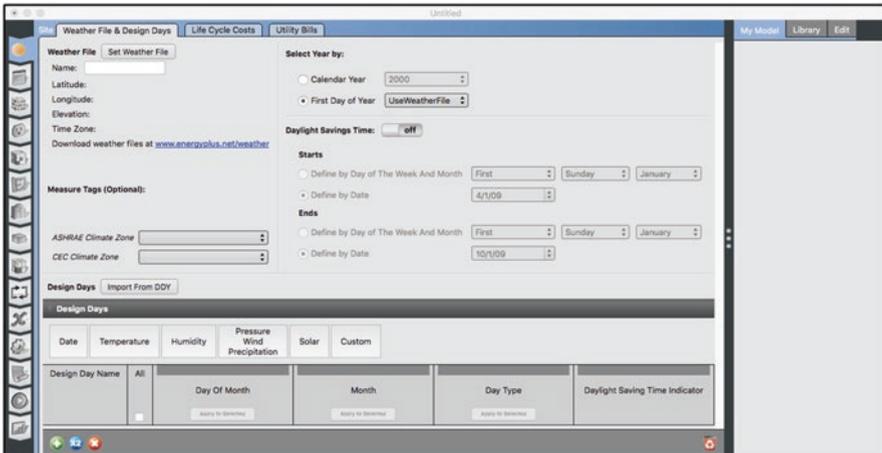**Fig. 2.19** OpenStudio launch dialog

Fig. 2.20 OpenStudio Application with a newly created model

As with any electronic document, it is a good practice to save work often and to create backups along the way. This allows you to restore your Model from the last save point rather than having to start completely over if you make a mistake. Get off to a good start by using the File Menu and selecting the Save option. A dialog opens allowing you to select the working directory and name of your first Model. Saving the empty Model creates an OSM (OpenStudio Model) file along with an identically named directory (Fig. 2.21). The OSM is an OpenStudio Model file and is the file you would send if you wanted to share your Model with someone. The corresponding Model directory will eventually contain supporting files, simulation results, and more.
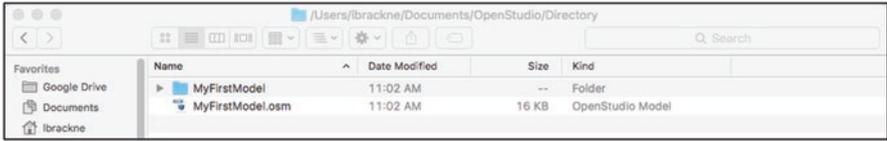
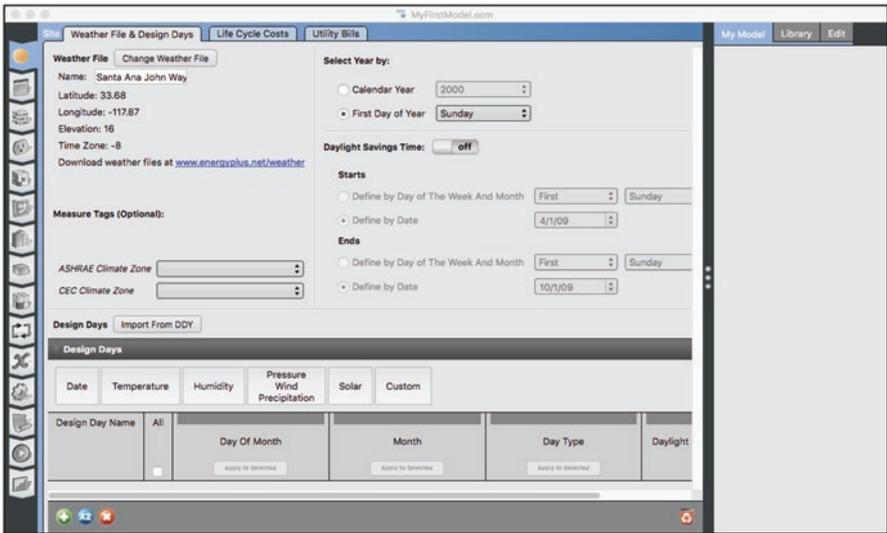**Fig. 2.21** A newly saved OpenStudio Model

Fig. 2.22 Adding EPW and DDY files in the OpenStudio Application

The OpenStudio Application initially opens in the Site (⬤) Tab used to specify site details like weather. Click on the [Change Weather File] Button and select the EPW file you have downloaded. This will attach the weather file to your Model and import location information such as latitude, longitude, and elevation as shown in Fig. 2.22.

Save the Model once again and note that the Model directory now includes a copy of the EPW in a "files" subdirectory as shown in Fig. 2.23.

2.8.2   Creating New Materials

The next step in the process is to define properties for some of the Materials in our building. Click on the Constructions (▤) Tab in the Application. This Tab contains three Sub-Tabs: Construction Sets, Constructions, and Materials. We need to start by defining some basic materials so click the [Materials] Sub-Tab. On the left side of the Materials Sub-Tab shown in Fig. 2.24 note the categories for Material Object types including "Materials," "No Mass Materials", and so on.
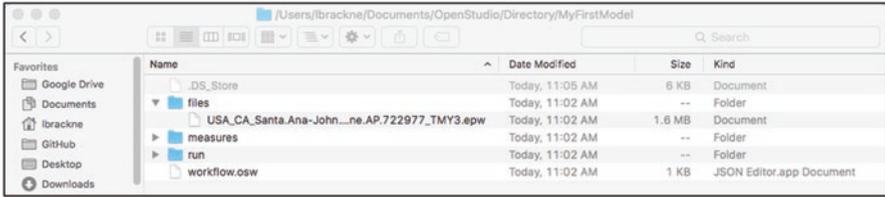
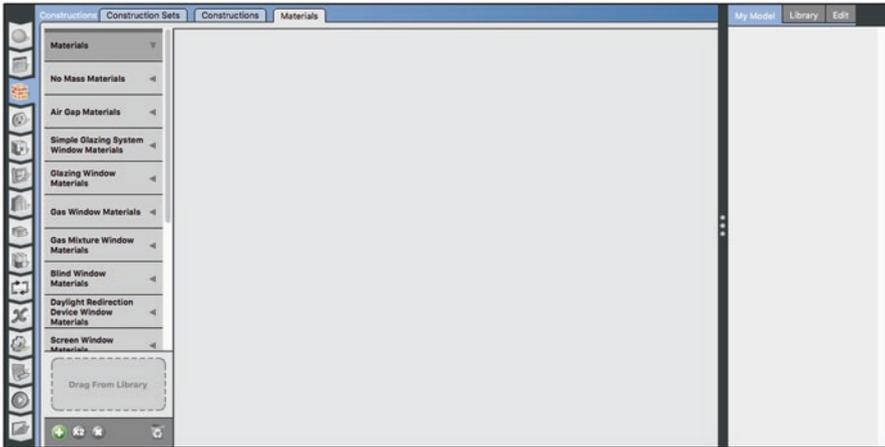**Fig. 2.23** Model directory with EPW file

Fig. 2.24 The OpenStudio Application Constructions Tab and Materials Sub-Tab

These are the different Material types supported in OpenStudio, which closely mirrors materials supported by EnergyPlus. Detailed information about these material types can be found in the EnergyPlus I/O Reference and Engineering Guides.[5] A mapping between Material types and EnergyPlus materials is given in Table 2.1.

We will start by making a new Material of type "No Mass Materials." Click on that label and press the ⊕ Button. This will create a new Object as shown in Fig. 2.25.

Name the Object "R25 Insulation" and set the properties as shown in Table 2.2. Repeat this process for the remaining material objects in the Table.

2.8.3 *Importing Materials from Existing Models*

We have now made several Material objects by hand and have a better understanding of how Materials are represented in OpenStudio and EnergyPlus. However, this process is tedious and prone to error when performed frequently. Instead, let's

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[5]The authors recommend bookmarking this site, because we will refer to it frequently in later Chapters – https://energyplus.net/documentation.

Table 2.1 OpenStudio to
EnergyPlus Material type
mapping

OpenStudio Material type	EnergyPlus Material type
Materials	Material
No Mass Materials	Material:NoMass
Air Gap Materials	Material:AirGap
Simple glazing system window Materials	WindowMaterial:SimpleGlazingSystem
Glazing window Materials	WindowMaterial:Glazing
Gas window Materials	WindowMaterial:Gas
Gas mixture window Materials	WindowMaterial:GasMixture
Blind window Materials	WindowMaterial:Blind
Screen window Materials	WindowMaterial:Screen
Shade window Materials	WindowMaterial:Shade
Air wall Materials	N/A
Infrared transparent Materials	Material:InfraredTransparent
Roof vegetation Materials	Material:RoofVegetation
Refraction extinction method glazing window Materials	WindowMaterial:Glazing:RefractionExtinctionMethod
Glazing group thermochromic window Materials	WindowMaterial:GlazingGroup:Thermochromic

explore how to load Materials from OpenStudio's built-in libraries as well as the online Building Component Library. The OpenStudio Application allows a user to extract data like Space Types, Constructions, and Materials from any OSM by loading it as a "Library". Users can then incorporate pieces of information from the Library OSM into their current working Model.

Select Load Library from the File Menu. This will bring up a dialog where you can browse for other OSM files to use as a Library. The dialog defaults to a directory within the OpenStudio installation package containing a number of useful OSMs as shown in Fig. 2.26, but the user is free to navigate to other directories containing OSMs.

For the purpose of this exercise, select CECTemplate.osm. On the right side of the Materials Tab click on the ▢Library Tab and expand the Materials section just beneath it. You can now see all of the Material objects in the Library. Any of these can be added to the current Model by right clicking, dragging, and dropping them on the space labeled "Drag From Library." Once a Material has been added to the Model it may be inspected, edited, and used in the same manner as any hand-generated
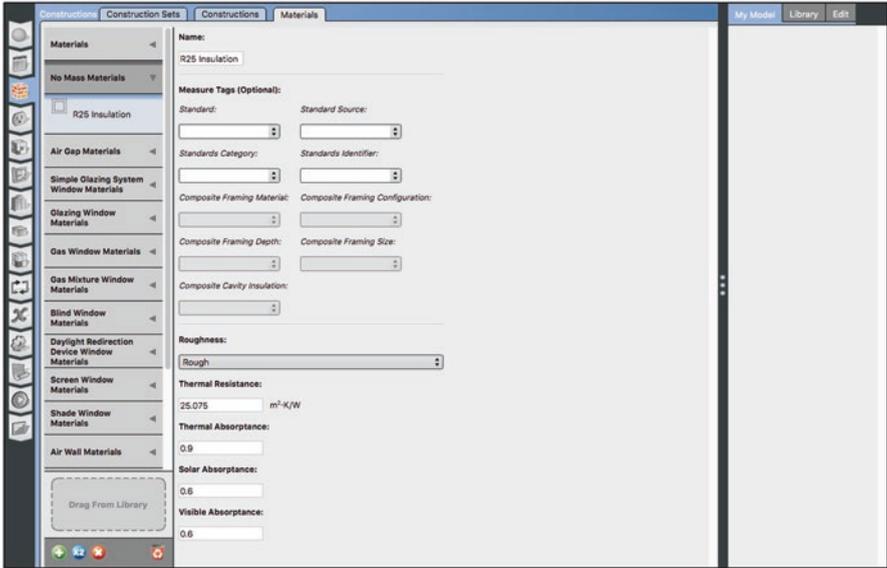
Table 2.2 Material properties for our first Model

	Material name	R25 Insulation	Air gap	Plasterboard	Fiberglass quilt	Roof deck	Timber flooring	Door shell	Interior wall	Wood siding	Glass	Window air fill
Properties	Material type	No mass	Air gap	Materials	Materials	Materials	Materials	Materials	Materials	Materials	Glazing window	Gas window
Material properties	Roughness	Rough	–	Rough	Rough	Rough	Rough	Very smooth	Rough	Rough	–	–
	Thickness (m)	–	–	0.012	0.066	0.019	0.025	0.0032	0.2	0.009	0.0032	0.013
	Conductivity (W/m-K)	–	–	0.16	0.04	0.14	0.14	1.06	0.51	0.14	1.06	–
	Resistance (m²-K/W)	25.075	0.1588	–	–	–	–	–	–	–	–	–
	Density (kg/m³)	–	–	950	12	530	650	2500	1400	530	–	–
	Specific heat (J/kg-K)	–	–	840	840	900	1200	750	1000	900	–	–
	Thermal Absorptance	0.9	–	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	–
	Solar Absorptance	0.6	–	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	–
	Visible Absorptance	0.6	–	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	–
	Optical data type	–	–	–	–	–	–	–	–	–	Spectral average	–
	Solar transmittance at normal incidence	–	–	–	–	–	–	–	–	–	0.862	–
	Front solar reflectance at normal incidence	–	–	–	–	–	–	–	–	–	0.078	–

Back solar reflectance at normal incidence	–	–	–	–	–	–	–	–	0.078	–
Visible transmittance at normal incidence	–	–	–	–	–	–	–	–	0.913	–
Front visible reflectance at normal incidence	–	–	–	–	–	–	–	–	0.082	–
Back visible reflectance at normal incidence	–	–	–	–	–	–	–	–	0.082	–
Infrared transmittance at normal incidence	–	–	–	–	–	–	–	–	0	–
Front infrared emissivity	–	–	–	–	–	–	–	–	0.84	–
Rear infrared emissivity	–	–	–	–	–	–	–	–	0.84	–
Gas type	–	–	–	–	–	–	–	–	–	Air

Fig. 2.25 Creating a new Material in the OpenStudio Application
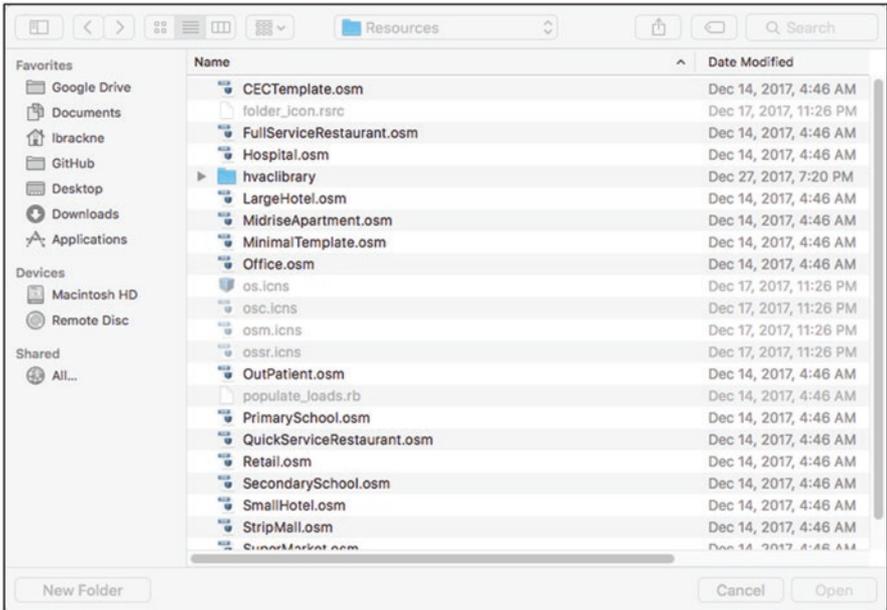
Fig. 2.26 OSM Load Library options included with OpenStudio
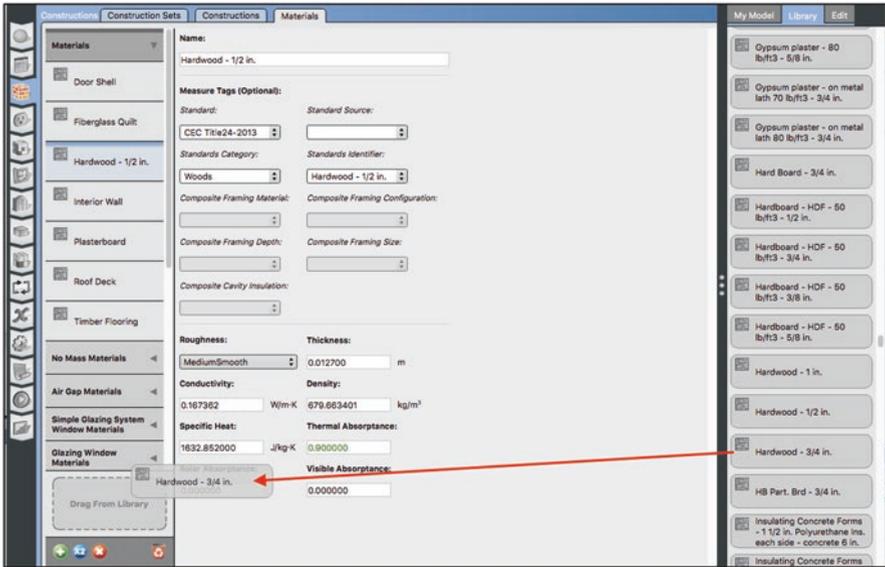
Fig. 2.27   Dragging and Dropping Materials from Library into a Model

Material. Figure 2.27 illustrates inspecting the properties of a ½″ Hardwood Material while adding a ¾″ Hardwood Material from the Library. We won't be using any Materials from this Library for our example Model, but feel free to experiment with them.

2.8.4   Importing Materials from the Building Component Library

Besides existing OSMs, another source for Material data is the Building Component Library (BCL). The BCL is an online repository of energy modeling tool agnostic data, but it has been designed to integrate with OpenStudio tools particularly well. A web interface to the BCL is available at http://bcl.nrel.gov, however it may also be accessed within the Application under the "Components & Measures" Menu category. Prior to using the BCL from within the Application, you will need to create an account on the BCL web page, navigate to "My Dashboard," and make note of your unique BCL "API Key." The OpenStudio Application will request this Key the first time you attempt to access BCL content.

Selecting "Find Components" within the Application launches an integrated browser that allows the user to search, inspect, and download components from the BCL directly into your Model. Click on the Material category and the Opaque
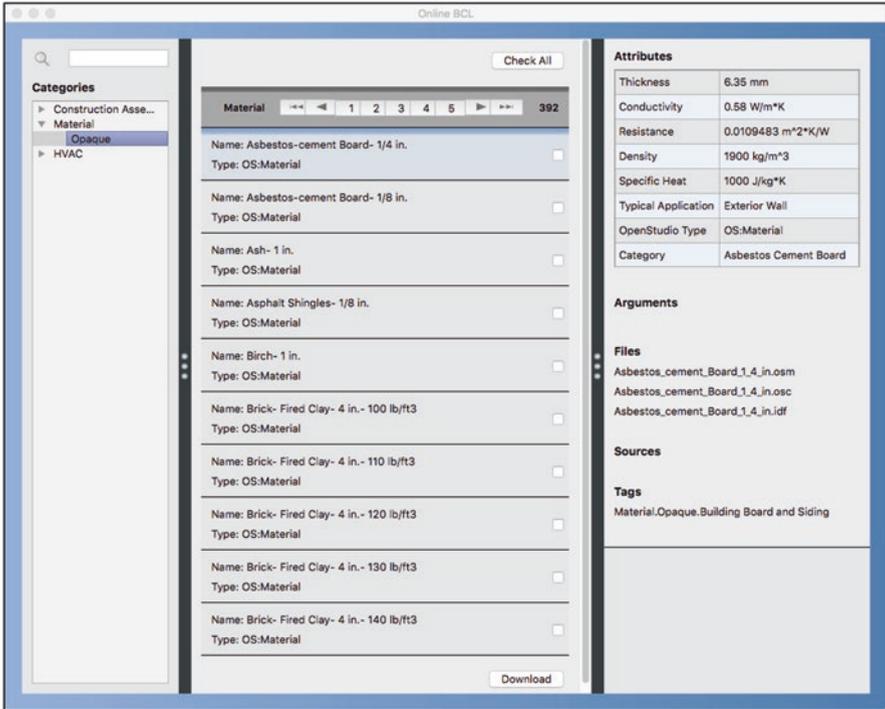
Fig. 2.28 Downloading a Construction Material from the Building Component Library

sub-category to bring up the list of materials shown in Fig. 2.28. Select one or more of these objects and press the [Download] Button at the bottom of the window to download Materials and add them to your Model. We will revisit the BCL in Chap. 6.

2.8.5   Creating Construction Assemblies

Now that Materials have been added to the Model, it is time to combine them to create Constructions using the [Constructions] Sub-Tab (Fig. 2.29). Select the "Constructions" Object type and press the 🟦 Button to create a new Construction Object. As in the [Materials] Sub-Tab, the right-hand pane may be used to inspect objects currently loaded in the working Model or library. Click either [My Model] or [Library] and select Materials to drag onto the "Drag from Library" drop zone in the Construction editor. This adds the selected Material to the currently edited Construction. Materials may be deleted from a Construction by clicking the ⊗ Button next to it. Remember that Construction layers are ordered from the outside layer at the top and move towards the Space interior as you progress down the layer list in the editor.
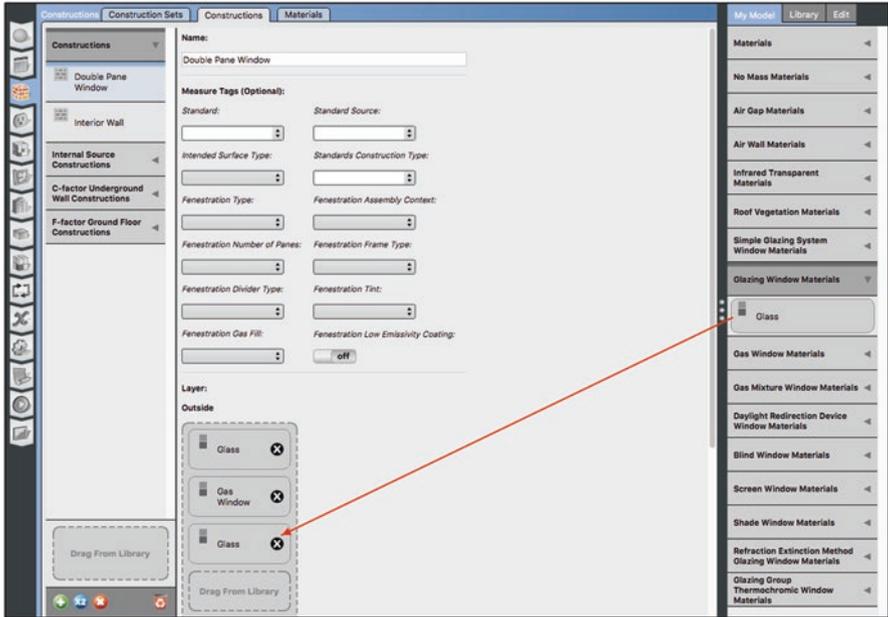
Fig. 2.29 Creating a double pane window Construction in the OpenStudio Application

Table 2.3 Defining Construction layers

Object name		Interior wall	Double pane window	Door	Floor	Roof	Wall
Space exterior	**Layer 1**	Interior wall	Glass	Door shell	R25 insulation	Roof deck	Wood siding
	Layer 2	–	Window air fill	Air gap	Timber flooring	Fiberglass quilt	Fiberglass quilt
Space interior	**Layer 3**	–	Glass	Door shell	–	Plasterboard	Plasterboard

Use the Constructions Sub-Tab to create the following Construction objects listed in Table 2.3.

Note that Libraries may also contain complete Constructions. Selecting the Constructions category under [Library] lists any Constructions that may have been imported from an OSM. As with Materials, Library Constructions may be dragged and dropped into the working Model to save time and reduce the opportunity for error. Adding Constructions in this manner also adds all requisite Materials from the Library with no additional effort required.
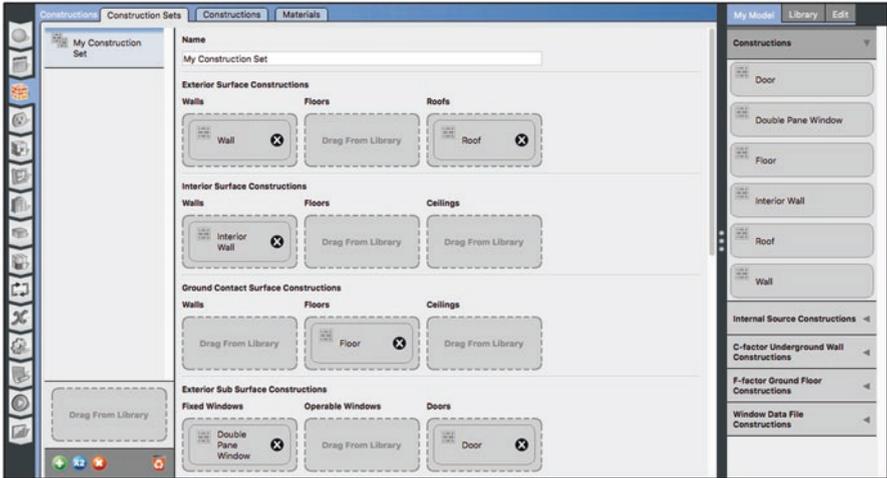
Fig. 2.30 Building a Construction Set in the OpenStudio Application
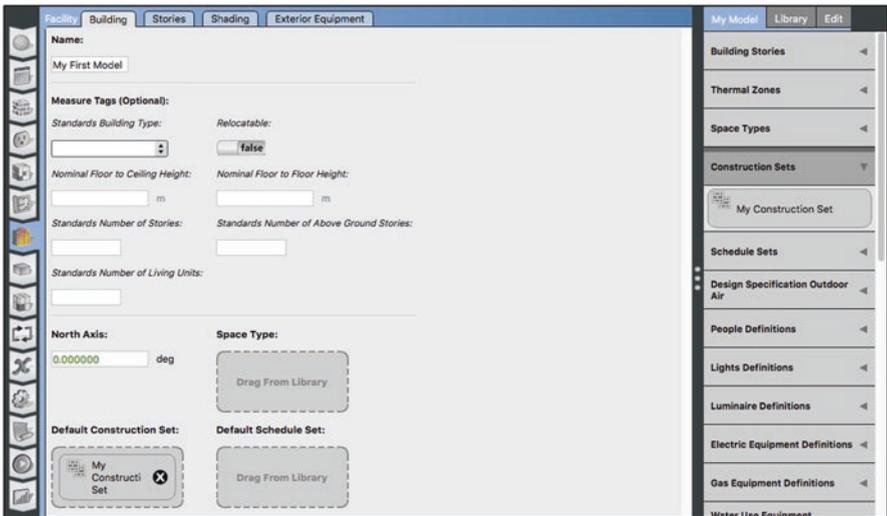
Fig. 2.31 Setting a Construction Set as the Default for a building

2.8.6 Creating a Construction Set

The next step in our process is to combine individual Constructions into a Construction Set that may be applied to the entire building. Go to the ⬚ Construction Sets ⬚ Sub-Tab and create a new Construction Set named "My Construction Set" using the ⬚ Button. Drag constructions from ⬚ My Model ⬚ into the appropriate slots within the Construction Set as shown in Fig. 2.30.

The last step is setting a Construction Set as the default for our entire building is performed on the Building (■) Tab. Select "My Construction Set" and drag it to the Default Construction Set slot as shown in Fig. 2.31.

As with Materials and Constructions, entire Construction Sets may be pulled in from [Library]. This allows the modeler to quickly assign Constructions to walls, floors, roofs, etc. at the Building level with a single drag-and-drop operation. Using pre-built Construction Sets is the most common way to begin creating a new Model in OpenStudio, but it is important for us to understand how Construction Sets are formed so that we may evaluate their suitability and modify them as needed for any given project.

2.8.7   Creating Geometry with the OpenStudio Floor Plan Editor

Having assigned weather files and a Construction Set to our Model, we are now ready to define the building's geometry. Click on the Geometry (■) Tab to open the OpenStudio Application's Geometry editor and previewer. You will initially see an empty window on the [Preview] Sub-Tab because the current Model does not yet contain any geometry. Click on the [Editor] Sub-Tab to reveal OpenStudio's floor plan geometry editor. The editor initially presents the user with some introductory text and the option to create a new floor plan. Clicking the [New] Button opens the QuickStart dialog shown in Fig. 2.32. Select "New" to create a new floor plan on an empty grid (Fig. 2.33).

Figure 2.33 points out key sections of the floor plan editor. These include:

• Drawing Editor Sub-Tabs used to:

  Draw the floor plan
  Assign Construction Sets, Space Types, Thermal Zones, etc. to regions of the floor plan
  Assign windows, doors, etc. to Surfaces on the floor plan
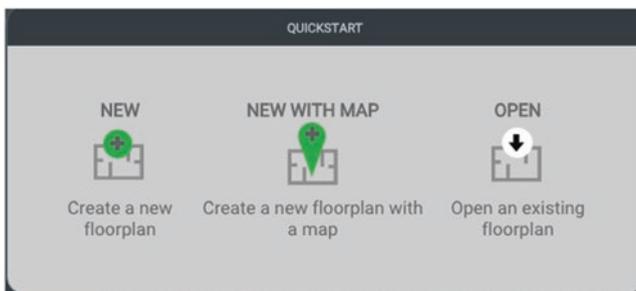
Fig. 2.32   Floor plan geometry Editor Quick Start Dialog
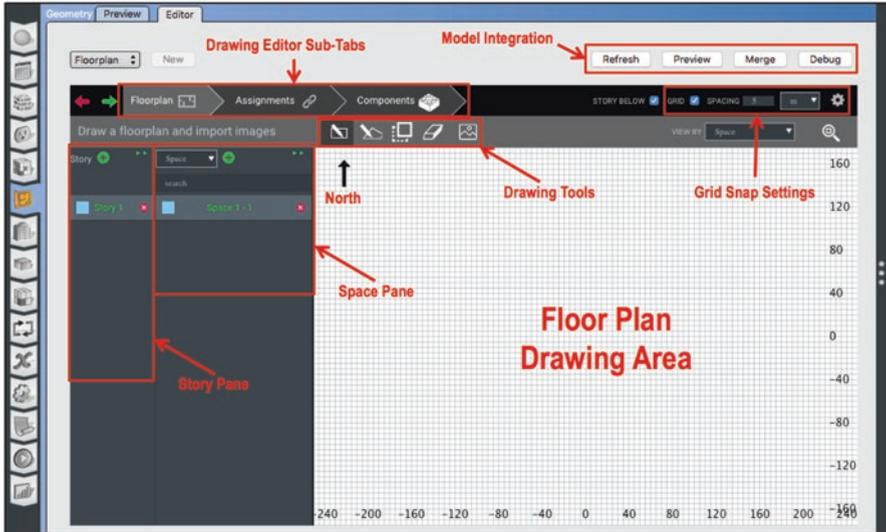
Fig. 2.33 Annotated floor plan editor with empty floor plan in the OpenStudio Application

- Drawing Tools including:

  Rectangular drawing tool
  Polygon drawing tool
  Floor-to-floor copy tool
  Rectangular erase tool
  Background image import for floor plan tracing

- Grid Settings used to manage draw snapping behavior
- Story pane allowing addition and editing of stories to the Model
- Space pane primarily used to add, delete, and edit Spaces from the Model

  The choice menu near the top of this pane also enables editing of shading surfaces and background images

- Model integration Buttons that convert the 2D floor plan drawing into OpenStudio 3D Model geometry

For this simple Model, we will rely on the editor's "grid snap" feature, which is active when the Grid check box is selected near the upper right-hand corner of the window. Grid spacing is set immediately to right of the check box. For this example, specify a 2 m grid and use a mouse wheel or track pad to zoom in so that an 8 m × 6 m rectangle will fit in the drawing area.

Notice that the editor opened with a single Story and Space already created for us. They are named "Story 1" and "Space 1-1" respectively. All that remains is to select the ◨ drawing tool to create an 8 m × 6 m rectangle for "Space 1-1" as shown in Fig. 2.34. If you make a mistake, use the undo/redo (⬅ ➡) Buttons near the upper
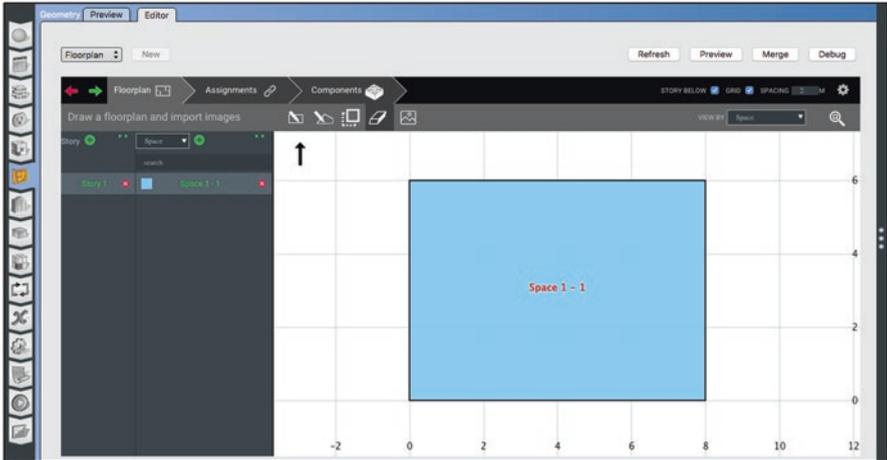
Fig. 2.34 Drawing BESTEST Case 600 in the OpenStudio Application
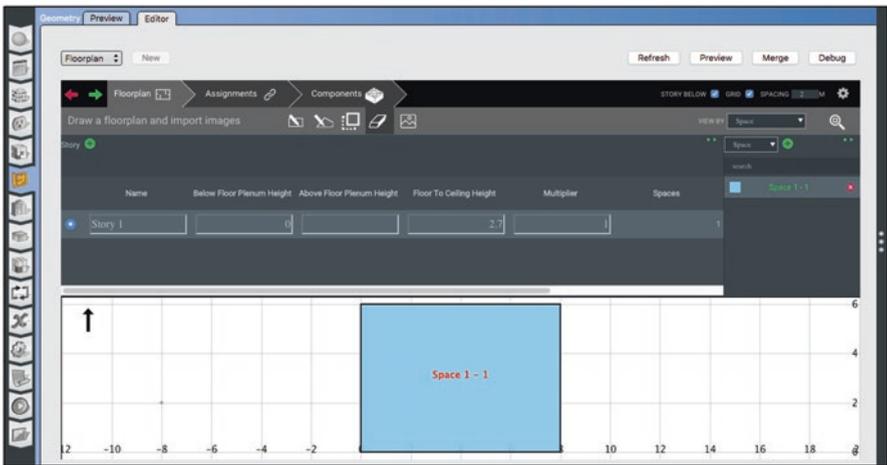
Fig. 2.35 Editing floor height in the OpenStudio Application

left-hand corner of the window. Drawing adjacent rectangles will add to the currently selected Space, while the ⬚ tool can be used to remove rectangular regions.

The height of our single Space is defined within the Story that contains it. Stories may be added and modified at the Stories pane of the editor window. Click on the ▪▪ Button to expand the Story editor as shown in Fig. 2.35, and change the floor to ceiling height from its default value to 2.7 m.

Near the top of the editor, click on the Assignments Sub-Tab. This Sub-Tab allows us to assign Construction Sets, Thermal Zones, Space Types, and more to sections of the Model. By default, the Assignment choice menu lists "Thermal
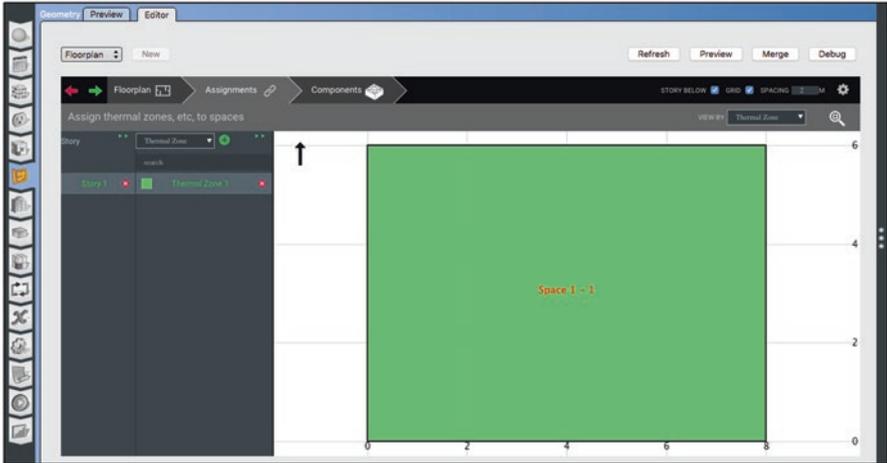
Fig. 2.36   Model with "Space 1-1" assigned to "Thermal Zone 1"
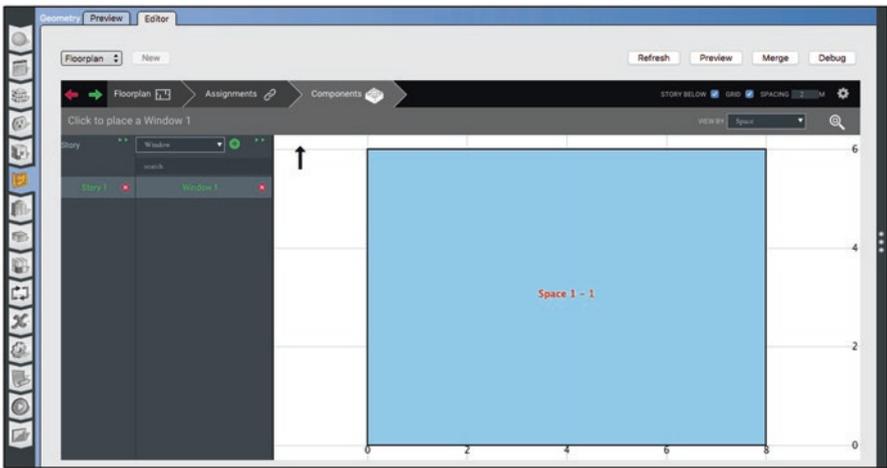
Fig. 2.37   Adding a Window definition with the Geometry editor

Zones" on the left-hand side of the window. Our Model doesn't yet have any, so press the ⬛ Button immediately to the right of the choice menu to create one, then click on Space 1-1 to assign it to that Thermal Zone as shown in Fig. 2.36.

Finally, we must add the two windows shown in Fig. 2.17 using the Components Sub-Tab. In the Components Sub-Tab, the Spaces Pane changes, allowing us to add Window definitions to the model (Fig. 2.37). Click the ⬛ Button to add a new definition, then expand it with the adjacent ⬛ Button.

Define "Window 1" to have width of 3 m, height of 2 m, and sill height of 0.2 m. Mousing over the perimeter walls indicates locations where windows will fit. Place windows on the South façade as shown in Fig. 2.38.
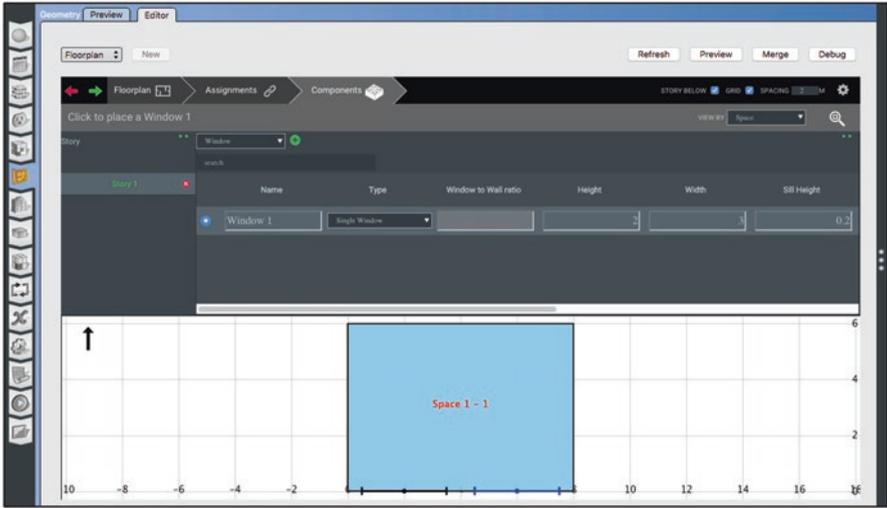
Fig. 2.38   Placing a Window with the Geometry editor
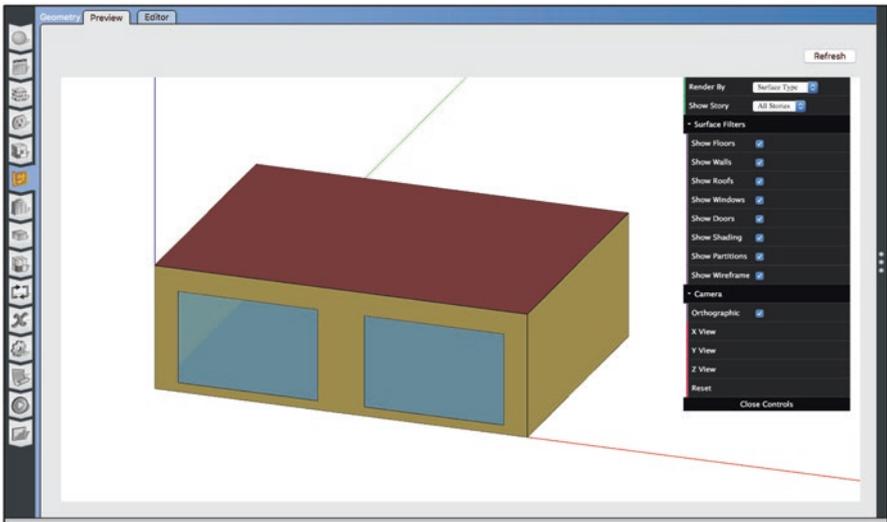
Fig. 2.39   Inspecting the BESTEST Case 600 Building in the OpenStudio Application

We are now done defining the geometry for our first Model. Press the [Merge] to translate your 2D floor plan to a full 3D model usable by OpenStudio. Switching back to the [Preview] Sub-Tab should look similar to Fig. 2.39. If your Model doesn't look quite right, switch back to the editor, make changes, and re-merge your work until you are satisfied.

In this view, the green axis is pointing North. Next to "Render By" choose "Boundary", this will color all of your surfaces by their boundary conditions.

Check all of the boundary conditions by clicking on each surface. Next, choose Render By "Construction". Verify that each of the surfaces have the appropriate construction assigned.

2.8.8 Running Your First Energy Simulation

You are almost ready to run your first simulation. Before doing so, we want to configure the simulation to write out some detailed time series data to examine. Select the Variables (▣) Tab to specify a number of detailed results that we can request from our simulation. Toggle the request Button to "On" next to "Surface Inside Face Temperature," "Surface Outside Face Temperature," "Zone Air Temperature," and "Zone Outdoor Air Drybulb Temperature." Also change the logging rate for each variable from Hourly to Timestep to capture data more frequently as shown in Fig. 2.40.

We are now ready to run the simulation. Go to the Run (▣) Tab and press the ◉ Button (Fig. 2.41). You will see simulation output until the EnergyPlus simulation completes.

Once the simulation is complete, select the Reports (▣) Tab to view simulation results. By default, two reports are available from the selector in the upper left-hand corner of the window: OpenStudio Results and EnergyPlus Results. The standard OpenStudio Results report is shown in Fig. 2.42.

Related to this Chapter's focus on building envelope, clicking on that report heading takes us directly to a summary of high level information about the building's shell as shown in Fig. 2.43. This can be a useful check to ensure that Constructions were applied as expected.
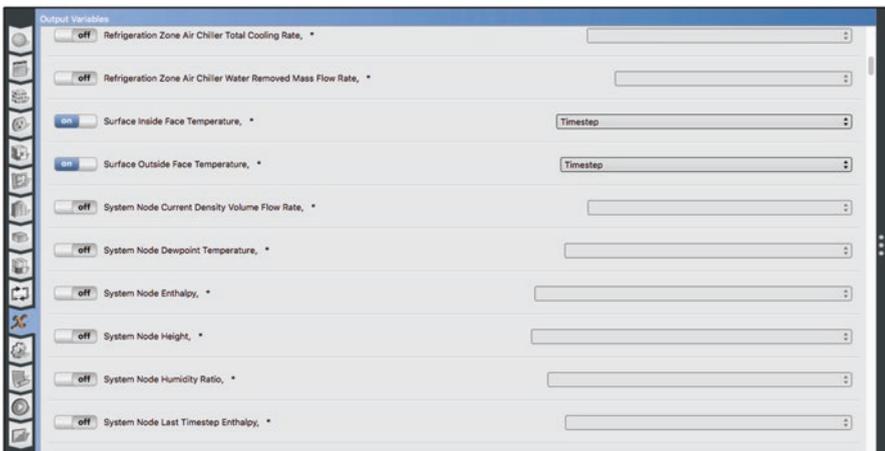
Fig. 2.40 The OpenStudio Application Output Variables Tab
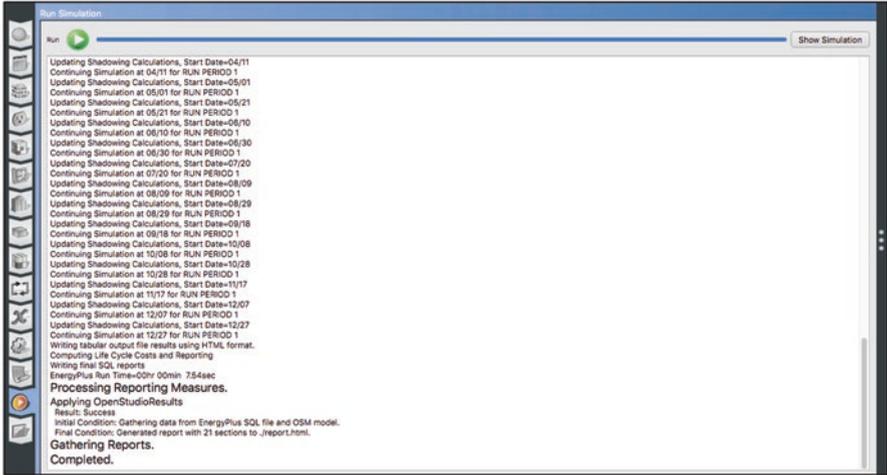
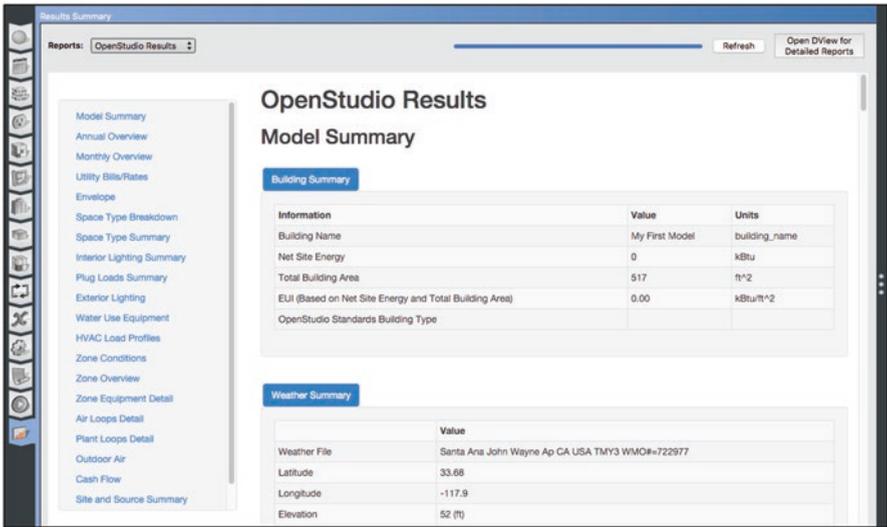**Fig. 2.41** The OpenStudio Application Simulation Run Tab

Fig. 2.42 The OpenStudio Standard Report within the Results Summary Tab

Figure 2.44 highlights another part of the summary report, presenting our building's Zone temperature and humidity for the entire year that we simulated. Since the air in our small building was unconditioned and subject to the ambient conditions described by our weather file, a great many hours spent throughout the year in our tiny building would be considered uncomfortable. This is why we use mechanical systems to condition spaces in our buildings and will be the subject of Chap. 4.
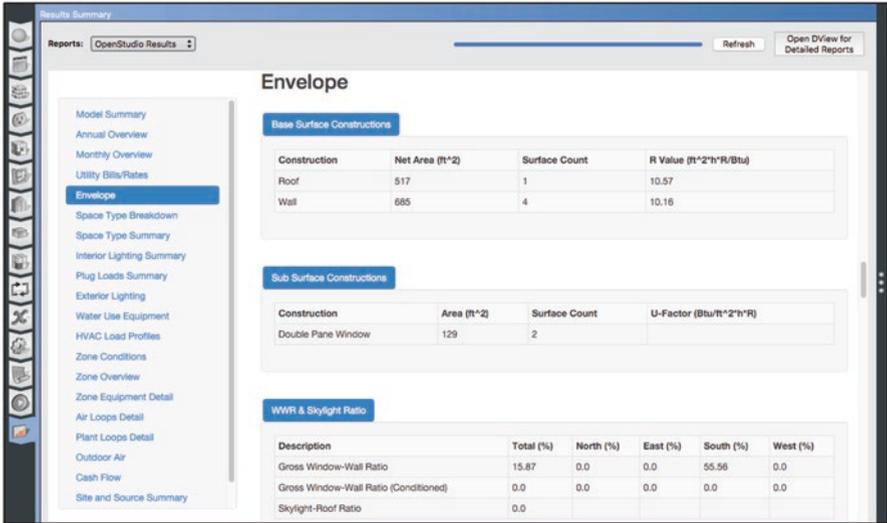
Fig. 2.43 The OpenStudio Standard Report with Envelope Summary
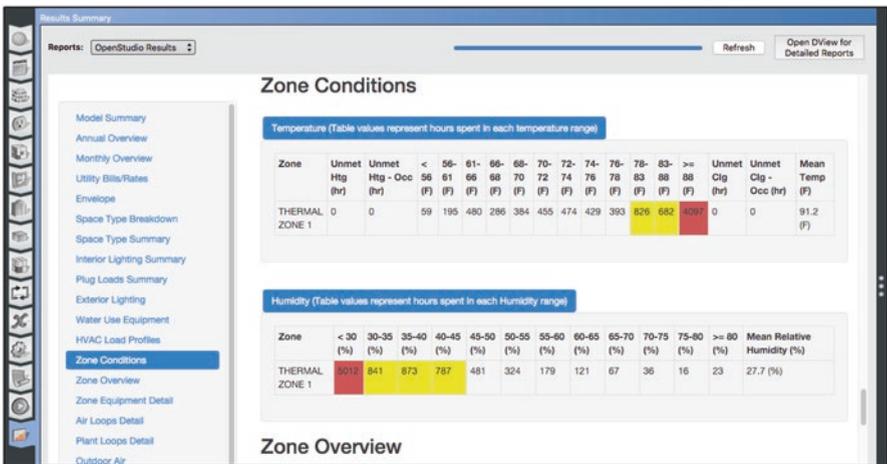
Fig. 2.44 The OpenStudio Standard Report with Zone Condition Summary

Changing the report selector near the top of the window switches to an alternative report. This summary (Fig. 2.45) is produced by the EnergyPlus engine itself and can be a useful supplement to the higher-level information presented in the OpenStudio report.

Since this represents our first complete simulation, it's worth revisiting the Model directory structure we discussed back in Sect. 2.8.1. Recall that the Application saves the OSM along with a directory structure that it populates throughout the
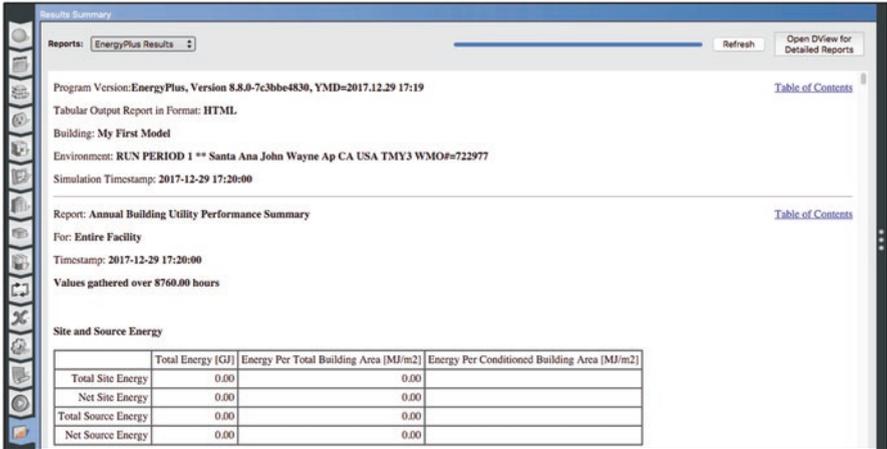
Fig. 2.45 The EnergyPlus Report Viewed within the Results Summary Tab
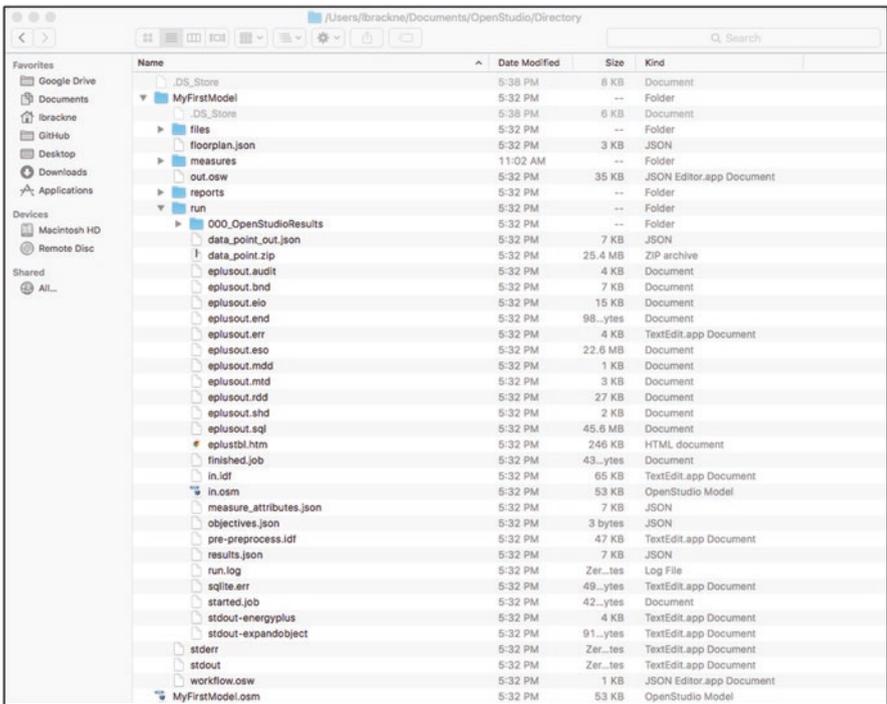
Fig. 2.46 Model directory after simulation

modeling and simulation process. We first noted that our weather EPW file was neatly tucked away in the "files" subdirectory but take a look in Fig. 2.46 at what OpenStudio produced when the simulation ran.

We will discuss a few of these files in subsequent Chapters, but let's take a moment to point out some of the more significant subdirectories and files. We have already seen the contents of the "reports" subdirectory in the Application itself. Both the EnergyPlus and OpenStudio reports are located here as simple HyperText Markup Language (HTML) documents viewable in any web browser.

Within the run directory are a number of files generated by OpenStudio and EnergyPlus itself. Key files of note include:

in.osm – The final[6] OpenStudio Model prior to calling EnergyPlus
in.idf – The EnergyPlus input file created by OpenStudio for simulation
eplusout.err – A file containing simulation warnings and error messages used for troubleshooting
eplusout.sql – A time series database of simulation results used by plotting software like DView

2.8.9   Studying Time Series Results

The eplusout.sql file is a natural segue into the final topic for our first checkpoint exercise - investigating time series results from building energy simulations. EnergyPlus is able to generate very large sets of time series data based on standard reporting variables along with additional variables we may have specified using the OpenStudio Application. These data sets are stored in a SQLite database format (SQL) instead of comma space delimited text files to save disk space and make subsequent access of the data more efficient. The DView application has been designed expressly to study time series data and is able to utilize the eplusout.sql file generate by EnergyPlus. This file may be opened manually within DView or using the convenient Button in the upper right-hand corner of the Application's Reports (◻) Tab (Fig. 2.45).

DView provides a number of ways to inspect and explore our simulation results. Figure 2.47 compares the outdoor drybulb and Zone temperatures for our Model at the finest time resolution available. A number of qualitative observations immediately spring forth:

1. Interior space temperatures lag ambient temperature trends by approximately an hour;
2. Interior temperature profiles are "smoother," having been effectively dampened by the inherent thermal capacitance of the structure;

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[6]Final model? I thought I was working on the final model in the OpenStudio Application! The distinction between models you edit in the OpenStudio Application and the "final" model that is actually simulated will become clearer in Chap. 6.
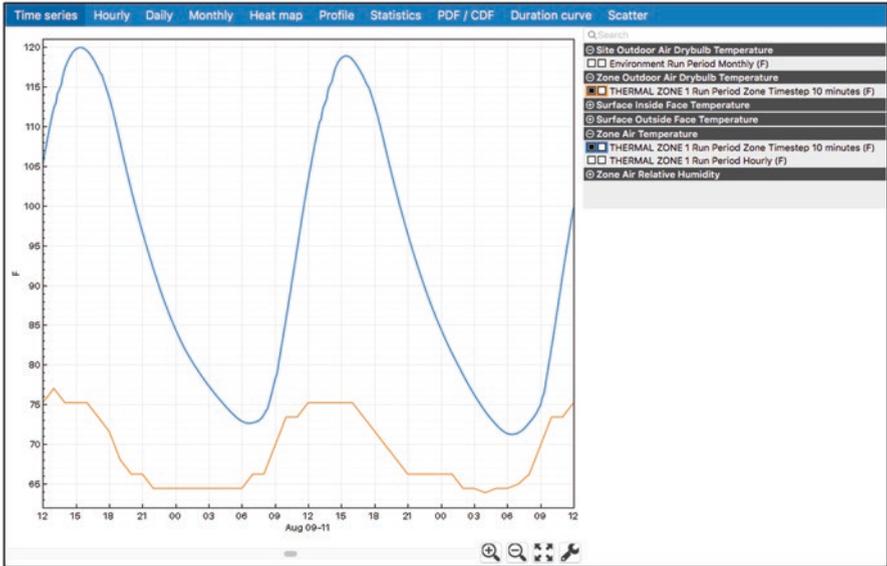
Fig. 2.47 Comparison of Outdoor and Zone temperatures in DView

3. Interior temperatures are elevated above ambient by radiant energy admitted through the South-facing fenestration;
4. And, lastly, this building would be an incredibly unpleasant structure to live or work in!

DView provides other ways to explore simulation results – for example examining exterior or interior surface temperatures. As an example, consider the temperatures of the South-facing façade of our building. Using the Geometry (▣) Tab previewer, we can inspect the South façade and note that OpenStudio has automatically assigned it the name "Face 2" (Fig. 2.48).

Once identified, variables associated with that surface's name can be selected in DView to plot surface temperatures in a variety of useful ways. Figure 2.49 displays the exterior surface temperature of the South façade as a "heatmap," a colored chart that allows the user to quickly identify thermal extremes by month of the year and time of day.

Figure 2.49 displays monthly "profiles" for the exterior and interior surface temperatures of the South Façade by averaging daily temperatures for each day of every month. Both visualizations can be useful in spotting performance trends, aberrant behavior in simulations, etc. We will make greater use of DView in Chaps. 3, 4, and 5 to examine Space, Zone, and HVAC system behavior in detail.

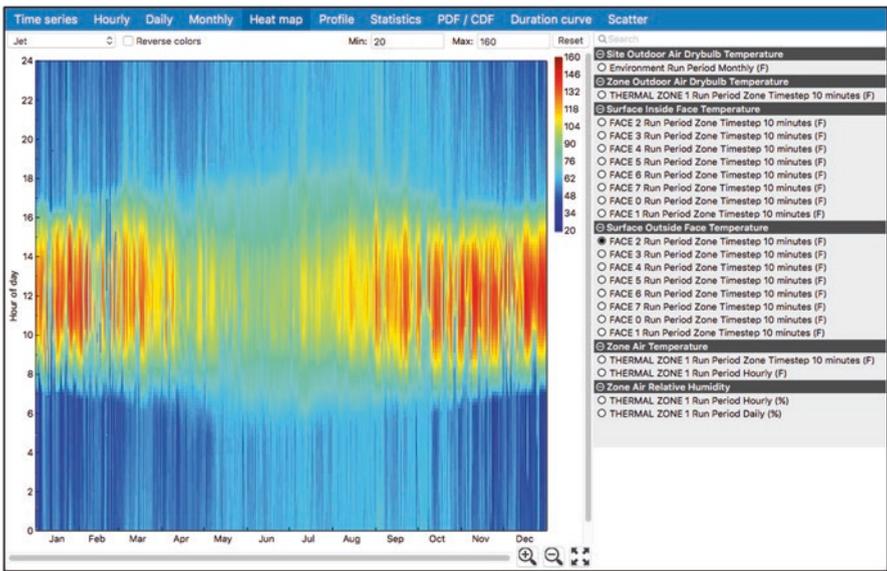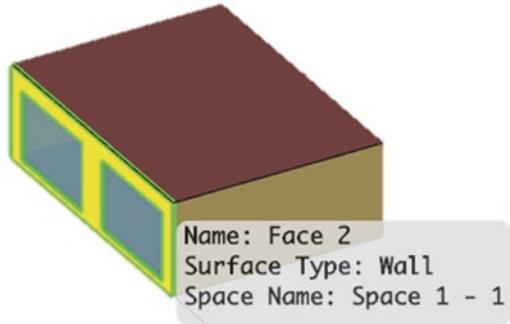**Fig. 2.48** Identifying the Surface name for the South Facing Façade

Fig. 2.49 South exterior wall surface temperature plotted in DView as a Heatmap

2.9 Checkpoint Two: Energy Model of a School

Now we are ready to begin work on our real capstone Model that we will improve upon throughout this book. We will be attempting to create a simple primary school Model using pre-built Library data to speed up the process. A floor plan for this building is shown in Fig. 2.51. Use the following steps to get started:

1. Create a new OpenStudio Model.
2. Under the Preferences Menu make sure that the default units are set to English (I-P).
3. Navigate to the Site (⬤) Tab and:
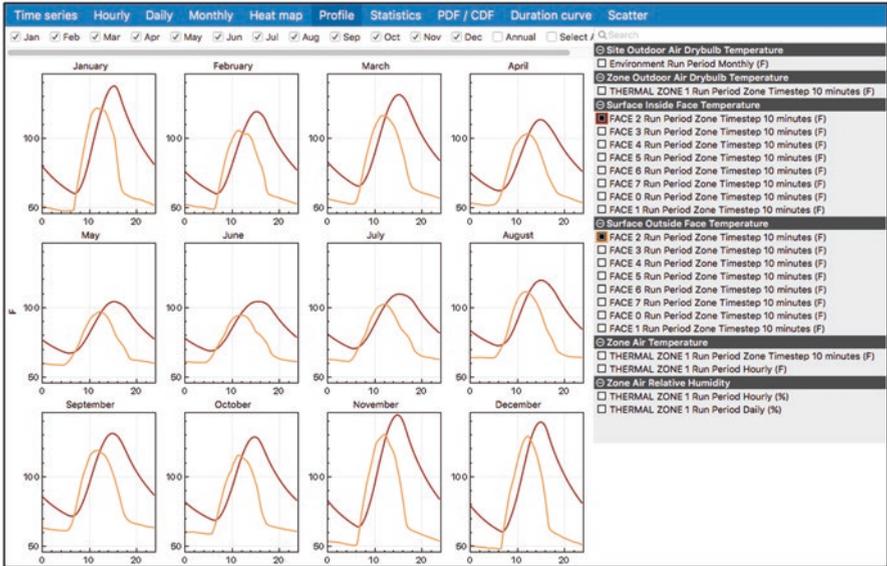
Fig. 2.50 Monthly temperature profiles for Exterior and Interior Surfaces on South Façade

  (a) Select the *USA_CO_Golden_NREL.72466_TMY3.epw* weather file.
  (b) Specify ASHRAE Climate Zone 5B from the Optional Measure Tags menu.[7]

4. Pick "Load Library" from the File menu and import *PrimarySchool.osm* to load the Model library with Construction Sets and other appropriate data.
5. Navigate to the Constructions (⊞) Tab, select the Construction Set named *90.1–2010-CZ5–6-PriSchl*, and drag it into your Model as shown in Fig. 2.50.
6. Navigate to the Buildings (🏠) Tab, select the Construction Set you just added, and drag it to become the Default Building Construction Set.
7. Save your Model.

Now we're ready to define our Envelope and Spaces using the Geometry (🏠) Tab. Create a new floor plan with the editor. Once again, decline to place this Model on a map. Select an appropriate grid spacing that will allow you to comfortably draw the floor plan shown in Fig. 2.51. Add additional Spaces with the 🟢 Button and use the 🔲 Tool to add them to the floor plan. The drawing cursor will turn into a larger red dot when you are on top of an adjacent vertex, which can help avoid leaving gaps between Spaces.

Expand the Space pane with the ⬛ Button to change Space names and colors to your liking. Your finished floor plan should look like the one shown in Fig. 2.52.

To complete this stage of your primary school Model:

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[7]Will discuss the significance of this in a later chapter, but for now know that this choice helps OpenStudio select Constructions and HVAC systems that are appropriate for Climate Zone 5B where our school is located.
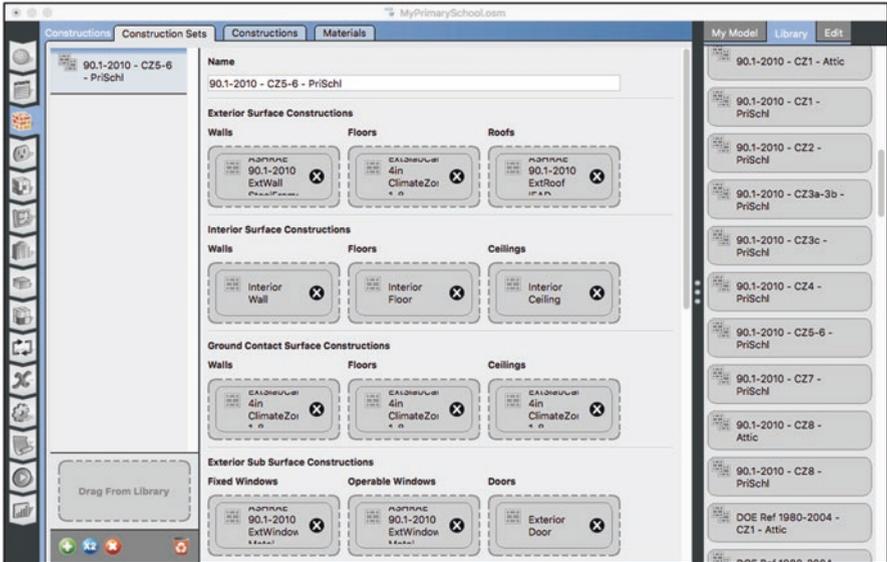
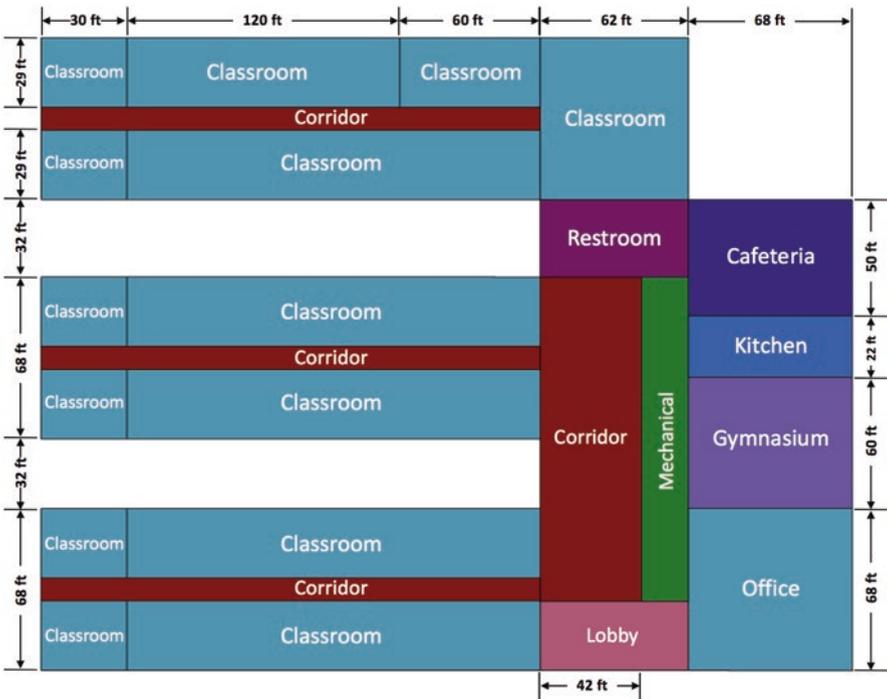**Fig. 2.51** Empty Model Loaded with ASHRAE 90.1-2010 Construction Set for a primary school

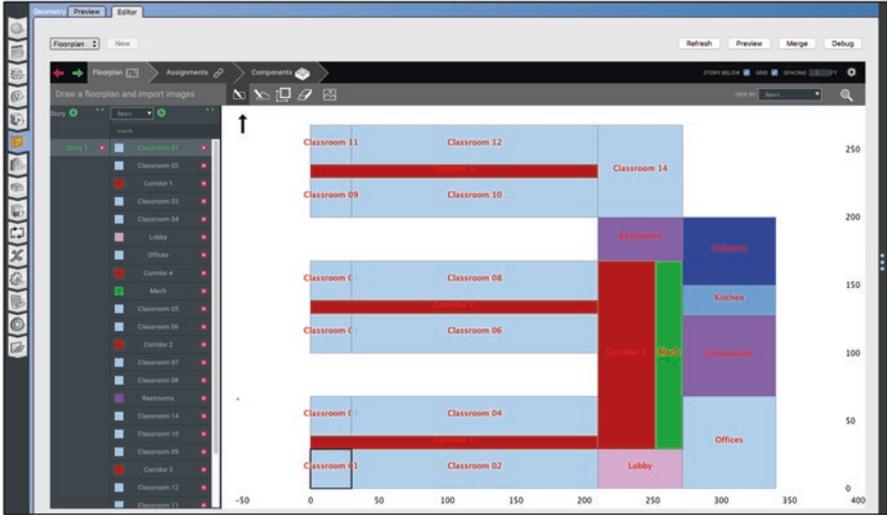**Fig. 2.52** Primary school floor plan

Fig. 2.53 Primary school floor plan drawn with the Geometry editor
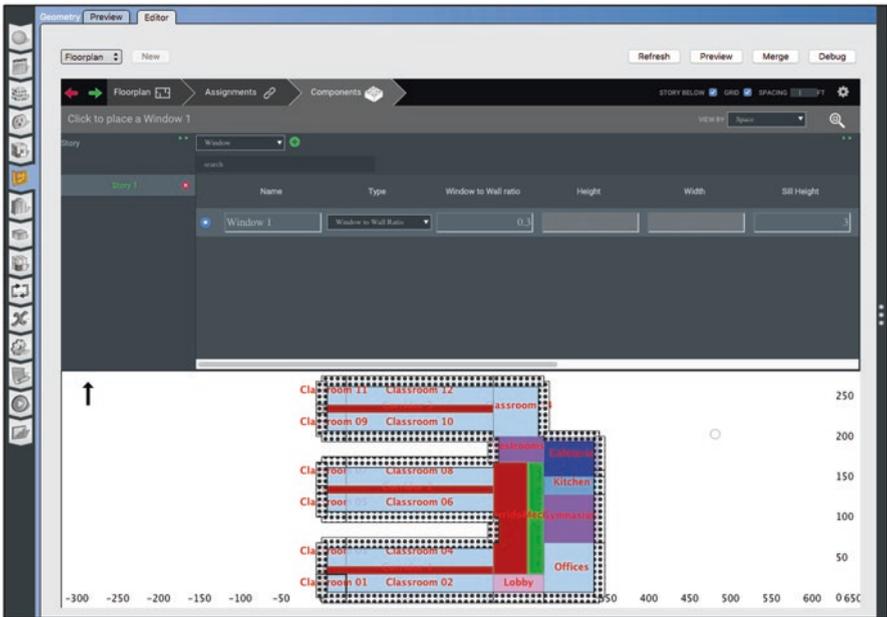

Fig. 2.54 Boundary condition view of primary school Model
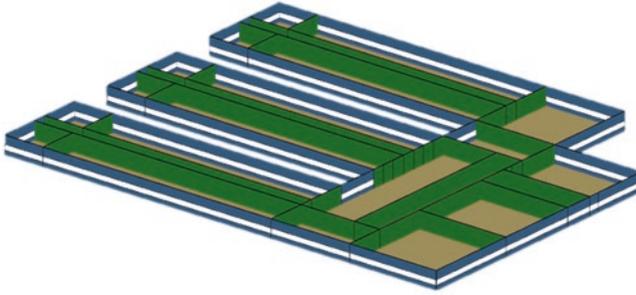
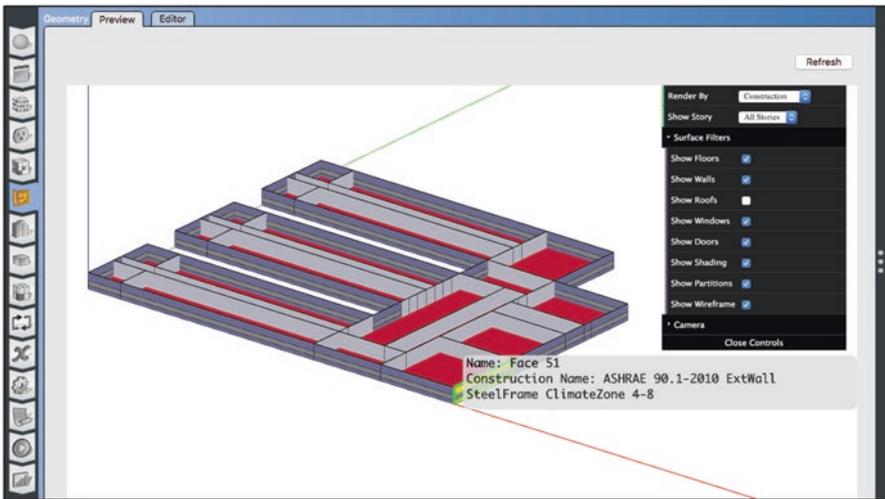Fig. 2.55 Boundary condition preview of primary school Model in editor

Fig. 2.56 Construction View of primary school Model

1. Expand the Story pane with the ▦ Button to specify a floor to ceiling height of 13 feet.
2. Use the Components Sub-Tab to define and add windows to your model.

   (a) Select a "Window to Wall Ratio" type window to create a band of windows on each surface.
   (b) A Window to Wall Ratio of 0.3 will produce a window roughly 4 feet tall (0.3 × 13 feet)
   (c) Select a sill height of 3 feet.
   (d) Add a window to each Space Surface around the perimeter of your Model as shown in Fig. 2.53.

3. Use the Assignments Sub-Tab to create Thermal Zones for each Space in the model. Change their names and colors to your liking.
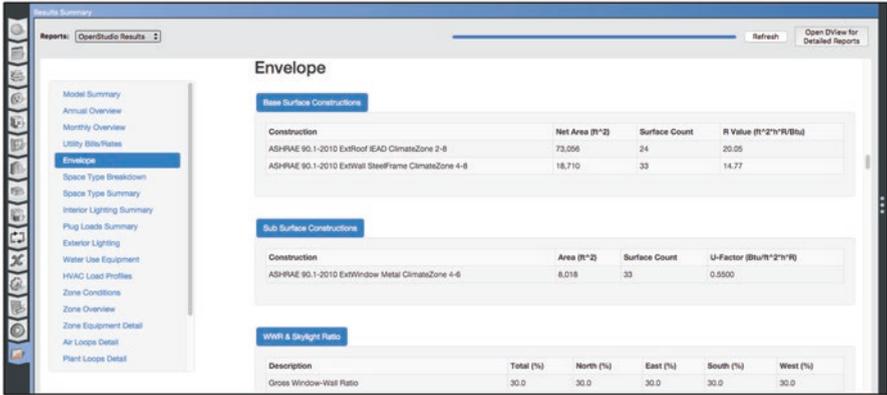
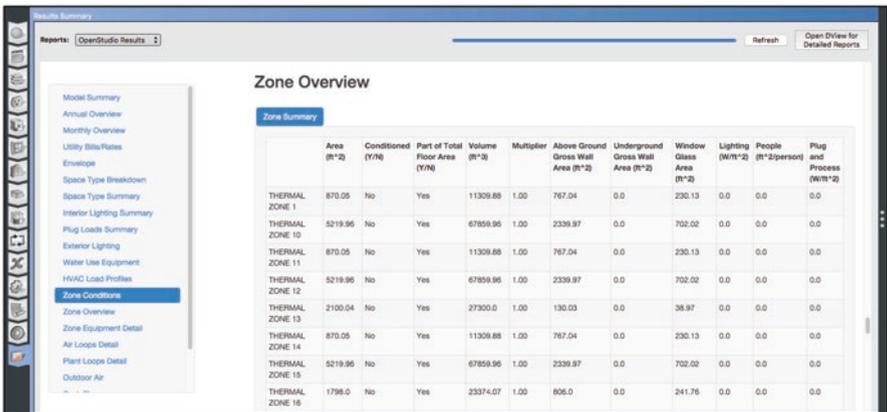**Fig. 2.57** Unconditioned primary school envelope summary report

Fig. 2.58 Unconditioned primary school zone overview
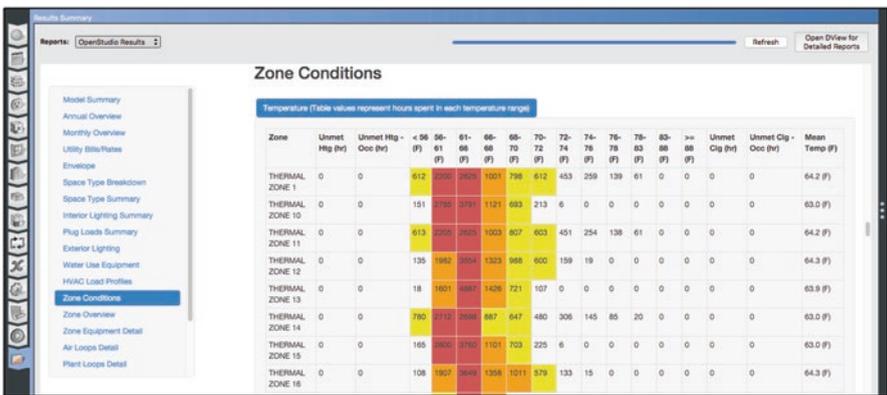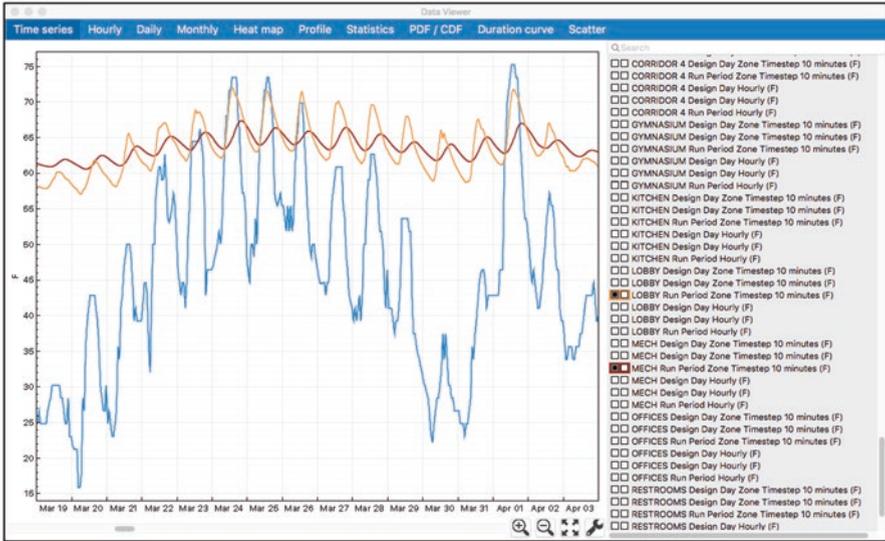

Fig. 2.59 Unconditioned primary school zone conditions

Fig. 2.60   DView time series plots of Outdoor, Lobby, and Mechanical room temperatures

4. Use the [Preview] Button to visually inspect your Model for defects using multiple render modes. The boundary condition view should look like Fig. 2.54.
5. When you are satisfied, press the [Merge] Button to integrate the floor plan with the rest of your Model. You can verify that your Model merged correctly by using the [Preview] Sub-Tab as shown in Fig. 2.55.
6. Save your Model and create a backup in case you wish to return to this step.

At this point, you should be able to run a simulation of the unconditioned envelope. Review the standard reports (Figs. 2.56, 2.57, and 2.58) to see if they make sense given what you have learned so far.

Consider the time series plots shown in Fig. 2.59 that compare the outdoor temperature (dark green) with the Lobby (red) and Mechanical Room (blue) Zone temperatures. The Lobby temperature fluctuates significantly more than the Mechanical Room. Does this make sense? Why? (Fig. 2.60).

Remember that our primary school does not yet include any definition of activities that happen within each Space. That is the topic for our next Chapter.

2.10   Additional Exercises

Creating additional exercises related to building envelope is as simple as using the floor plan editor to create a new Model. One editor feature that we didn't mention in the previous exercises is the ability to import images for tracing to create floor plans of existing buildings. Image imports are most effectively used when creating a new
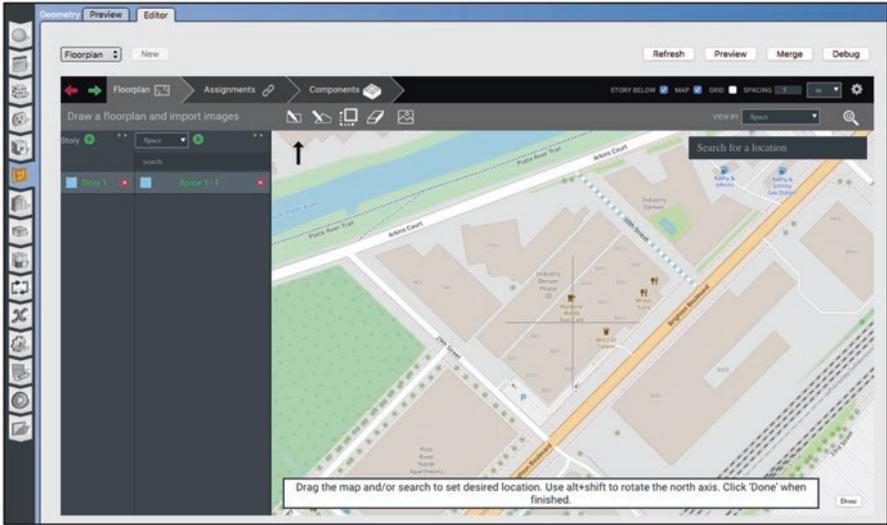
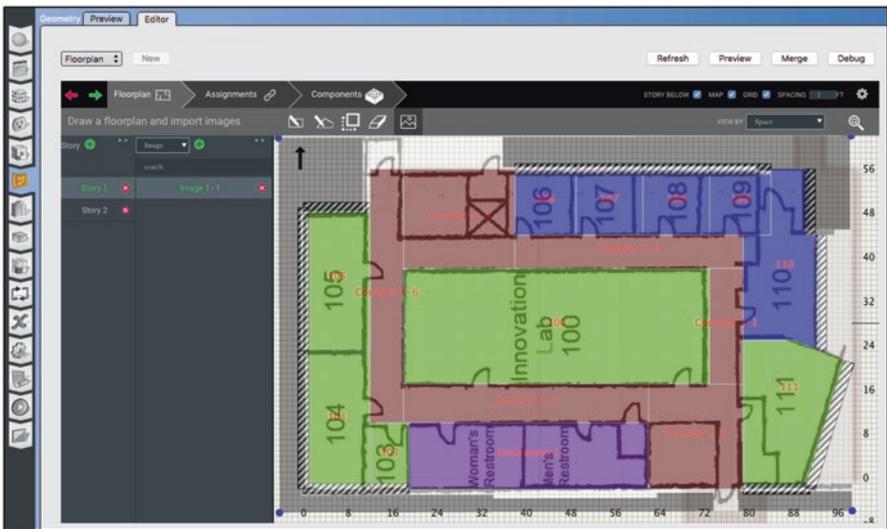**Fig. 2.61** Geolocating a new Model with the floor plan editor

Fig. 2.62 Tracing over an image with the floor plan editor

floor plan and selecting "New with Map" from the floor plan quick start dialog
shown in Fig. 2.32. The interface allows the user to search for a specific address,
pan, zoom, and rotate to establish a region for drawing the foot print of a proposed
or existing building (Fig. 2.61). The ⊞ Button is then used to select an image that
can be scaled, rotated, and placed on top of the map for tracing spaces. Figure 2.62

shows a snap shot of a fire escape drawing that was used to create the first floor of
the Model shown in Figs. 2.3 and 2.4. Multiple images may be imported and associated with various floors of the Model.

As an exercise:

- Take a photo of a fire escape drawing of the building you study or work in,
- Create a new OpenStudio model with an appropriate weather file,
- Enter the building's address in the floor plan editor to geolocate it,
- Import your fire escape photo(s) - scaling and rotating as needed to register it on
  the map,
- Trace Spaces on your Model using the imported image(s),
- Import an appropriate Library of Constructions from a similar Model (e.g.
  School, Office, etc.),
- Assign Thermal Zones to your Spaces so you can simulate the unconditioned
  response, and
- Save your Model for use in subsequent Chapters.

Compare your Model with the previous exercises, when run with different
weather files. Do your results make sense?

References

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