

Washington University in St. Louis

Washington University Open Scholarship

Mechanical Engineering and Materials Science
Independent Study

Mechanical Engineering & Materials Science

5-1-2016

Accented Models: Evaluating their effectiveness in Building Energy Simulation

Gary Hu

Washington University in St. Louis

Ramesh K. Agarwal

Washington University in St. Louis

Follow this and additional works at: <https://openscholarship.wustl.edu/mems500>

Recommended Citation

Hu, Gary and Agarwal, Ramesh K., "Accented Models: Evaluating their effectiveness in Building Energy Simulation" (2016). *Mechanical Engineering and Materials Science Independent Study*. 2.
<https://openscholarship.wustl.edu/mems500/2>

This Final Report is brought to you for free and open access by the Mechanical Engineering & Materials Science at Washington University Open Scholarship. It has been accepted for inclusion in Mechanical Engineering and Materials Science Independent Study by an authorized administrator of Washington University Open Scholarship. For more information, please contact digital@wumail.wustl.edu.

MEMS400 Independent Study Report

**Accented Models: Evaluating their effectiveness
in Building Energy Simulation**

by

GARY HU

Advisor: Dr. Ramesh Agarwal

Submitted in partial fulfillment of the requirements

for independent study Spring 2016

Department of Mechanical Engineering & Materials Science

Washington University in St. Louis

April, 2016

Abstract

This report examines the effectiveness of the accented modeling method for building energy simulation. The traditional full-zone modeling method is too time consuming and in some cases unnecessary, so a more efficient building modeling method – accented modeling is introduced. The purpose of this research is to analyze if, and under what conditions, an accented building model is an effective representation of the actual building. By using DesignBuilder and EnergyPlus as software packages for model development and simulation, two building models for the Lofts on the Washington University campus in St. Louis, MO were created for comparison – a full-zone model and an accented model. This report first examines the accuracy of the full-zone model, and then, by comparing the accurate full-zone model to the accented model, shows that the accented modeling method is effective in this case.

TABLE OF CONTENTS

Abstract	ii
1 Introduction	1
1.1 EnergyPlus	2
1.2 Full-zone Modeling Example – the Glennan Building	3
2 Case Study – The Lofts 117A.....	4
2.1 Building Description	5
2.2 Building HVAC System	6
2.3 Suite Occupancy	6
2.4 Suite Lighting and Equipment	7
3 Modeling and Simulation.....	7
3.1 Full-zone Method	8
3.2 Accented Modeling Method	9
3.3 Simulation using EnergyPlus	11
4 Calibration and Results	13
4.1 Calibration	13
4.2 Results	15
5 Analysis	17
6 Conclusion	18
7 Recommendation	19
References	21
Appendix A. Glossary	22
Appendix B. The Lofts Floor Plans	23
Appendix C. Procedural Report.....	25

LIST OF ILLUSTRATIONS

Fig. 1 World energy consumption since 1820	1
Fig. 2 The Lofts exterior	5
Fig. 3 Entrances at Enright Ave and McGinnis Alley (Google Map 3D).....	5
Fig. 4 Ceiling-suspended ducts in suite 117	6
Fig. 5 Full-zone model of the Lofts in DesignBuilder	8
Fig. 6 Hierarchy in DesignBuilder	9
Fig. 7 Full-zone model and accented model of the Lofts first floor.....	10
Fig. 8 Text editor screen and IDF editor screen	11
Fig. 9 The Lofts is oriented 6 degrees with the north (Google Compass)	12
Fig. 10 Daily consumption during June after calibration	14
Fig. 11 Consumption rates from actual readings and simulation results.....	15
Fig. 12 Actual and simulated monthly electricity consumption in 2013	16
Fig. 13 Monthly electricity consumption of suite 117	16
Fig. 14 Daily electricity consumption of suite 117.....	17
Fig. 15 The Urbauer Building exterior view	20
Table 1 Costs vs. savings for each ECM applied to the Glennan Building	4
Table 2 Results of paired T-test on the accented model and full-zone model.....	18

1 Introduction

Global energy consumption rates, as shown in Fig. 1, have been increasing rapidly in recent years [1] because of manufacturing power needs, the growth of the population and their direct energy consumption, and climate changes or some other factors.

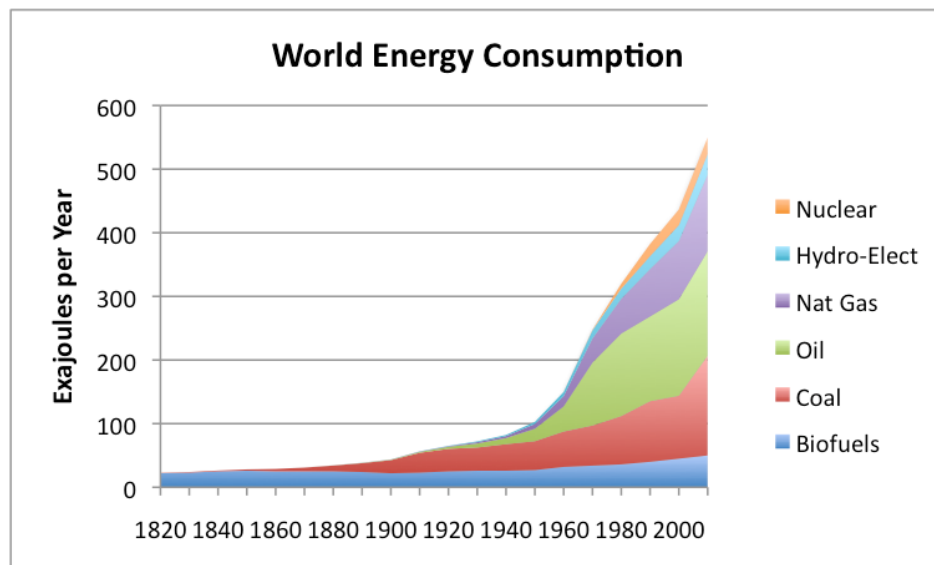


Fig. 1 World energy consumption since 1820

Meanwhile, the limited availability and cost of natural resources have raised the need for more efficient and less power-consuming buildings. A more *energy-efficient* (Refer to Appendix A for explanations of terminologies) building can be achieved at the design stage but also during operation through smart decision-making about building controls, equipment and insulation materials. Of course each building has specific requirements, and energy efficiency improvements are oftentimes specific to a building's shape, orientation, size, age, operational capabilities and more. [2]

Different software packages are available for the purpose of building energy modeling, and while cumbersome to run, this software can accurately investigate and ultimately help prioritize *energy conservation measures* that may be implemented for energy savings [2]. The software packages require a *computational representation* of the building, inputs about the information about building occupancy and equipment power usage, schedules, building

components' materials, and other related factors. The software simulates the inputs and predicts the energy consumption of the building allowing a comparison between different building models and the actual building, and evaluate the model's effectiveness.

Using software to model an existing building takes a considerable amount of time. For an 8-floor commercial building, it usually takes more than 6 months to complete the modeling process, including gathering building information, constructing building model based on floor plans, investigating building occupancy and equipment power usage schedules, etc. However, for the sake of research and in many practical applications, only the energy consumption rates of certain rooms in a building are relevant, which raises the need of less time-consuming modeling method. One way of simplifying the modeling process is to elaborate the model of the relevant rooms, while approximate the effect of other rooms by treating them as component blocks or simple thermal zones. This method is called *accented modeling*.

The objective of this research is to evaluate the effectiveness of accented modeling. Building models were created and associated energy simulations were run using the traditional full-zone method and the accented modeling method, results were then compared using statistical method. It was found that the accented model of the Lofts Building is effective, thus the method can be generalized and applied to other similar cases (see discussion in Recommendation on page 19).

1.1 EnergyPlus

In this study, EnergyPlus were used as the simulation engine. EnergyPlus is arguably the most sophisticated building load simulation and energy analysis program available today. It is the official building simulation program of the United States Department of Energy, and with its wide capabilities and sub-hourly time steps it has become one of the most popular energy modeling software programs for engineers and researchers, and has been rated by experts as the most powerful software for energy analysis and energy efficiency measures [3] with greater capabilities than BLAST and DOE-2.1E programs (which EnergyPlus was based upon) [4].

In EnergyPlus, one must input the data that represents the building and its operational conditions. A geometry model needs to be created for the building that is to be simulated, its orientation and location (longitude, latitude, and elevation) defined, and its corresponding weather file to be chosen. Weather files consist of average weather data for a specific location created from data recorded over a long duration. Special weather information can also be defined. Appropriate construction materials must be inputted to the software, allowing the calculation of the heat transfer rates throughout the simulation. *Internal gains* are used to estimate the loads inside the building allowing engineers to choose the right HVAC system. The HVAC system schedule must also be defined, and an individual equipment schedule set. While each room can be simulated as a *thermal zone*, rooms served by the same HVAC equipment can be combined as one zone if they share similar conditions, which will reduce simulation time and data input requirements.

1.2 Full-zone modeling example – the Glennan Building

In our previous research, a full-zone model was created for the Glennan Building located on the Case Western Reserve University Campus in Cleveland, Ohio. Developing the model for Glennan Building was an arduous task, requiring more than 6 months of document referencing (e.g. blueprints and floorplans), researching materials in the building, surveying occupied space (e.g. for equipment and plug load schedules) and then inputting all this information into DesignBuilder and EnergyPlus. **The building model contains 263 thermal zones and takes 254 minutes to run a thorough simulation.**

Different energy conservation measures (ECM) were applied to the Glennan to assess their potential impact. Building geometry was first developed using the DesignBuilder program, while the EnergyPlus program was used to define the different parameters and systems in the building and to run the energy simulation. A customized weather file for the year 2013 was created using actual weather data on a six-minute interval basis. The energy simulation was run and the model was calibrated to the required accuracy. Using the calibrated model as a baseline, different energy conservation measures were applied to the building model and the corresponding energy savings were evaluated as shown in Table 1.

Table 1 Costs vs. savings for each ECM applied to the Glennan Building

ECM	Estimated cost	Annual energy saving [kWh]	Expected annual saving	Payback period [years]
ECM# 1 (Cooling/heating set point temperature)	\$0	334855	\$16,831	0.0
ECM# 2 (HVAC system AHUs and pumps schedules)	\$0	625729	\$32,243	0.0
ECM# 3 (Additional insulation for the external walls)	\$210,000	192301	\$8,094	25.9
ECM# 4 (Adding vestibule to building entrance)	\$60,000	105604	\$4,671	12.8
ECM# 5 (Plug loads and equipment schedules)	\$0	520053	\$47,531	0.0
ECM# 6 (LED lighting fixtures)	\$145,000	111176	\$10,325	14.0
ECM# 7 (Heat recovery devices)	\$90,000	92923	\$2,532	35.5
ECM Set# 1 (All combined)	\$505,000	1887039	\$118,213	4.3
ECM Set# 2 (All combined without heat recovery devices)	\$415,000	1813701	\$116,001	3.6
ECM Set# 3 (ECMs with low or no cost)	\$0	1470661	\$95,971	0.0

ECM set# 3 (changing the cooling/heating set point temperature, the HVAC system schedules and the plug loads schedules) requires minimal investment but offers significant energy savings. Other ECMs are less attractive due to their long payback period.

2 Case Study – the Lofts suite 117

An overview, introducing the Lofts building that is to be modeled in this research (shown in Fig. 2), is provided for the building layout, location and orientation. The description also includes the building type, occupancy, lighting type, and equipment. It also includes a description of the Heating, Ventilating and Air Conditioning (HVAC) system.



Fig. 2 The Lofts exterior

2.1 Building Description

The building modeled in this work is the Lofts on Danforth campus of Washington University in St. Louis, MO. It is comprised of four separate buildings, and the one considered in this work has entrance at 6300 Enright Ave. The Lofts was built in 2012 and opened officially in January 2013. The building is located on the north side of the Danforth campus and is accessible from Enright Avenue as well as McGinnis Alley, as shown in Fig. 3. It is a university managed residential building for upper-class students. The Lofts is a four-story building with furnished apartments, common area lounges, a laundry room, a bicycle storage room, a trash room, and many mechanical and electrical facility rooms. Most of the windows are located on the east and south side; there are no windows on the south side of first floor as shown in Fig.3.



Fig. 3 Entrances at Enright Ave and McGinnis Alley (Google Map 3D)

2.2 Building HVAC system

The Lofts uses Variable Refrigerant Flow (VRF) zoning system. VRF zoning is a method of providing precise comfort control to buildings with multiple floors and areas by moving refrigerant through piping to the zone to be cooled or heated. VRF zoning system can simultaneously cool some zones while heating others. Regardless of time of day, sun or shade, season of the year or special requirements. The outdoor units (shown in Fig. 3) on the building roof feature an Inverter-driven compressor that varies the motor rotation speed, allowing it to precisely meet each zone's load requirement by transferring refrigerant through ceiling-suspended ducts (shown in Fig. 4). The central controller in the mechanical room located on the first floor can monitor, schedule and control all 56 indoor units.



Fig. 4 Ceiling-suspended ducts in suite 117

2.3 Suite Occupancy

Suite 117 is a three-bedroom suite with a restroom, a sitting room and a kitchen. I am currently living in room 117A, so my personal schedules were used as the occupancy of 117A. On weekdays, I leave for class at 8 am in the morning and come back at about 5 pm. On weekends, I go out for 6 hours on average and stay at home for the rest of time. I go out for dinner every day from 5:30 pm to 7 pm. When I am in the suite, I spend approximately half of the time in my bedroom and another half in the sitting room. Both of my roommates are studying abroad this semester, so room 117B and 117C are considered to be empty.

2.4 Suite Lighting and Equipment

The suite has a 250W refrigerator, a 1000W microwave, a 2150W stove with oven, a 1200W dishwasher, and two 100W personal computers. Four light bulbs installed in the suite are fluorescent T8 2ft 20W. Two 42W four-pin bulbs are used in the restroom and sitting room. The term equipment in EnergyPlus also includes all socket loads. All of these tools and equipment are considered to be power-consuming devices as well as heat-generating devices. When doing energy simulation, these devices have to be allocated in a service zone, along with their schedule of operation and percentage of loading, if applicable.

3 Modeling and Simulation

Different phases and steps for creating a full-zone model and an accented model were considered. A model is a virtual building created with computer software, and should dynamically represent the actual building and any systems that consume power along with their corresponding manner of operation.

In this study, two models were created for the Lofts. One used the traditional full-zone method which accurately built the model of the entire building with complete information of structure, occupancy, equipment, and HVAC. Another one used the accented modeling method which only fully modeled the interested rooms, in this case suite 117, and modeled other rooms as a few thermal zones. Simulation results of the two models would then be compared to evaluate the effectiveness of the accented modeling method.

The geometry of the building can be created using one of the graphical interface software programs, as the energy simulation program (EnergyPlus) does not have a user-friendly graphical interface by itself. DesignBuilder is an easy-to-use software that requires minimal expertise and only a basic understanding of building engineering [5]. It is integrated with EnergyPlus and has extensive material libraries which are helpful when selecting the materials.

The energy simulation is run after all the data input has been completed for the created virtual model. The default weather file for St. Louis in DesignBuilder's library was used.

3.1 Full-zone Method

An accurate building model was created using full-zone method, where all thermal zones were modeled with full information in construction, occupancy, equipment, and HVAC.

When starting a new project, the location and analysis type is chosen. For this work, St. Louis, MO and EnergyPlus were selected, respectively. The highest level in the model hierarchy is the Site, and therefore a site name is first chosen. The second level in the hierarchy is the Building; a new building is added under the previously-named site, and a building name can be assigned to it. Multiple buildings can be assigned under the same site, each with its own name. The third level in the hierarchy is the Block. The block usually represents one floor, and is commonly named with that floor name or number. Based on the floor plans provided by WUSTL Residential Life Office shown in Appendix B, the building construction model is created and is shown in Fig. 5.



Fig. 5 Full-zone model of the Lofts in DesignBuilder

The zoning phase separates the different thermal zones. For this work, each suite in the Lofts is considered a zone, totaling 78 thermal zones. Significant data input and simulation time is required to achieve this representation, but more accurate results were expected. The full-zone method also allows the assigning of different operational schedules to each zone.

Each of the walls in each zone is called surface. Surface is the next level in the model hierarchy. Exterior windows were assigned where applicable, and the DesignBuilder software

recognizes windows as sub-surfaces and are called openings. The hierarchy of the Glennan building is partially shown in Fig. 6.

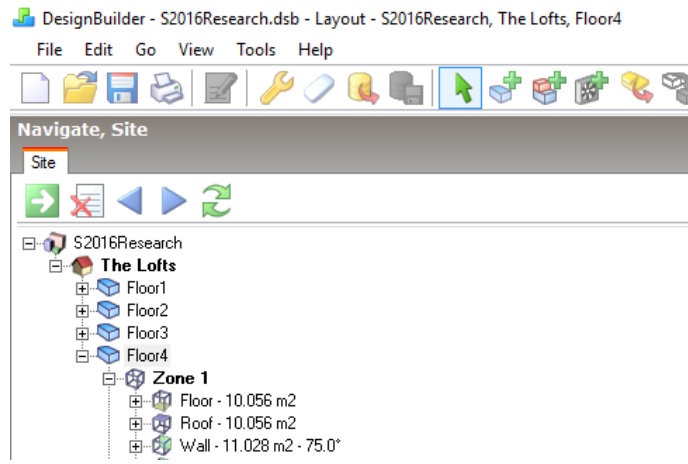


Fig. 6 Hierarchy in DesignBuilder

The DesignBuilder program gives the ability to choose the materials used in the construction of the building through its material libraries, and the chosen materials are assigned to the specified parts of the building. These steps were repeated for all floors to complete the entire building model.

3.2 Accented Modeling Method

Zoning, or creating thermal zones, is an important task. While assigning a more discrete number of zones can improve the accuracy of the simulation results, using a fewer number of zones is recommended for faster simulation.

Considering that this building model is being created for the purpose of energy simulation, different thermal zones can be joined to form one thermal zone if they share the same thermostat, have similar thermal loads, or use the same HVAC system.

In this case, suite 117 is the study focus, which means only the accurate energy consumption rate of suite 117 will be studied using the model, then all the other thermal zones on each floor can be combined into one thermal zone containing the combined information of construction, temperature load, occupancy, equipment, and HVAC.

Construction information of several thermal zones was combined by removing all the internal partitions between selected zones. Since heat transfer through these partitions used to have losses, now that these partition were removed, additional power generating unit had to be added into the new combined thermal zone. The power generation rate of the added unit was approximated using the formulae:

$$q = UA\Delta T$$

$$\frac{1}{U} = \frac{L}{kA} + \frac{1}{hA}$$

where q is the heat generation rate of the added unit, U is the total transfer rate of removed partitions, A is the cross-section area of the partition, ΔT is the temperature difference between the temperature set points of two thermal zones, and k and h are material properties of the partition.

Temperature load of the new combined thermal zone was modified by averaging the original temperature set points using the following equation:

$$\bar{T} = \frac{\sum_i T_i A_i}{\sum_i A_i}$$

where \bar{T} became the temperature set point of the combined thermal zone, T_i and A_i were the temperature set points and construction area of the original thermal zones, respectively.

The occupancy, human activities, equipment power usage and schedules, and HVAC settings of the original thermal zones do not vary before and after removing partitions, therefore they were left unchanged and the DesignBuilder automatically incorporated them into the new combined thermal zone. Fig. 7 shows the first floor before and after combining zones.

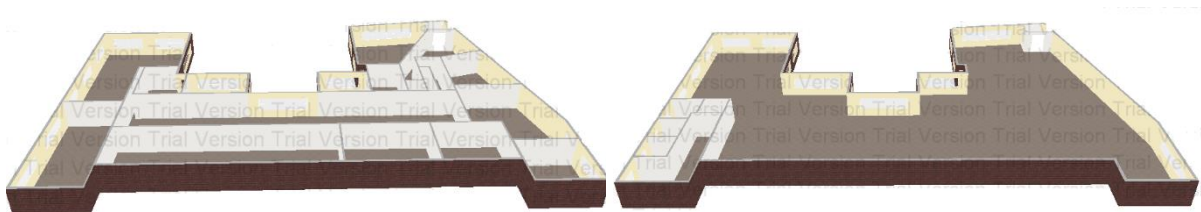


Fig. 7 Full-zone model (left) and accented model (right) of the Lofts first floor

3.3 Simulation using EnergyPlus [2]

The process of setting up EnergyPlus is described in “Energy Efficiency Analysis and Optimization for the Glennan Building at Case Western Reserve University” by A. Elshamy, and is reproduced here. Once the building model is created by DesignBuilder, it is then exported to the EnergyPlus input data file (idf), and energy modeling and simulation continues using EnergyPlus. Following the DesignBuilder import, additional data input required by EnergyPlus can be accomplished either through the IDF editor or the Text editor, as shown in Fig. 8. The text editor requires greater experience and familiarity with EnergyPlus. The IDF editor was largely used for this study since it was found to be more convenient.

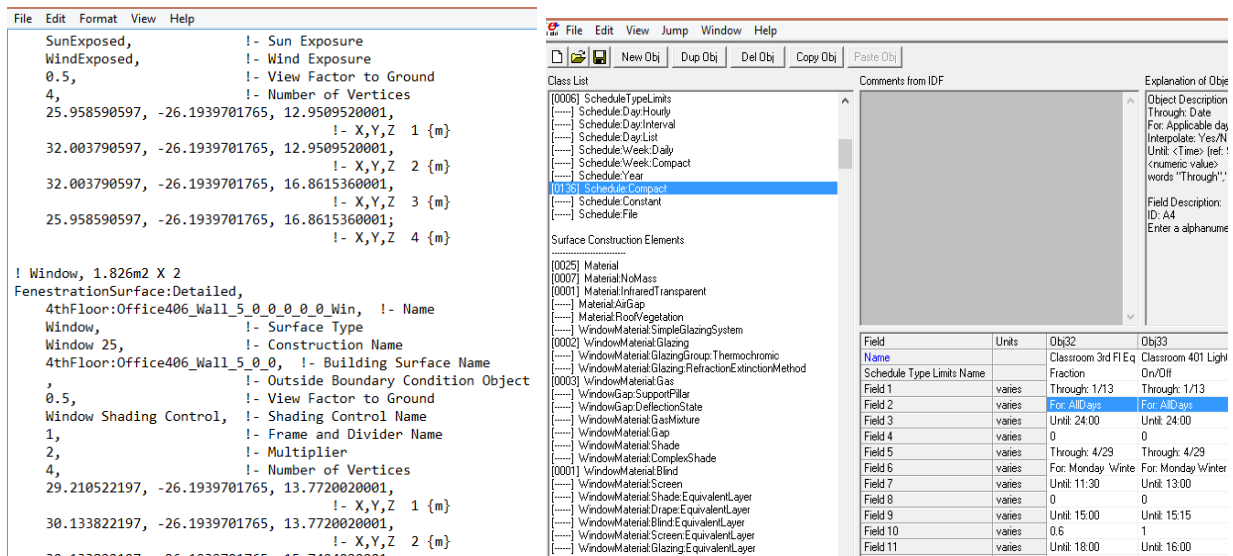


Fig. 8 Text editor screen (left) and IDF editor screen (right)

The weather file is a file that describes the different weather parameters throughout the year. Different weather files for different locations around the world can be found in the EnergyPlus library and are downloaded with the program. The Department of Energy’s Office of Energy Efficiency & Renewable Energy website has more than 2,100 locations available in the EnergyPlus weather format [6]. More than 1,000 of these locations are in the USA. These weather files represent the Typical Meteorological Year (TMY), which corresponds to the average weather across several years for a particular location. For this study, the nearest location TMY weather file (St. Louis and Lambert) was used.

In EnergyPlus, each data that is to be input is a *Field*. Different fields are arranged under a common *Object*. Different objects are arranged under a common *Group*. The different groups form the information included in the Input Data File. It is important here to note that not all the Groups, Objects, or Fields data will have entries since some are not applicable for the specific building. For example, the fields about solar collectors should be left blank if solar panels are not present.

The first group is the *Simulation Parameters*. The first object in this group is the Version which describes the version of the software; version 8.4.9 was first used and was then updated to 8.5.0. The second object is the *Simulation Control*, the chosen fields are Do Sizing Calculation, Do System Calculation, Run Simulation for Sizing Periods, and Run Simulation for Weather File Run Periods.

The next object (with its fields) describes the building. It was named: The Lofts, with a 6 degrees' orientation with the north axis (as shown in Fig. 9), with values of 0.08 watts and 0.4C as the *Loads Convergence Tolerance Value* and the *Temperature Convergence Tolerance Value*, respectively. When either one of the tolerances is achieved, the convergence is considered done. This tolerance represents the relation between the heat balance and the HVAC system. Using loose tolerances will minimize the run time; however, the results will not be accurate.

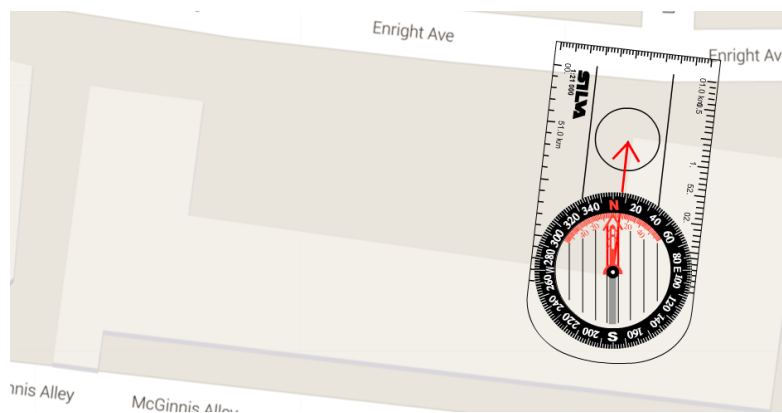


Fig. 9 The Lofts is oriented 6 degrees with the north (Google Compass)

The *Minimum and Maximum Number of Warm-Up Days* represents the days that the program simulates before convergence is achieved. If convergence is not satisfied by the

maximum number of days, the program will show an error, and an increase in the maximum number of days will be required. The minimum number of days is set to avoid false early conversions. In this case study, 40 and days were used as maximum and minimum, respectively. In fact, the EnergyPlus input/output help file recommends using 6 days as the minimum to avoid a false convergence. The *Shadow Calculation* object with its fields describes the criteria used to assess the shadowing effect around the Lofts Building. For this study, a frequency of 20 days was used such that the average sun position over the 20 days is employed to determine the magnitude of the sunlight impinging on the building.

4 Calibration and Results

Since the usage of equipment inside each suite varies in a wide range depending on personal behaviors, it becomes difficult to accurately model the building in a specific year, and even trickier when it comes to a specific suite, in this case, suite 117. As a result, the full-zone model was created as an intermediary connection between the accented model and the actual building – as long as the settings of suite 117 are the consistent in both models after calibration – the results can be compared on the same baseline.

4.1 Calibration

In energy modeling, calibration is the act of adjusting the different model parameter uncertainties to improve the model to achieve a high level of accuracy. ASHRAE guideline 14-2002 provides recommendations on at what level an acceptable uncertainty is achieved. This is accomplished at a normalized mean bias error (NMBE) of 5% and a coefficient of variation of the root mean square error (CVRMSE) of 15% relative to monthly calibration data [6] such that:

$$NBME = \frac{\sum_i (y_i - \hat{y}_i)}{(n - p)\bar{y}} \times 100$$

$$CVRMSE = \frac{\sqrt{\frac{\sum_i (y_i - \hat{y}_i)^2}{n - p}}}{\bar{y}} \times 100$$

where y is the dependent variable of some function of the independent variable(s), \bar{y} is the arithmetic mean of the sample of n observations, \hat{y}_i is the regression model's predicted value of y , n is the number of data points or periods in the baseline period, p is the number of parameters or terms in the baseline model, as developed by a mathematical analysis of the baseline data.

Guideline of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) states that $p = 1$ when the simulation is compared to actual building meter readings [7]. For the full-zone model, the initial simulation run led to an NMBE of 5.44 and CVRMSE of 7.94. The NMBE was out of the ASHRAE accepted 5%, requiring attention to be focused on input uncertainties.

To overcome these issues, revisions were made to those data with the highest uncertainty – the scheduled fraction of the used equipment in the different suites. Each suite is equipped with many tools and equipment that sometimes are rarely used, and for most suites no schedule for equipment was known. Given the relatively large contribution of this equipment to the electricity usage, the uncertainty of this equipment is of particular concern, and in order to do such adjustments, the fractions that represent the percentage of the used equipment during the different hours in each suite were modified in their corresponding schedules. Fig. 10 shows daily consumption during June after calibration.

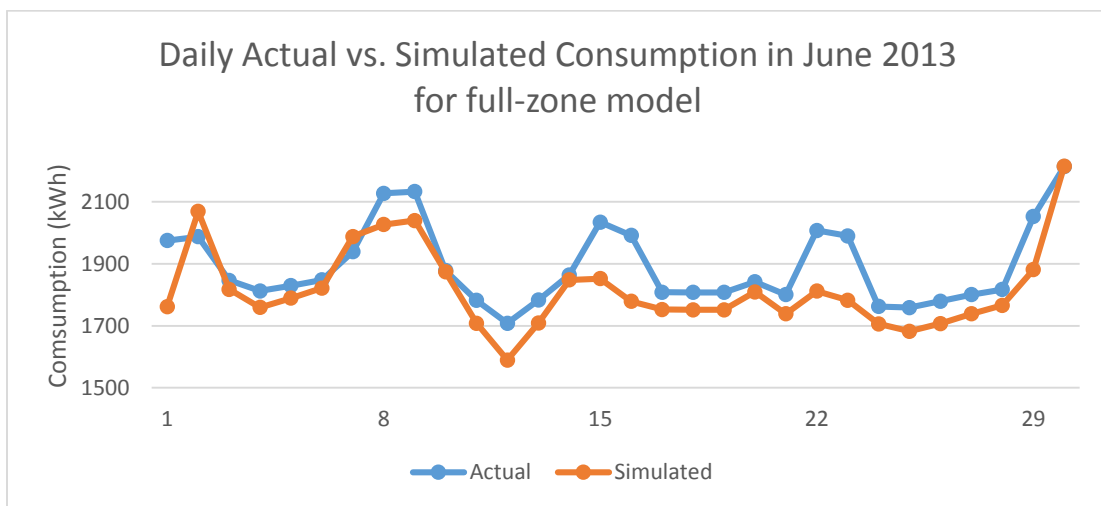


Fig. 10 Daily consumption during June after calibration

4.2 Results

An annual comparison between the actual and the simulated power consumption after calibration for the full-zone model is shown in Fig. 11.

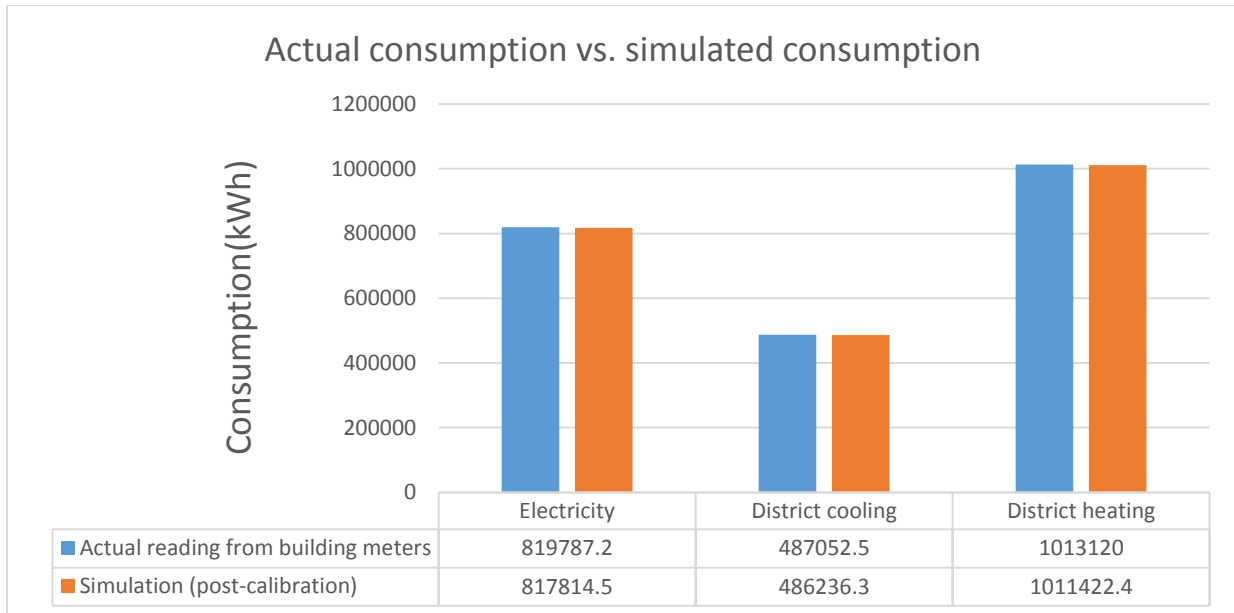


Fig. 11 Consumption rates from actual readings and simulation results

By re-running the simulation after each calibration and analyzing the results, followed by re-calibration and re-simulation, a final model was reached that meets the ASHRAE-approved accuracy with an NMBE of 0.183 and CVRMSE of 4.79, which are impressive values in consideration for the ASHRAE guidelines.

A comparison between actual and simulated monthly electricity consumption during the year 2015 is shown in Fig. 12. Again, the consumption is similar for both the actual and simulated results with only September demonstrating a large difference. Oftentimes, simulation of the “shoulder” months such as September can exhibit a high uncertainty due to large fluctuations in temperature over the month and the building’s corresponding occupancy variations.

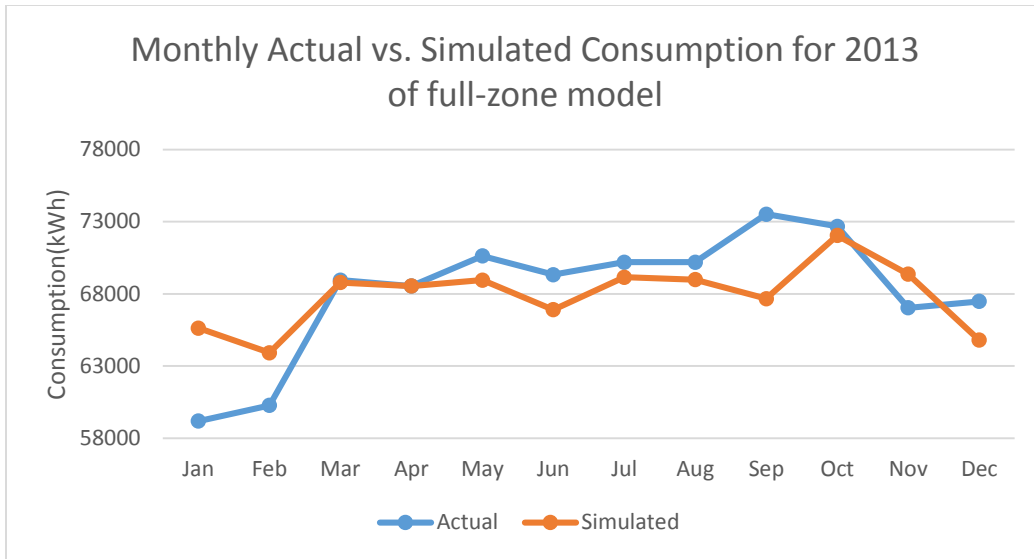


Fig. 12 Actual and simulated monthly electricity consumption in 2013

Once the full-zone model was created and calibrated with respect to actual meter readings, it became a baseline of evaluating the effectiveness of the accented model. To be consistent, exact same calibration “tweaks” were applied to the accented model, and simulation was run. Energy consumption of the interested room, suite 117, calculated from the accented model was compared to the results from full-zone model, both on a monthly basis and daily basis. Fig.13 and Fig.14 show the comparisons between the full-zone model and the accented model on a monthly basis and daily basis, respectively.

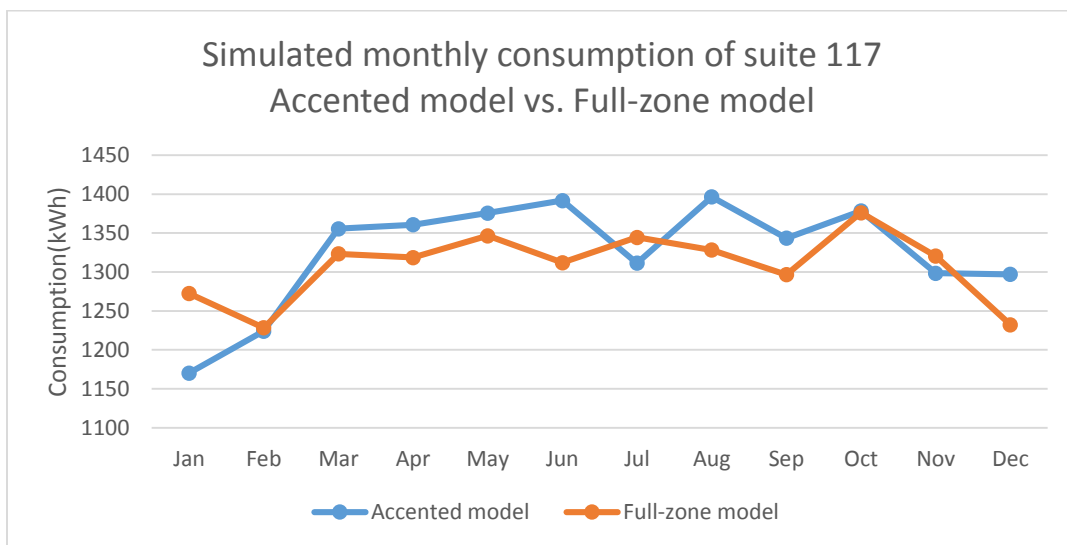


Fig. 13 Monthly electricity consumption of suite 117

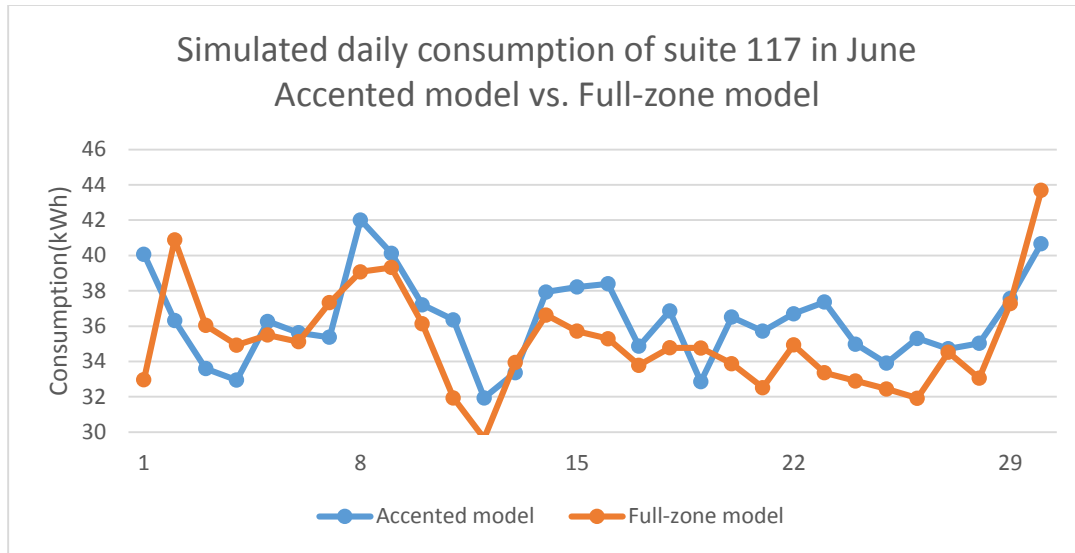


Fig. 14 Daily electricity consumption of suite 117

5 Analysis

Since the actual energy consumption was calculated from the meter readings in 2015, it is impossible to accurately model the occupancy and equipment schedules in a previous year, and it is meaningless to compare the accented model to the actual readings. However, the full-zone model can be calibrated on the building level – variations in occupancy and equipment schedules will become insignificant when the sample size becomes large.

After calibration, a final full-zone model was reached that meets the ASHRAE-approved accuracy with an NMBE of 0.183 and CVRMSE of 4.79, which are impressive values in consideration for the ASHRAE guidelines. Now that it can be said that this full-zone model can accurately represent the behavior of the actual building.

Then, by focusing on the energy consumption in suite 117 calculated using the full-zone model, the simulated results using accented model can be compared with consistency. A statistical paired T-test with significance level of 0.05 was performed on the daily consumption rate calculated from the two models using Excel, and the results were summarized in Table 2.

Table 2 Results of paired T-test on the accented model and full-zone model

	<i>Accented model</i>	<i>Full-zone model</i>
Mean	36.63	34.91
Variance	9.19	6.94
Observations	365	365
Pearson Correlation	0.76	
Hypothesized Mean Difference	0	
df	29.00	
t Stat	4.73	
P(T<=t) one-tail	0.00003	
t Critical one-tail	1.70	
P(T<=t) two-tail	0.00005	
t Critical two-tail	2.05	

The relevant stats in Table 2 are really the T-value and the critical T-value for two-tailed test. If the T-value is less than the critical value, we reject the null hypothesis which the means of two samples are the same. If the T-value is greater than the critical value, we fail to reject the null hypothesis and the two samples share the same mean.

The T-value given by the paired T-test is 4.73, and the critical T-value was 2.05 for a two-tailed test. Since the T-value was greater than the critical value, we were 95% confident to say that the means of two samples were the same, or in other words, the results given by the accented model were close to the full-zone results and actual readings. So, in this case, the accented modeling method was proved to be effective.

6 Conclusion

Two modeling methods are available for building-energy simulation and analysis – the full-zone method and the accented modeling method. Since the accented model is a simplification of the full-zone method, it usually requires less time to build but is less accurate than the full-zone model.

To evaluate the effectiveness of the accented modeling method, two models were created using DesignBuilder; one using full-zone method, and another using accented modeling

method. Both models were then exported into EnergyPlus for simulation. The energy consumption rate calculated using the full-zone model was compared to the actual meter readings and then calibrated. After calibration, the same schedule changes were applied to the accented model for consistency, and the simulation was run using the modified accented model.

By performing statistical analysis for the results calculated using the accented model, it was found that the daily energy consumption rates were close to that of the calibrated full-zone model, thus the accented model is effective under certain circumstances described in the following section.

7 Recommendation

Limitations do apply to accented modeling method. Based on the assumptions and approximations made in this study, an accented model is appropriate only when:

- only a small number of rooms need to be accurately modeled.
- other rooms share the same HVAC settings and can be combined into several simple thermal zones.
- internal partitions of the combined rooms do not have a significant influence on the overall energy consumption of the building.
- information of occupancy, human activities, equipment schedules, and HVAC settings is available

With limitations mentioned above, accented modeling is still preferred in some cases because time used for constructing and simulating the accented model was significantly less than that of the full-zone model. It is recommended that accented modeling method can be used when energy consumption rates of a small number of rooms need to be considered.

One application of accented modeling method would be pre-research for building retro commissioning. Often times building retro commissioning was performed and then found that the effect of applying certain ECMs was negligible, which was disappointing because budget was spent on the retro commissioning process and no changes could be made. This

embarrassing situation can be avoided by modeling several rooms with high energy consumption rates using accented modeling method, which costs a relatively small amount of money and helps to decide whether a full-zone building model is desirable for retro commissioning.

Another application would be research of projects that study only certain rooms in a building. For example, the Urbauer building at Washington University in St. Louis is an educational building which was recently reconstructed. Since only a few rooms were reconstructed, an interesting research would be investigating possible ECMs for these reconstructed rooms. However, it becomes cumbersome to build a full-zone model for the entire Urbauer building if only certain rooms are interested. In such situation, accented modeling method can be introduced to accurately model the reconstructed rooms rather efficiently. A procedural report summarizing steps needed to create a building model is included in Appendix C. It is written in such a way that any person with essential building engineering knowledge will be able to create a building model by following the steps.



Fig. 15 The Urbauer Building exterior view

References

- [1] G. Tverberg, "World Energy Consumption Since 1820," *Our Finite World*, 12-Mar-2012. [Online].
- [2] A. Elshamy, "Energy Efficiency Analysis and Optimization for the Glennan Building at Case Western Reserve University," Electronic Thesis or Dissertation, May-2014.
<https://ourfiniteworld.com/2012/03/12/world-energy-consumption-since-1820-in-charts/>
- [3] A. Burgard, "Sefaira Deploys EnergyPlus in the Cloud," *Sefaira*, 27-Aug-2013. [Online].
<http://sefaira.com/news/sefaira-deploys-energyplus-in-the-cloud-3/>
- [4] D. Crawley, "EnergyPlus: DOE's next generation simulation program," *EnergyPlus*, 16-Feb-2010.
- [5] Building Energy Software Tools Directory. [Online].
<http://www.buildingenergysoftwaretools.com/>
- [6] U.S. Department of Energy. Energy Efficiency and Renewable Energy. [Online].
http://apps1.eere.energy.gov/buildings/energyplus/weatherdata_about.cfm
- [7] *ASHRAE guideline 14-2002*.: American Society of Heating, Ventilating and Air Conditioning Engineers, 2002.

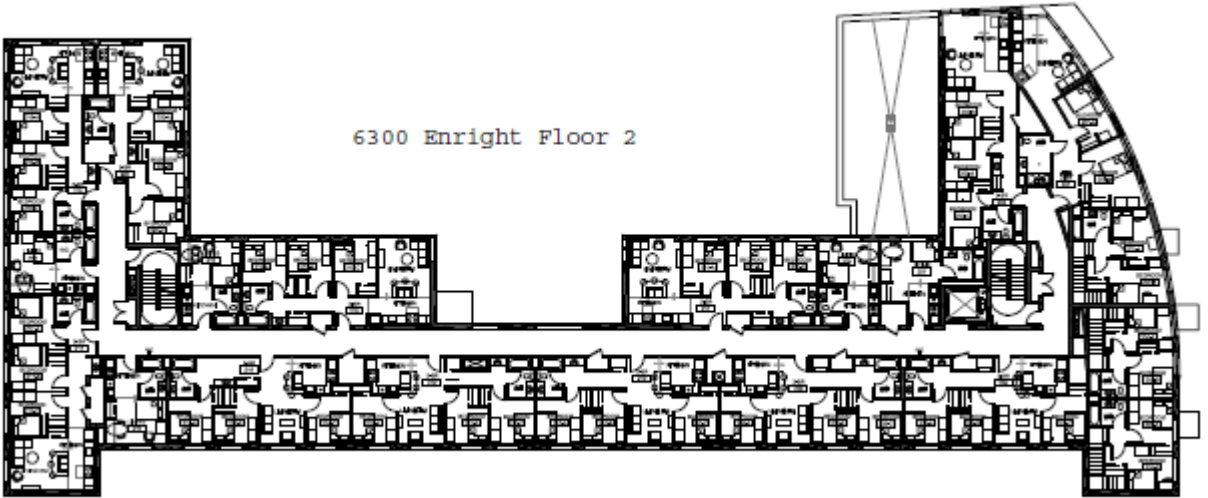
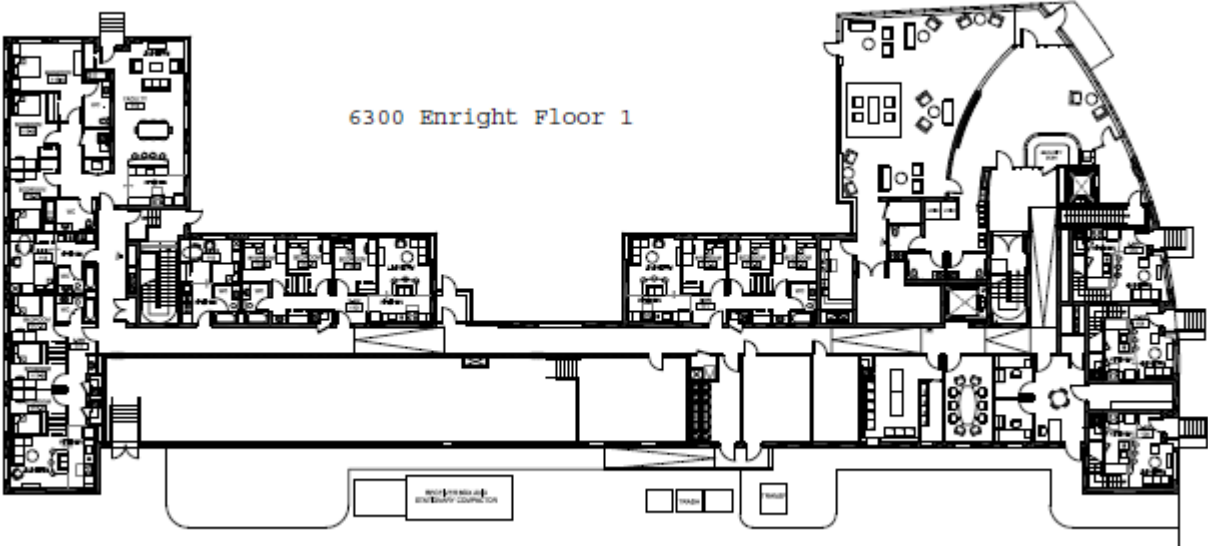
Appendix A. Glossary

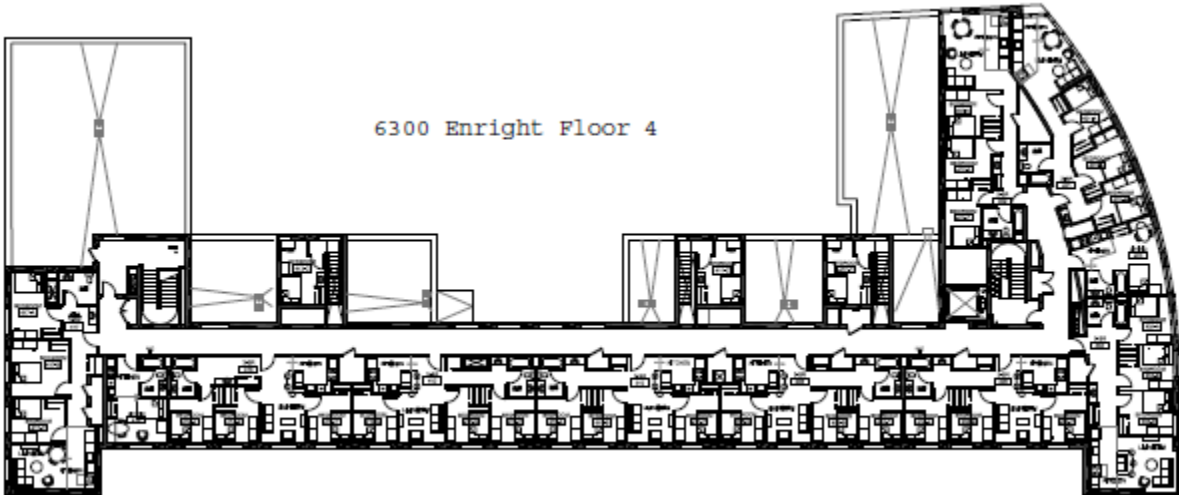
<i>energy efficient</i>	the goal to reduce the amount of energy required to provide products and services
<i>energy conservation measure (ECM)</i>	any type of project conducted, or technology implemented, to reduce the consumption of energy in a building.
<i>computational representation</i>	combination of data describing the building model
<i>full-zone modeling</i>	building modeling method representing each room as a thermal zone
<i>accented modeling</i>	a simplification of full-zone modeling which focuses and elaborates on certain rooms
<i>EnergyPlus</i>	a simulation engine for building modeling
<i>DesignBuilder</i>	a graphical user interface for EnergyPlus
<i>thermal zone</i>	combination of structures sharing the same thermodynamic properties
<i>internal gain</i>	heat gained by thermal zones from inside activities
<i>set point temperature</i>	temperature limit in a thermal zone
<i>null hypothesis</i>	a general statement or default position that there is no relationship between two measured phenomena, or no difference among groups
<i>significance level</i>	the probability of rejecting the null hypothesis given that it is true

Appendix B. The Lofts Floor Plans (6300 Enright Ave)

Provided by Residential Life at Washington University in St. Louis

Uses without permission are not allowed.





Appendix C. Procedural Report

The procedural report begins next page.

Procedural report

**CREATE A BUILDING MODEL
USING DESIGNBUILDER AND ENERGYPLUS**

by

Gary Hu

Department of Mechanical Engineering & Materials Science

Washington University in St. Louis

April, 2016

TABLE OF CONTENTS

1 Introduction	28
1.1 DesignBuilder	28
1.2 EnergyPlus	28
1.3 The Lofts Building	28
2 Create Computational Representation	29
2.1 Construct the Model.....	29
2.2 Partitioning and Zoning	31
2.3 Modification of Zone Details	32
2.3.1 Activity	32
2.3.2 Occupancy.....	32
2.3.3 Metabolic	33
2.3.4 Environmental Control	35
2.3.5 Equipment.....	35
2.3.6 Materials	36
2.3.7 Openings	36
2.3.8 Lighting.....	38
2.3.9 HVAC	39
2.4 Visualize.....	40
2.5 Export EnergyPlus Input File	40
3 Run simulation	41

1 Introduction

This report describes general procedures needed to building modeling using DesignBuilder and EnergyPlus. Introduction of software packages, creation of computational model, and simulation will be discussed in details.

Anyone with basic knowledge of building engineering should be able to reproduce the results and do similar building modeling following the procedures described in this document.

1.1 DesignBuilder



DesignBuilder is the oldest, easiest to use, most powerful graphical UI to EnergyPlus. It is available for download at <http://www.designbuilderusa.com/>. First-time users have a 30-day trial to evaluate the software, and an Engineering Kit is available for students at \$169.9. Useful tutorials for DesignBuilder can also be found at their website, noticing that the access of tutorials needs registration.

DesignBuilder used to generate this report is version 4.7.0.027 with Engineering Essentials Packages.

1.2 EnergyPlus



EnergyPlus is a whole building energy simulation program developed by US. Department of Energy. It is incorporated in the DesignBuilder, so it is automatically installed during the installation of the DesignBuilder. It is also available for free download at <https://energyplus.net/>.

EnergyPlus used to generate this report is version 8.5.0, the newest version from the Official website.

1.3 The Lofts Building

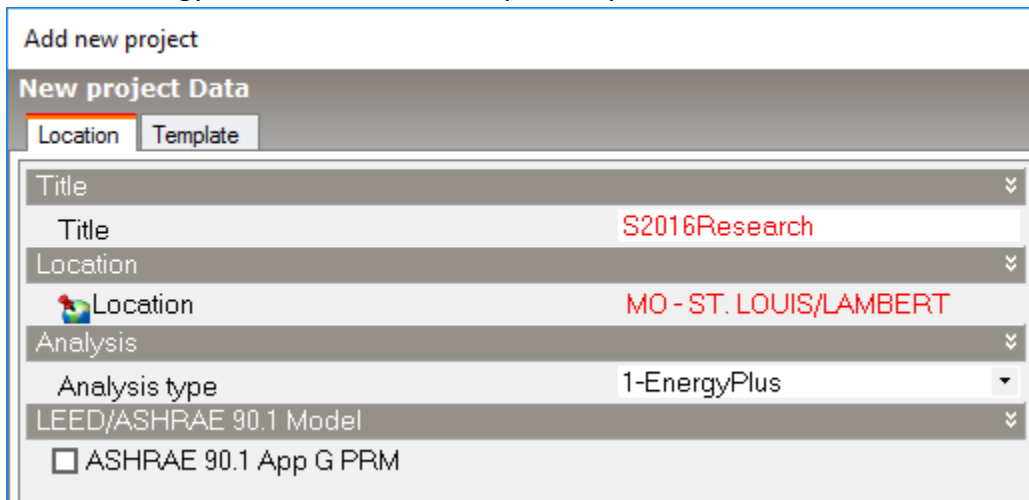
Building used to generate this report is the Lofts Building at North campus of Washington University in St. Louis. It has an entrance at 6300 Enright Ave. Suite 117 is of particular interest for the purpose of illustration in this document.

The Lofts is a residential building including various equipment and types of rooms inside, which can be a good example to illustrate the use of software packages.

2 Create Computational Representation

This chapter describes how to create a building model ready for simulation using DesignBuilder. Procedures and various input options are explained.

When starting a new project, the location and analysis type is chosen. For this work, St. Louis, MO and EnergyPlus were selected, respectively.



The screenshot shows the 'Add new project' dialog box. The 'New project Data' section is active, with two tabs: 'Location' and 'Template'. The 'Location' tab is selected. The fields are as follows:

Field	Value
Title	S2016Research
Location	MO - ST. LOUIS/LAMBERT
Analysis	1-EnergyPlus
LEED/ASHRAE 90.1 Model	
ASHRAE 90.1 App G PRM	<input type="checkbox"/>

Notice that modified items in DesignBuilder are shown in red. After the project is created, a DesignBuilder “.dsb” file will be created under the default folder.

The highest level in the model hierarchy is the Site, and therefore a site name is first chosen. The second level in the hierarchy is the Building; a new building is added under the previously-named site, and a building name can be assigned to it. The Building is named “The Lofts” in this case.

Multiple buildings can be assigned under the same site, each with its own name. The third level in the hierarchy is the Block. The block usually represents one floor, and is commonly named with that floor name or number.

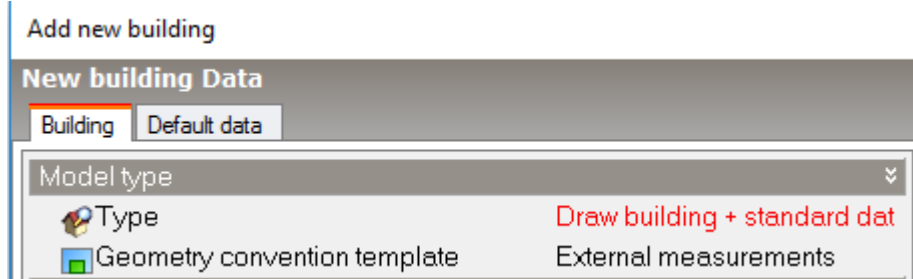


2.1 Construct the Model

For most buildings, building and floor plans are available and owned by the administrator of the building. For the Lofts building, floor plans are available for download at <https://reslife.wustl.edu/residential-areas/floor-plans/>. They are appended at the end of this

report. To accurately construct the model, a scale must be calculated at the very beginning. For the Lofts floor plans, the scale is measured to be 220:1.

By clicking “Add new building”, you are able to select the model type and project details. In this case, “Draw building + standard data” is chosen for “Type”, and “External measurements” is chosen for “Geometry convention template”. Notice that the most accurate energy consumption results can be obtained by selecting “Detailed design with HVAC”, which is for detailed design and analysis if you have component-based HVAC definition.

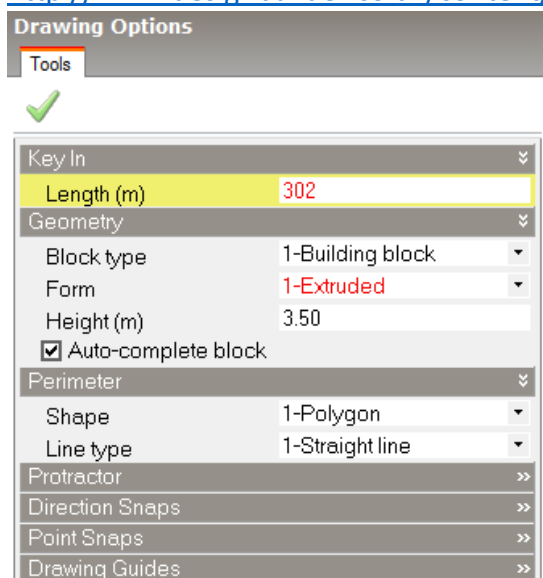


Then you draw the building. Blocks are defined in 3 stages.

- First, select the plane on which to draw the base perimeter.
- Second, draw a base perimeter on the selected plane by moving the mouse cursor to the first corner and clicking. Then move to the next point and click. Notice that by entering the length of the edge and press “Enter” can achieve the same result. Continue in this way, completing the block perimeter by joining up with the first point.
- Third, when block perimeter is completed, the block is generated by “extruding” the perimeter.

Additional tutorials for constructing the building is available at

<http://www.designbuilder.co.uk/content/view/105/184/>.



This procedure is repeated for all floors of the building. After a building model is initially constructed, each block is represented by 1 zone by default. To change that, you need to enter zoning mode and use partitions to divide the block.

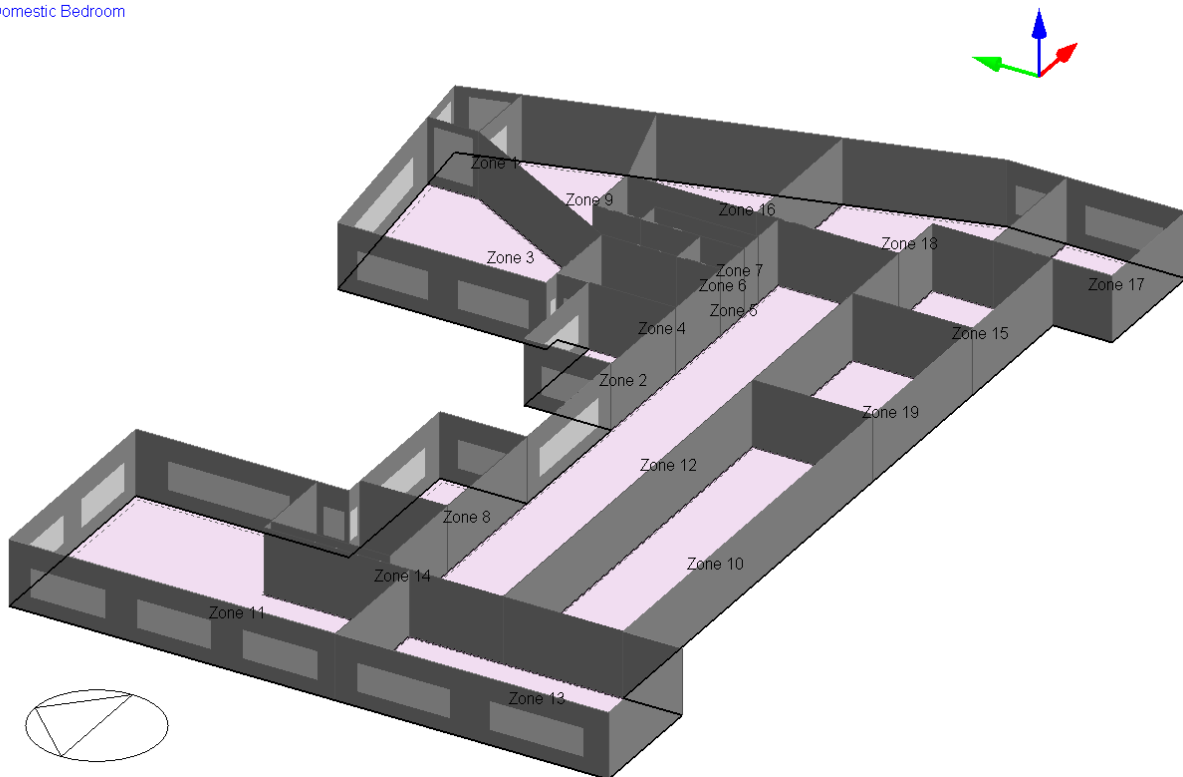
2.2 Partitioning and Zoning

By clicking on the floor/block name in the navigation panel, you will be able to edit the block layout. Blocks can be partitioned up into 2 or more zones by drawing internal walls. When the region of the block is enclosed by external and/or internal walls it becomes a zone and is modelled separately in simulations.



As an example, the fully zoned Lofts 1st floor is shown below:

 Domestic Bedroom



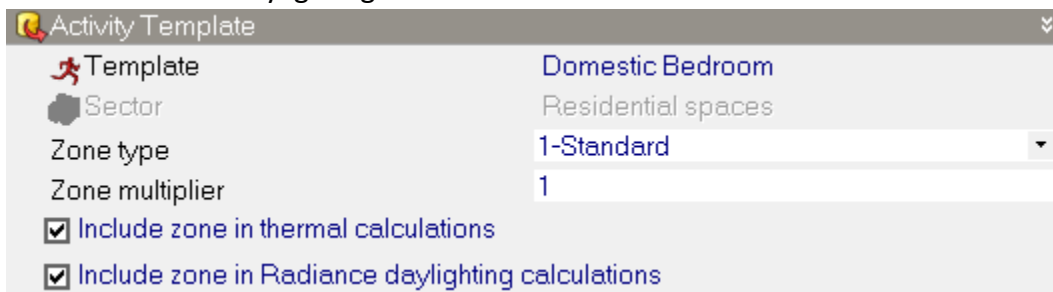
However, as you can see, all zones in the block are by default modeled as “Domestic Bedroom” (The default can be changed at building level). In order to change detailed settings of each zone, activity, construction, openings, lighting, HVAC, and CFD information must be input for each zone. The more information the model has, the more accurate simulation result you will get.

2.3 Modification of Zone Details

Details about various types of input data are discussed in this chapter.

2.3.1 Activity

To edit activity data, you can make a generic selection from the activity template list. This loads data from the selected template into the current block. Alternatively, you can open the group header boxes to access the data directly. In this case, for suite 117, the default template “Domestic Bedroom” is chosen for “Template”, and “1-Standard” is selected for “Zone type”, it is very important to check the boxes of “Include zone in thermal calculations” and “Include zone in Radiance daylighting calculations”.



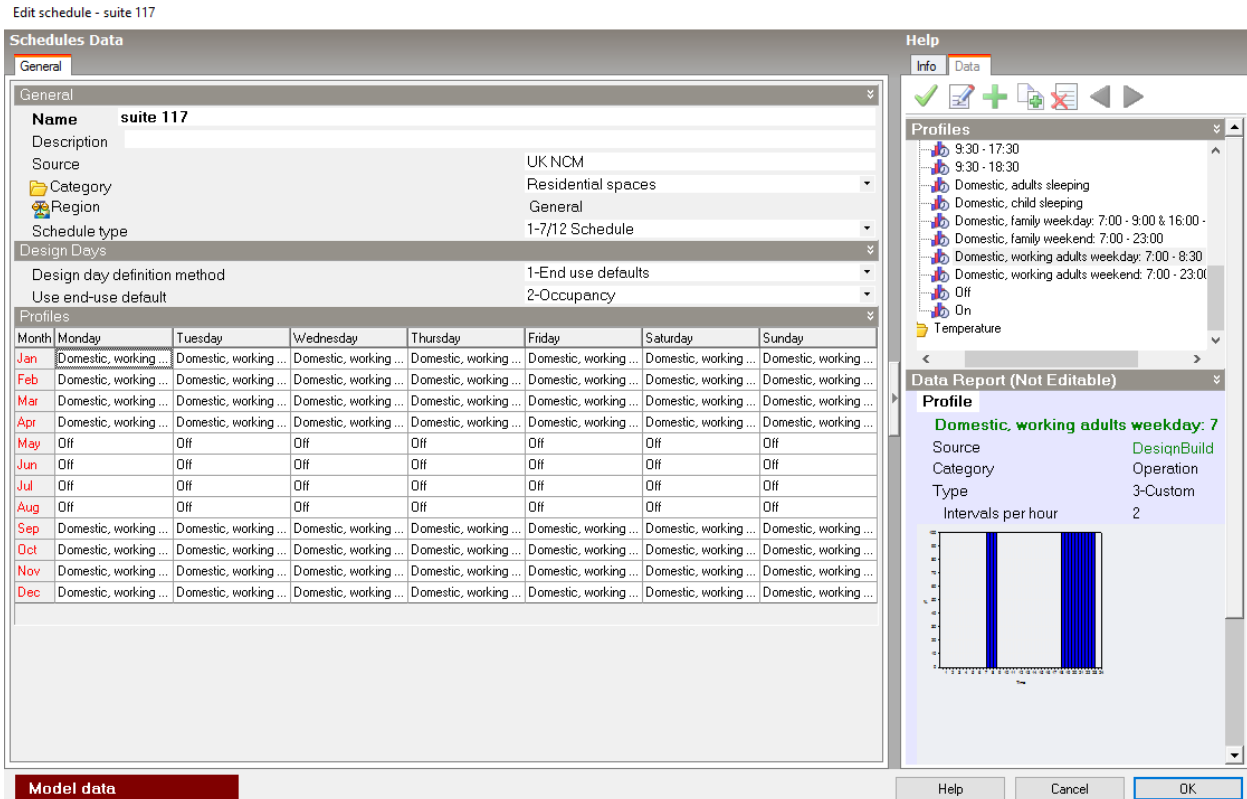
2.3.2 Occupancy

Set the number of people (per unit floor area) and the occupancy times. The occupancy times are controlled by a schedule. In this case, the total area of suite 117 is measured to be 112.9 m², and there are three people inside the suite at maximum, so the occupancy density is set to be 0.0266 people/m².



The default schedule for domestic bedroom is “Dwell_DomBed_Occ”, which is not properly representing the schedule in suite 117. To edit the schedule, first make a copy of the template (The original template is not editable), then rename it to “suite 117” and click on “edit template”.

It is found that the schedule is most easily edited by selecting “1-7/12 Schedule” for “Schedule type”. Each cell inside the “Profile” section is editable.



2.3.3 Metabolic

Set the metabolic rate according to the level of activity within the space. The metabolic factor accounts for people of various sizes. enter 1.00 for men, 0.85 for women, 0.75 for children, or you can use an average value if there is a mix of sizes. Table below is adapted from ASHARE handbook 2009 (table: 4 P.9.6)

	Btu/h · ft ²	met*
Resting		
Sleeping	13	0.7
Reclining	15	0.8
Seated, quiet	18	1.0
Standing, relaxed	22	1.2
Walking (on level surface)		
2.9 fps (2 mph)	37	2.0
4.4 fps (3 mph)	48	2.6
5.9 fps (4 mph)	70	3.8
Office Activities		
Reading, seated	18	1.0
Writing	18	1.0
Typing	20	1.1
Filing, seated	22	1.2
Filing, standing	26	1.4
Walking about	31	1.7
Lifting/packing	39	2.1

For suite 117, about half of the time people are sleeping, and another half reading, writing or typing. So an average metabolic rate of 0.85 is used.

Metabolic	
Activity	Bedroom (dwelling)
Factor (Men=1.00, Women=0.85, Childr...	0.85
CO2 generation rate (m3/s-W)	0.0000000382
Clothing	
Winter clothing (clo)	0.50
Summer clothing (clo)	0.50

Notice that since the suite is maintained at a relatively constant temperature throughout the occupied time period, both winter and summer clothing factors are chosen to be 0.50.

2.3.4 Environmental Control

The heating and cooling set point temperatures, minimum fresh air and illuminance requirements are related to the activity and are accessed by opening the Environmental Control Group header. All values in this sections are kept default except the heating and cooling set points.

If the building you are modeling is a commercial building, you might be able to get heating and cooling temperature set points from corresponding department. If, instead, there is a temperature control panel inside the room, the values shown on that device should be input as the set points.



Environmental Control	
Heating Setpoint Temperatures	
Heating (癩)	19
Heating set back (癩)	17
Cooling Setpoint Temperatures	
Cooling (癩)	28
Cooling set back (癩)	30
Humidity Control	
RH Humidification setpoint (%)	10.0
RH Dehumidification setpoint (%)	90.0
Ventilation Setpoint Temperatures	
Natural Ventilation	
<input checked="" type="checkbox"/> Indoor min temperature control	
Min temperature definition	1-By value
Min temperature (癩)	24.0
<input type="checkbox"/> Indoor max temperature control	
Minimum Fresh Air	
Fresh air (l/s-person)	10.000
Mech vent per area (l/s-m2)	0.000
Lighting	
Target Illuminance (lux)	100
Default display lighting density (W/...	0

2.3.5 Equipment

The sum power consumption and energy gains of all equipment inside the zone needs to be calculated and input into “Computers”, “Office Equipment”, “Miscellaneous”, “Catering”, and “Process” sections. The uncertainty of simulation results mainly come from this section, so you should play around with these values when doing calibration.

2.3.6 Materials

With “General” construction detail you can make a generic selection from the construction template list. This loads data from the selected template into the current block. Alternatively, you can open the group header boxes to access the construction of walls, partitions, floors etc. directly.

To inspect the details of a selected construction, click on the icon to the left of the appropriate data entry box and open the Data Tab. Different materials should be selected for each type of surface.

The screenshot shown on next page shows the materials used for sub surfaces. A “Lightweight 2 x 25mm gypsum plasterboard with 100mm cavity” template is selected to describe the construction of subsurfaces.

2.3.7 Openings

Openings include windows, external doors, and internal doors. They are automatically constructed when you finished constructing the building model. However, the default construction of openings is based on the “Project Glazing” template, and you may want to change that according to the actual floor plans.



Definition

Definition method 1-Layers

Calculation Settings

Simulation solution algorithm 1-Default
 Involves metal cladding No

Layers

Number of layers 3

Outermost layer

Gypsum Plasterboard
 Thickness (m) 0.0250
 Bridged? No
 Heat transfer integration mode 3-Integrated Surface Outside Fa

Layer 2

Air gap 10mm
 Thickness (m) 0.1000
 Bridged? No

Innermost layer

Gypsum Plasterboard
 Thickness (m) 0.0250
 Bridged? No

Outside Surface

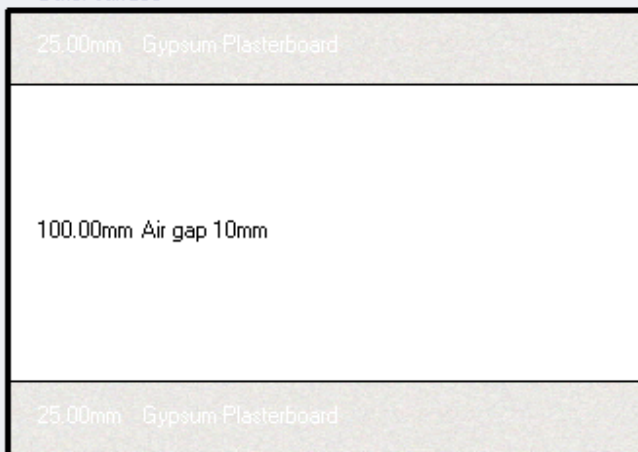
Fix convective heat transfer coefficient No

Inside Surface

Fix convective heat transfer coefficient No

Cross Section

Outer surface

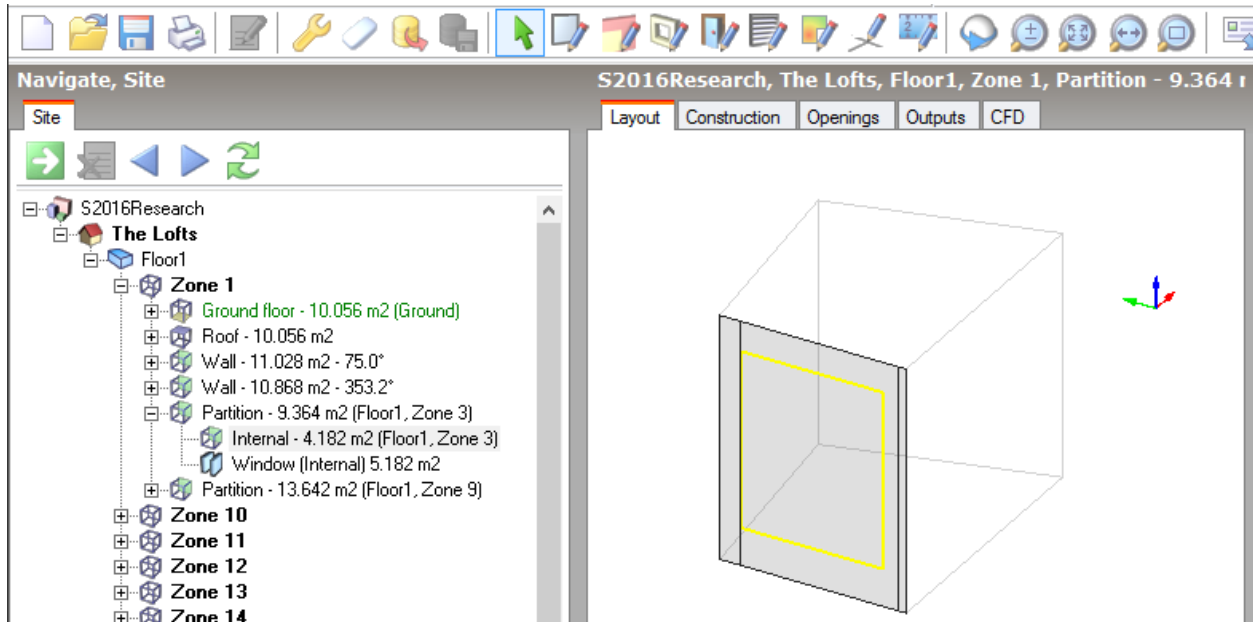


Inner surface

Inner surface

Convective heat transfer coefficient (W/m²-K) 2.152
 Radiative heat transfer coefficient (W/m²-K) 5.540
 Surface resistance (m²-K/W) 0.130

To change openings, you need to go back to the Layout section where you constructed the building model. By clicking on a zone or a specific surface, an opening graph will be shown on screen. To modify openings for a specific surface, expand the zone, and expand the sub surface you want to edit, a menu for drawing openings will be shown at the top.

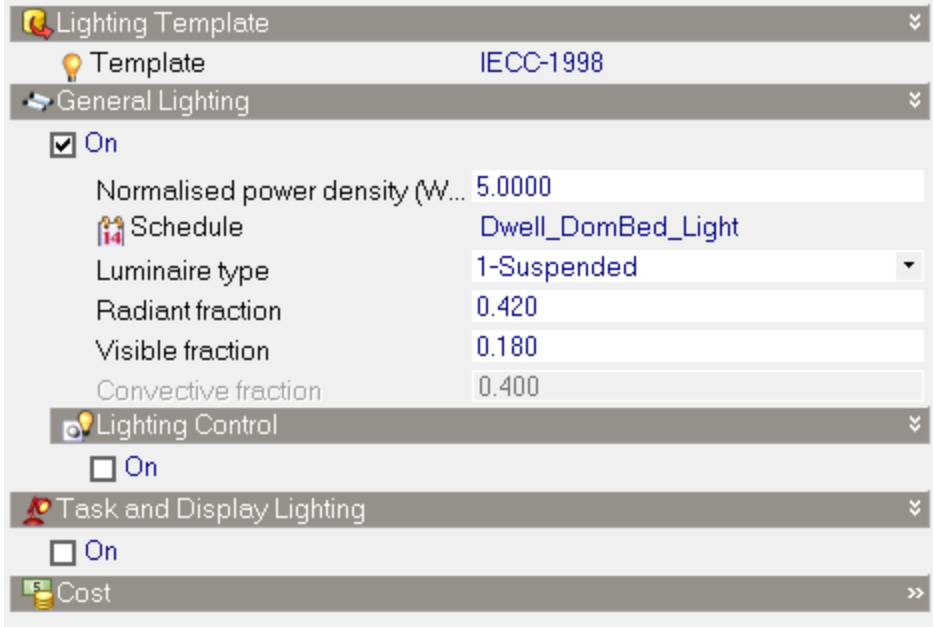


Repeat this procedure for all surfaces and sub surfaces of the building, until you have the correct setup of openings. This can be the most arduous work in the entire modeling process.

2.3.8 Lighting

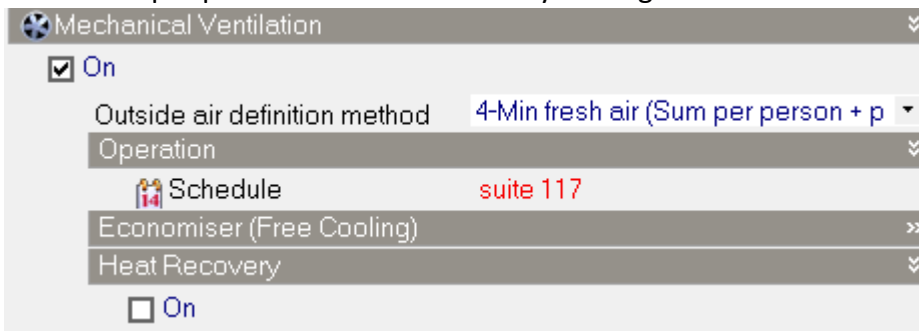
When using the “W/m²-100 lux” lighting model option, the lighting gains used in the simulation are calculated by multiplying the lighting energy “in W/m²-100 lux” by the required activity illuminance level divided by 100, and multiplied by zone floor area. There is an alternative model option to enter lighting gains in units of W/m².

You can control the lights according to the daylighting illuminance on the working plane. For daylighting control check the Lighting Control check box. Note that when lighting control is on, the sum of ‘% of zone covered by lighting zone 1’ and ‘% of zone covered by lighting zone 2’ can add to less than 100%, must not exceed 100%. If it is less than 100%, the remainder of the zone is modelled as uncontrolled.

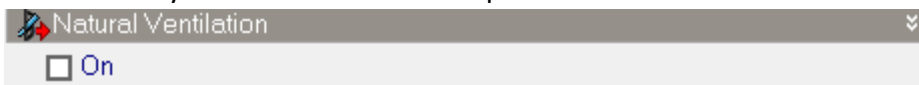


2.3.9 HVAC

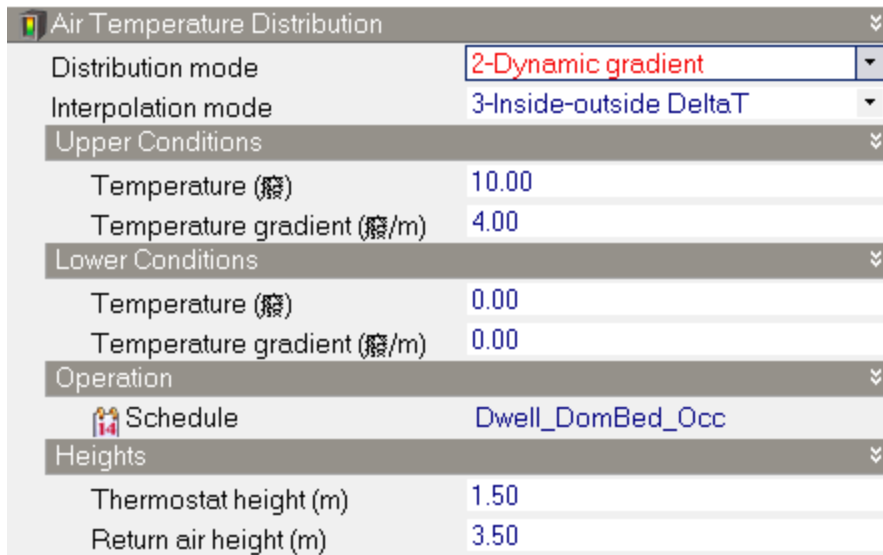
The outside mechanical ventilation air flow rate and its operation can be defined. The flow rate is set either by specifying it directly as air changes per hour or by accessing the minimum ventilation per person data on the Activity tab together with the number of people.



The natural ventilation rate and its operation can be set. “Scheduled” natural ventilation is active when the air temperature in the zone is higher than the natural ventilation set-point. You can set a very low value to avoid temperature control of natural ventilation.



By default, EnergyPlus assumes that air temperature within a zone is completely uniform. The Air Temperature Distribution data allows you to set up a vertical temperature gradient which varies dynamically depending on outside temperature, inside temperature, inside-outside temperature difference, heating load, and cooling load.



2.4 Visualize

After modeling is done, you can click on Visualize on the bottom control panel to see the rendering of your building model.



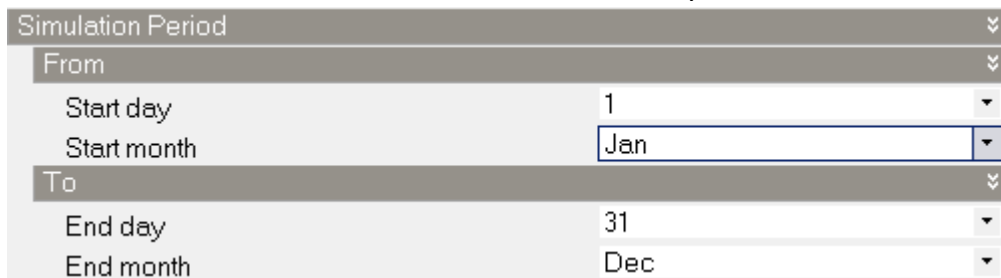
2.5 Export EnergyPlus Input File

DesignBuilder is only a graphical user interface for EnergyPlus, it cannot run simulation on its own. To run simulation, you need to go to File → Export → Export EnergyPlus input file → Simulation, to create an idf file which is readable by EnergyPlus.

3 Run simulation

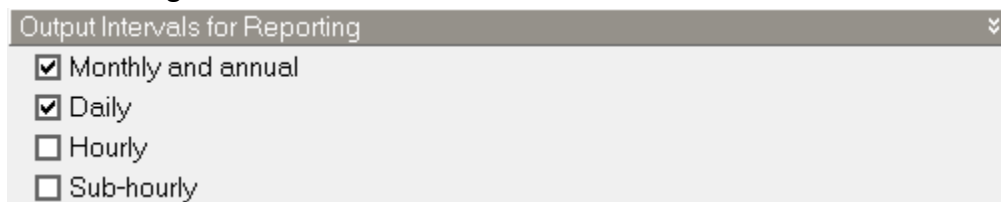
You can edit simulation settings using EnergyPlus or using the Simulation Manager provided by DesignBuilder. The latter is used because it is found to be much more convenient than the user interface provided by EnergyPlus.

In Simulation Period Tab, select the start and end days for the simulation.



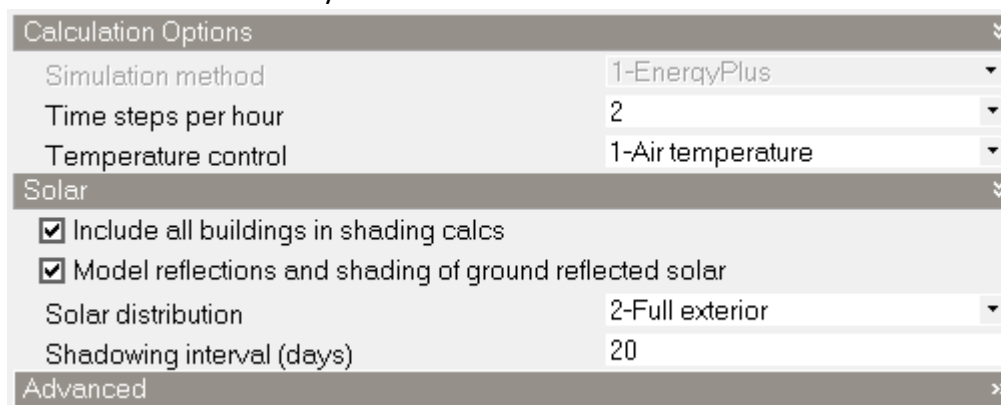
Simulation Period	
From	
Start day	1
Start month	Jan
To	
End day	31
End month	Dec

In Interval tab, Monthly and annual output is always generated and daily, hourly, and sub-hourly data can be selected by checking the appropriate boxes. Note that selecting output at hourly or sub-hourly intervals can produce large amounts of data which slows processing and results in large file sizes.



Output Intervals for Reporting	
<input checked="" type="checkbox"/>	Monthly and annual
<input checked="" type="checkbox"/>	Daily
<input type="checkbox"/>	Hourly
<input type="checkbox"/>	Sub-hourly

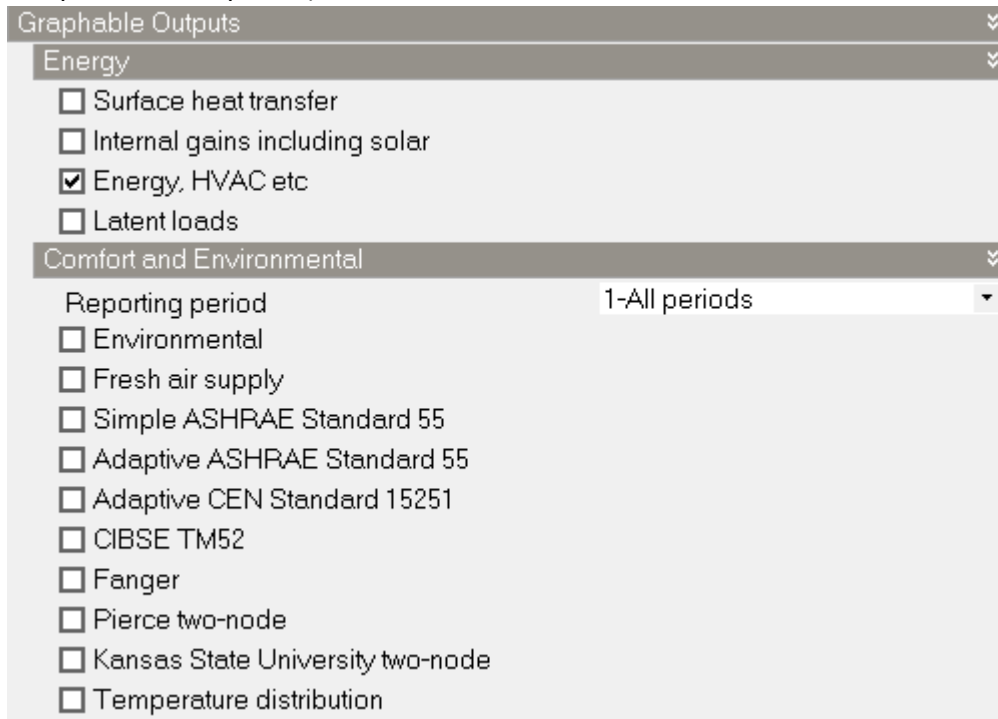
In Time Steps tab, increasing the number of time steps improves accuracy but slows the simulation, in general. In this case, 2 time steps per hour to get a relatively quick simulation with reasonable accuracy.



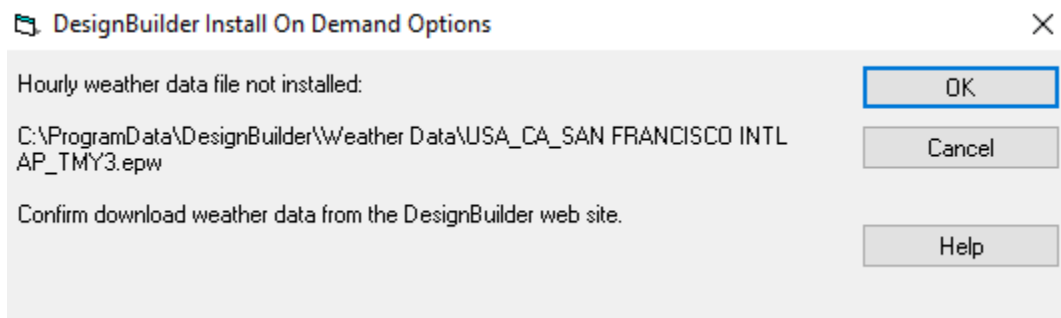
Calculation Options	
Simulation method	1-EnergyPlus
Time steps per hour	2
Temperature control	1-Air temperature
Solar	
<input checked="" type="checkbox"/>	Include all buildings in shading calcs
<input checked="" type="checkbox"/>	Model reflections and shading of ground reflected solar
Solar distribution	2-Full exterior
Shadowing interval (days)	20
Advanced	

For purpose of building energy research, “Energy, HVAC etc” is selected for “Graphable Outputs”. This will generate energy consumption data of each zone as well as the entire

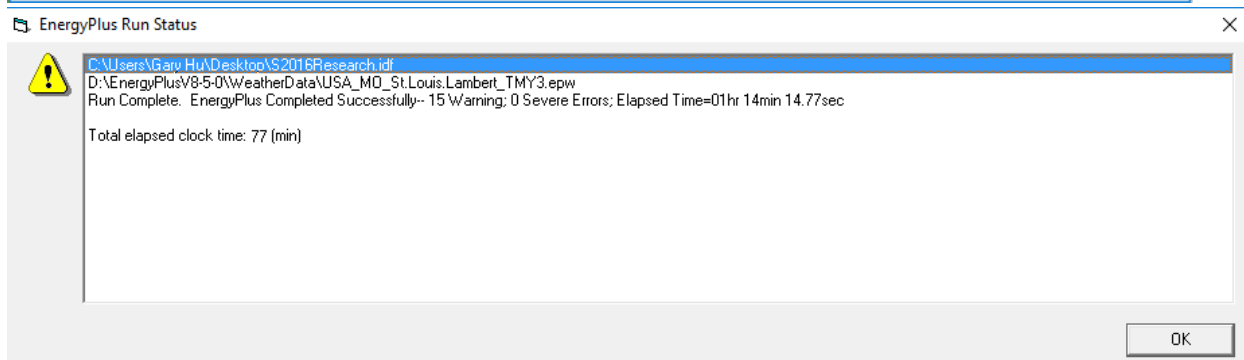
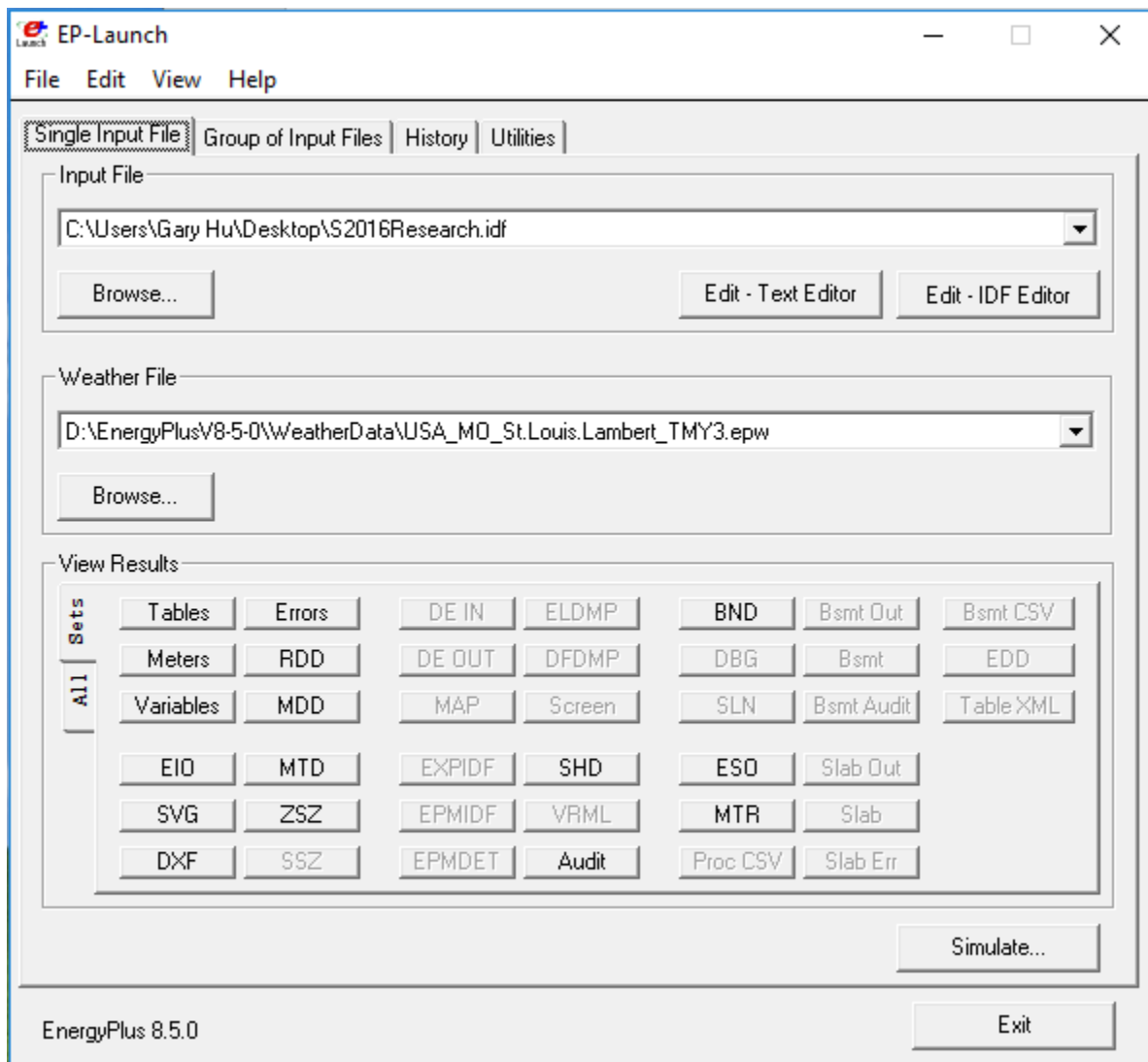
building. Other report types can be selected as needed, including zone environmental and comfort reports, building and block output of zone data, surface heat transfer (can see heat transfer map for each floor), temperature distribution (can be generated to optimize temperature set points), etc.



If you did not include customized weather data with your building model, the following warning may pop out:



By clicking "OK" you will be able to download the default weather data. This default weather file will not be used in EnergyPlus if you include any other weather file later. So it does not matter which weather file you choose at this point.



The EXO and DSF files are parsed and analyzed using DesignBuilder result viewer. The analysis is included in the formal report titled “Accepted Models: Evaluating their effectiveness in Building Energy Simulation”.